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Recent Developments on Mobile Ad-Hoc Networks and Vehicular Ad-Hoc Networks

Edited by
Dimitris Kanellopoulos and Francesca Cuomo
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About the Editors

Dimitris Kanellopoulos received a Diploma in Electrical Engineering and a PhD in Electrical and Computer Engineering from the University of Patras, Greece. Since 1990, he has been a research assistant in the Department of Electrical and Computer Engineering at the University of Patras and involved in several EU R&D projects. Since 2001, he has been a member of the Educational Software Development Laboratory (ESD Lab) in the Department of Mathematics at the University of Patras. Since 2010, he has served as an editor of Informatica and International Journal of Multimedia Intelligence and Security. In 2019, he was appointed as a topic editor of Sensors (MDPI) and Electronics (MDPI). He has also served as a program committee member of many international conferences. He was the Technical Committee Chair of the First International Conference on Multimedia Information Networking and Security (MINES2009), held in Wuhan, Hubei, China during 18–20 November 2009. He is serving as a professional reviewer for many academic journals, including those of IEEE, Elsevier, Springer, Wiley, IET, MDPI, Hindawi, Taylor and Francis, Emerald, IGI Global, and Inderscience. He is a member of the IEEE Technical Committee on Multimedia Communications. He has published over 120 international journal and conference papers in his field. He has edited two books on ”Multimedia Networking” (published by IGI Global). His current research interests include multimedia networks, TCP variants for congestion control, and wireless ad hoc networks, such as mobile ad hoc networks (MANETs) and wireless sensor networks (WSNs). He has been a Guest Editor for various journals such as *Applied Sciences* (MDPI), *Electronics* (MDPI), *Information* (MDPI), *Electronic Commerce Research* (Springer), *Journal of Internet Technology, Informatica*, and *Journal of Computational Methods in Science and Engineering* (IOS Press).

Francesca Cuomo (Professor) received her ”Laurea” degree in Electrical and Electronic Engineering in 1993, magna cum laude, from Sapienza University of Rome, Italy, where she also earned her PhD in Information and Communications Engineering in 1998. From 2005 to October 2020, she was an Associate Professor, and from November 2020, she joined “Sapienza” as Full Professor teaching courses in Telecommunication Networks. Prof. Cuomo has advised numerous master’s students in computer engineering, and has been the advisor of 11 PhD students in Networking. Her current research interests focus on: vehicular networks and sensor networks, low power wide area networks and IoT, 5G networks, multimedia networking, energy saving in the Internet and in the wireless system. She has participated in several national and European projects on wireless network systems (to cite a few: IST WHYLESS, IST EPERSPACE, IST CRUISE, H2020 symbIoTe, H2020 ELEGANT). Francesca Cuomo has authored over 150 peer-reviewed papers published in prominent international journals and conferences. Her Google Scholar h-index is 29, >3700 citations. Relevant scientific international recognitions: 2 Best Paper Awards. She has been on the editorial board of *Computer Networks* (Elsevier) and now is a member of the editorial board of *Ad-Hoc Networks* (Elsevier), *IEEE Transactions on Mobile Computing*, *Sensors* (MDPI), and *Frontiers in Communications and Networks Journal*. She has been the TPC co-chair of several editions of the ACM PE-WASUN workshop, TPC Co-Chair of ICCCN 2016, TPC Symposium Chair of IEEE WiMob 2017, General Co-Chair of the First Workshop on Sustainable Networking through Machine Learning and Internet of Things (SMILING), in conjunction with IEEE INFOCOM 2019; Workshop Co-Chair of AmI 2019: European Conference on Ambient Intelligence 2019. She is an IEEE senior member.

Preface to ”Recent Developments on Mobile Ad-Hoc Networks and Vehicular Ad-Hoc Networks”

Mobile ad hoc networks (MANETs) are deployed mainly in emergency situations like natural disasters and battlefields, as there is no need to deploy any infrastructure to make nodes to communicate with each other. The topology of MANET changes dynamically due to the movement of the nodes and the resulting route failures and re-computations, difficulty in maintaining sessions, and so on. Each MANET node typically maintains the information of end-to-end delay, jitter, loss rate stability, and distance for each link in order to feed routing algorithms. However, this state information is inherently imprecise due to changes in the topology and the fact that resources such as bandwidth, battery, processing, and storage are limited. These peculiar characteristics of MANETs complicate quality of service (QoS) provision and, thus, multimedia communication over MANETs. In the last decade, much research effort has been devoted to addressing various challenges such as (1) effective QoS-based routing protocols and congestion control mechanisms for MANETs, (2) effective TDMA scheduling algorithms that guarantee QoS provisioning over MANETs by reducing the end-to-end delay and drop rate, (3) video streaming over MANETs, and (4) tools that evaluate MANET performance. Topics of interest for this Special Issue are not limited strictly to traditional MANET problems, but also ones that address vehicular ad hoc networks (VANETs). The articles of this Special Issue cover interesting topics such as power-aware optimization solutions for MANETs, data dissemination in VANETs, adaptive multi-hop broadcast schemes for VANETs, multi-metric routing protocols for VANETs, and incentive mechanisms to encourage the distribution of information in VANETs. This volume will be a good collection for designers and engineers in both academia and industry that would like to develop an understanding of emerging technologies of MANETs and VANETs. Students will also find this book to be a useful reference.

Dimitris Kanellopoulos, Francesca Cuomo
Editors

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Editorial

Recent Developments on Mobile Ad-Hoc Networks and Vehicular Ad-Hoc Networks

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1. Introduction

Mobile ad-hoc networks (MANETs) have a decentralized nature that makes them suitable for a variety of applications. The main advantage of a MANET [1] is that its nodes can communicate without any infrastructure. As a result, MANETs are usually deployed in battlefields, natural disasters, etc. MANETs differ from the long-established computer networks, as they have unique characteristics. For example, in a MANET, we observe a frequent link breakage because of node mobility, a high channel-error rate, severe link-layer contentions, and different path properties such as delay, bandwidth, and packet loss rate. Due to these characteristics, the overall performance of a MANET is disturbed in terms of packet delivery ratio, end-to-end delay, network throughput, and network overhead. By applying the principles of MANETs, a vehicular ad-hoc network (VANET) [2] can be established in an ad-hoc mode by vehicles. Using a VANET, vehicles can directly communicate among them, with no supporting infrastructure. Besides, VANETs are employed for road monitoring and infotainment applications, which constitute an integral part of the intelligent transportation system paradigm.

This Special Issue, entitled "Recent Developments on Mobile Ad-Hoc Networks and Vehicular Ad-Hoc Networks", aims to expose the readership to the latest novel works in terms of solutions and techniques for MANETs and VANETs. The Special Issue is composed of five referred papers, covering interesting topics such as power-aware optimization solutions for MANETs, data dissemination in VANETs, adaptive multi-hop broadcast schemes for VANETs, multi-metric routing protocols for VANETs, and incentive mechanisms to encourage the distribution of information in VANETs. The Issue sets out to demonstrate pioneering work in these fields, investigate novel solutions and methods, and discuss future trends in these fields.

2. The Papers in this Special Issue

Using the expected utility theory of conventional economics, we can introduce reward-based incentive mechanisms to enable vehicle nodes to share information in a VANET. These mechanisms often assume that the positive and negative effects (formed by an equivalent quantity of gain and loss) are equal in terms of absolute value. Nevertheless, the theory of loss aversion indicates that the above effects are not equal. Moreover, this can result in a divergence between the last decision-making behaviors of vehicle nodes and the real, most favorable situation.

In the first paper [3], the authors propose a Loss-Aversion-based Incentive Mechanism (LAIM) to encourage the complete awareness and sharing of information in VANETs. To stimulate the cooperation among vehicle nodes, the authors designed the incentive threshold and the threshold factor. The authors redesigned the utility function of nodes to correct the assumption that a gain and a loss of an equal quantity could equalize each other in conventional economics. The simulation results demonstrate that the LAIM mechanism can increase the average utility of nodes by more than 34.35%. This result, in turn, promotes the cooperation of vehicle nodes.

In the past decade, data dissemination in VANETs has attracted much attention, as it is a crucial function for the well-organized exchange of traffic and road information. In VANETs, a research challenge is to propose a multi-hop broadcast scheme that will be adaptive and obtain high reachability whilst utilizing the bandwidth by avoiding redundant transmissions. In the light of this context, the authors of the second paper [4] introduce an intelligent fuzzy logic-based density and distribution adaptive broadcast protocol for VANETs. The new protocol calculates the spatial distribution of vehicles in the network. To enhance reachability, the new protocol uses the Nearest Neighbor Distance method to adapt the transmission range. This adapts the contention window size to the network density and spatial distribution, and thus decreases packet collisions. It also uses the Bloom filter technique to decrease the overhead resulting from the inclusion of the neighbor IDs in the header of the broadcast message. The simulation results demonstrate that the new protocol is effective, as it improves reachability and the ability to utilize bandwidth.

In the third paper [5], the authors introduce an epidemic algorithm (EPIC) for message dissemination in VANETs. The main design goal of the EPIC is "to have the highest number of vehicles "infected" by the message, without overloading the network" [5]. From the literature on the connected cover set, the authors derive a theoretical bound. Then, they compare EPIC with this bound to evaluate the near-optimality of EPIC. It is well-known that ETSI ITS-G5 GeoNetworking is one standard of vehicular communication. In this standard, one of the basic forwarding methods is Contention-Based Forwarding (CBF). As a consequence, the authors compare EPIC with CBF and CBF+ (an evolution of CBF) and prove that, in real urban scenarios, the performance gain of the EPIC algorithm attains a satisfactory result. For example, EPIC can reach many vehicles and involve a small number of relay vehicle nodes.

Moreover, the research community has proposed a plethora of power-aware optimization solutions for MANETs. Such solutions are energy-efficient proactive (link state-based) and reactive (source-initiated-based) routing protocols, routing protocols based on adaptive load balancing, location-based routing protocols, multicast-based and cross-layer based routing protocols, transmission power control-based routing protocols, and approaches based on adaptations of the radio state operational mode. The fourth paper [6] considers key issues on power-aware optimization solutions for MANETs and classifies the existing power-efficient optimization solutions for MANETs into eight categories. The authors extensively review these solutions and discuss open research directions in the field, such as hybrid optimization algorithms for topology management in cluster-based MANETs and the design of cooperative MAC protocols.

From another perspective, existing routing protocols for VANETs often use several metrics to select the best route in a VANET. Such metrics are speed, position, distance, density, and link stability. In the fifth paper [7], the authors present an analysis of those routing protocols which are based on multiple metrics. The authors describe the most often-used metrics in various routing schemes for VANETs and their application scenarios. Their survey employs a systematic literature review methodology that allows them to study the existing high-tech routing schemes for VANETs. In their survey, the authors also confirm that speed and distance are the most accepted and flexible metrics.

Many research challenges have yet to be addressed by the community. For example, it is vital to invent and test new mathematical models [8] for the flooding techniques applied to famous power-efficient routing protocols for MANETs and VANETs. This direction may assist the research community in introducing novel energy-aware flooding methods in ad-hoc networks.

To conclude, we hope the reader will find this Special Issue useful for future research activities in MANETs and VANETs, as well in emerging paradigms related to these topics.

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Article

Cooperation Promotion from the Perspective of Behavioral Economics: An Incentive Mechanism Based on Loss Aversion in Vehicular Ad-Hoc Networks

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Abstract: As a special mobile ad-hoc network, Vehicular Ad-hoc Networks (VANETs) have the characteristics of high-speed movement, frequent topology changes, multi-hop routing, a lack of energy, storage space limitations, and the possible selfishness of the nodes. These characteristics bring challenges to the design of the incentive mechanism in VANETs. In the current research on the incentive mechanism of VANETs, the mainstream is the reward-based incentive mechanism. Most of these mechanisms are designed based on the expected utility theory of traditional economics and assume that the positive and negative effects produced by an equal amount of gain and loss are equal in absolute value. However, the theory of loss aversion points out that the above effects are not equal. Moreover, this will lead to a deviation between the final decision-making behavior of nodes and the actual optimal situation. Therefore, this paper proposed a Loss-Aversion-based Incentive Mechanism (LAIM) to promote the comprehensive perception and sharing of information in the VANETs. This paper designs the incentive threshold and the threshold factor to motivate vehicle nodes to cooperate. Furthermore, based on the number of messages that the nodes face, the utility function of nodes is redesigned to correct the assumption that a gain and a loss of an equal amount could offset each other in traditional economics. The simulation results show that compared with the traditional incentive mechanism, the LAIM can increase the average utility of nodes by more than 34.35%, which promotes the cooperation of nodes.

Keywords: vehicular ad-hoc networks; loss aversion; incentive mechanism; message transmission

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1. Introduction

VANETs are a service system integrating information perception, processing, and interaction [1]. Through wireless communication, VANETs can exchange information with vehicles, roads, pedestrians, and the Internet and can comprehensively perceive and share various static information of traffic participants and the traffic environment.

VANETs contribute to the construction of smart cities [2–5], which can greatly improve the urban environment and improve the living standards of residents, such as traffic congestion [6,7], environmental pollution [8], and so on. However, at the same time, due to the highly dynamic topology, frequently disconnected links [9], restricted movement directions (subject to road directions, signal lights, etc.), the lack of energy, and storage limitations [10–12], the message transmission among nodes cannot be effectively guaranteed. Moreover, the time for vehicle nodes to pass through the coverage of a Road Side Unit (RSU) is usually less than one minute. Therefore, it is difficult for vehicle nodes to download large files directly from the RSU in a short time (for example, videos may be as large as 100 MB). Similarly, the vehicle node cannot always be in the communication range of the RSU, and the transmission of information has a high delay. Therefore, it is necessary to establish a self-organizing network among vehicle nodes.

Existing works had shown that the message transmission status of VANETs can be improved through the incentive mechanism [13–16]. Since VANETs requires a large number of mobile vehicles to participate in cooperative behaviors, cooperative guarantee mechanisms [17–21] are proposed based on incentives. For example, reference [19] proposed a bidding mechanism to encourage vehicles to contribute storage resources. Reference [20] designed a task assignment mechanism based on a contract to improve the utilization rate of vehicle resources. Reference [21] used block chain technology to protect users' privacy while encouraging users to provide reliable information in the form of remuneration and a margin. Most of these mechanisms assume that the same amount of gain can offset the same amount of loss and that nodes transmit messages to surrounding nodes in order to maximize their utility. Behavioral economics studies [22,23] show that an equal amount of loss will have a much more significant impact on nodes than an equal amount of gain, and nodes do not always make decisions to maximize benefits. If this problem is ignored, the actual revenue of users and the number of users who choose to cooperate will be lower than the expected result. Therefore, we need to design an incentive mechanism that takes loss aversion into account.

For a single node, this paper designs an incentive mechanism based on loss aversion by establishing the mapping of loss aversion in a vehicle network. When designing the utility function of a node, this paper first analyzes the number of messages faced by the nodes and then proposes the incentive threshold and the threshold factor. This paper also redesigns the utility function of the nodes, which corrects the assumption that the same amount of gain and loss could offset each other in traditional economics. When designing the decision model of the node, this paper uses the cost and utility of the node as the influencing parameters to define the node's p for different coalitions. Furthermore, this paper designs the merger and separation strategy of coalitions and proposes an algorithm for incentive mechanism based on loss aversion.

The main contributions of this paper are summarized as follows:

1. The Loss-Aversion-based Incentive Mechanism (LAIM) is proposed. Taking the coalition formation game as the analysis tool, this paper proposes the incentive threshold and threshold factor to improve the cooperation rate of vehicle nodes.
2. The coalition merger strategy M and the coalition separation strategy P based on loss aversion are proposed. Vehicle nodes can maximize their utility based on these two strategies.

The remainder of this paper is organized as follows. Section 2 introduces related work on the incentive mechanism of VANETs based on traditional economics while detailing loss aversion. Section 3 introduces a system model for the LAIM. Section 4 verifies the effectiveness of the proposed LAIM through simulation experiments. Finally, Section 5 is the conclusion.

2. Related Work

This section discusses the incentive mechanism of VANETs based on traditional economics and related research on loss aversion.

2.1. Incentive Mechanism of VANETs

In order to further improve people's traveling environment, Intelligent Traffic Systems (ITS) are gradually applied to VANETs. Through the use of ITSs, computer technology and sensor technology can be linked to enhance people's travel experiences. The development of ITSs has solved many problems in VANETs, such as communication difficulties and traffic congestion. Whether in communication technology or practical applications, the success of VANETs needs the message transmission incentive mechanism to ensure the effective transmission of messages. The incentive mechanisms of message transmission in VANETs can be divided into four aspects: reward-based [24], reputation-based [25–28], punishment-based [29], and mobile-social-network-based [30–32].

The incentive mechanisms based on reward provide rewards for nodes to promote cooperation. Reference [24] proposed a Reward and Bonus-based Incentive mechanism (RBI). RBI provides rewards for the nodes participating in message transmission according to their efforts and provides an additional bonus for the last two nodes participating in forwarding. In [25], an incentive-based cooperation content downloading mechanism was proposed. The incentives obtained by nodes were jointly determined by the rewards and the consumption of content transmission. In the incentive mechanism based on reputation, nodes tend to cooperate with nodes with higher reputation values. The Privacy-preserving Trust-based Relay Selection scheme (PTRS) proposed in [26] used the Dirichlet distribution to calculate the feedback reputation, which made the vehicle reputation evaluation more reliable and maintained the robustness of the system at the same time. Reference [27] counted the information of the nodes that had participated in the transmission of messages in the past and calculated the reputation value of the nodes based on these messages. The judgment of the reliability of information in [28] depended on whether the reputation value of the node that generated the information was high. The incentive mechanism based on punishment will detect the behavior of nodes in the network and punish the nodes that show malicious or selfish behaviors in the network. Furthermore, it clears the malicious nodes out of the network to ensure the regular operation of the system. Reference [29] proposed a Payment Punishment Scheme (PPS). The node with the most resources will be selected as the cluster-head node, and the node in the cluster that deliberately provides false information will be punished accordingly. Reference [30] used the tit-for-tat strategy to restrict malicious nodes. The incentive mechanism based on social networks [31] drew on the idea of the mobile social network, explored the possible social relations among nodes in VANETs, and used the social relations among nodes to promote node participation in cooperation. In [32], a Vehicular Social Network Protocol (VSPN) was proposed to establish a social network by collecting the communication information of vehicles to promote cooperation among nodes.

However, current incentive mechanisms are mostly based on traditional economics and ignore the irrational aspects of participants, resulting in the following problems.

They all assume that the more rewards the vehicle nodes receive, the more cooperative they are [24–26]. For example, reference [24] proposed a scheme to allocate rewards to intermediate nodes to increase coalition and proposed an efficient scheme based on an additional reward to increase availability in the network. Reference [25] formulated the cooperative vehicle selection problem as an optimal multiple stopping problem and derived the optimal multiple stopping rules for cooperative downloading to maximize the utilization of benefits. Reference [26] combined rewards and credibility to motivate vehicle nodes to cooperate.

They all assumed that the utility function of nodes is just the revenue minus the cost [28–30]. Reference [28] analyzed the cost of rejoining the system with a new identity. The nodes make decisions based on the compensation minus costs. Reference [29] established models to encourage truth telling during the election process of the nodes in a cluster and directly used the revenue minus the cost as a utility function. Reference [30] changed the node-to-node cooperation decision by rewarding the cooperative nodes and punishing the selfish nodes. The utility of nodes is the reward they finally get. To address the above two issues, this paper introduces loss aversion theory to VANETs. In the following sections, we present the theoretical research on loss aversion from behavioral economics.

Aiming at addressing the deficiencies in the current research, this paper introduces loss aversion theory in behavioral economics to VANETs. Loss aversion in behavioral economics [33] means that people are more averse to lose than gain. Behavioral economics has been widely used in the computer field [34–36]. In mobile crowdsourcing [34], loss aversion is used to redefine the utility function of nodes. Reference [35] used reciprocal altruism in behavioral economics to promote message delivery in the Internet of Vehicles. Reference [36] used reciprocal altruism to improve the cooperation rate of social networks and to promote the spread of cooperation behaviors.

2.2. Loss Aversion

Loss aversion [37] refers to the fact that when people face the same amount of gain and loss, the pain caused by loss is much higher than the pleasure brought by gain. Figure 1 shows the different value curves of decision-makers in traditional economics and behavioral economics. The origin o in the graph represents the point at which the decision-maker measures his/her gain or loss: the positive half axis of x represents the decision-maker's gain; the negative half axis of x represents the decision-maker's loss; and the y-axis represents the actual perceived value of the loss or gain.

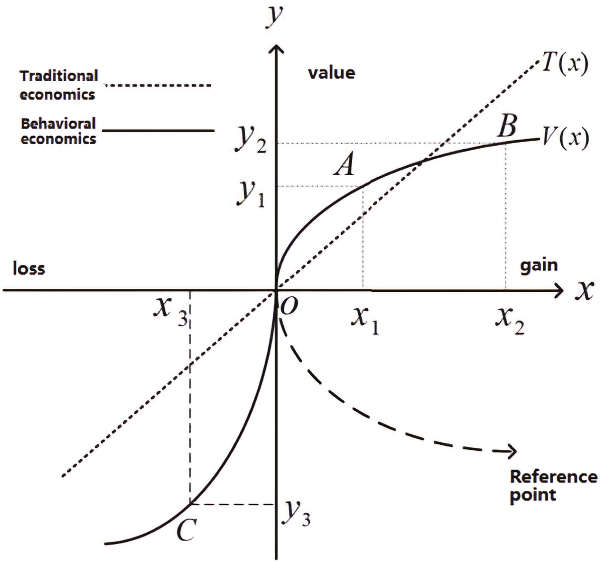


Figure 1. Value function of loss aversion.

As shown in Figure 1, the value curve $T(x)$ of traditional economics reflects the decision-maker's gain and loss of the same amount, and the actual value perceived by the decision-maker is also equal. In other words, for the decision-maker, the happiness brought by an equal amount of gain and the pain caused by the equal amount of loss can offset each other, with $T(x) = x$.

As for the value curve $V(x)$ of behavioral economics, when the point is on the positive half axis of x, the decision-maker acts based on gain; on the negative half axis of x, the decision-maker shows a loss, and it has $|x_1| = |x_3|$ and $|V(x_3)| = |V(x_1)|$ for point $A(x_1, y_1)$ and point $C(x_3, y_3)$. In other words, for decision-makers, the pain caused by the loss is much higher than the pleasure of obtaining the gain. In order to facilitate the analysis, this paper draws on the utility function model of loss aversion [38–43] based on piece-wise linear function, which has seen good research results in the field of behavioral economics. It is an approximation of the nonlinear utility function model proposed by Kahneman and Tversky [37].

At present, there are many types of research on loss aversion in economics. In the aspect of supply chain research, reference [44,45] studied the coordination of the supply chain in the case of retailers and suppliers with loss aversion. In the aspect of auction mechanism research, reference [46] studied bidders with loss aversion. References [47,48] respectively took all-pay auction and reverse auction as research objects and analyzed the impact of participants with loss aversion on the auction. In terms of game theory, reference [49] studied the influence of loss-averse participants on the two-matrix game. Reference [50] studied the Nash balance in the case of loss aversion based on the newsboy game model. Reference [51] took gambling behaviors as the research object and studied the phenomenon that loss aversion makes gamblers prefer to take risks. In the field of biology, reference [52] studied the changes of neural cells' state when people are faced with loss and gain, to introduce the causes of loss aversion.

In summary, no previous study has applied loss aversion to VANETs. Therefore, this paper introduces loss aversion to design the incentive mechanism in VANETs.

3. Design and Analysis of the LAIM

The model in this paper is mainly inspired by the marketing strategy of Amazon's online bookstore. It uses individual nodes' loss aversion psychology to amplify individual nodes' perception of loss and promote nodes to form coalition groups, thereby achieving the purpose of promoting node cooperation.

3.1. Mapping of Loss Aversion

In real life, many merchants will launch preferential activities such as full discounts and free shipping. These activities use consumers' loss aversion to attract customers to spend money [53]. Inspired by the marketing strategy of Amazon's online bookstore, this paper introduces loss aversion into VANETs. The brief introduction of the marketing strategy is as follows:

Amazon's online bookstore has introduced a promotional method that allows free shipping if someone purchases books over a certain amount. For example, if someone only buys a book for \$16.95, he/she will also need to pay \$3.95 for shipping. However, if he/she buys another book, the total amount of which exceeds \$30, there will be no shipping charge. Many book buyers may not have intended to buy another book, but free shipping is so attractive that they are willing to pay for another book in exchange for free shipping [54].

In this example, exempting shipping costs makes people willing to spend more money. This strategy reflects the impact of loss aversion on people's decision-making behaviors. We assume that the incentive threshold is X; in other words, when the consumers' consumption amount reaches X, they can get free freight for d. Since the purchasing behavior only occurs when the utility U_1 of the commodity is higher than the price paid for it, assuming that the consumer has consumed P_c, then the expected utility obtained by the consumer is $U_1 - P_c$. If consumers do not choose to continue to consume, then they will lose the free shipping. For consumers, due to the existence of loss aversion, they will get a loss aversion utility U_2, with $U_2 > d$. At this time, the utility of the consumer is $U_1 - P_c - U_2$. If the consumer chooses to keep consuming and reaches the incentive threshold X, this paper assumes that the utility brought by continued consumption is U_3, then $U_3 > X - P_c$, and the expected utility of the consumers is $U_1 + U_3 - X$. Obviously, with $U_1 + U_3 - X > U_1 + X - P_c - X = U_1 - P_c > U_1 - P_c - U_2$, consumers will choose to continue to consume.

Based on the above example, this paper maps the specific application of loss aversion in promotional means and nodes in VANETs participating in cooperation. The mapping table is shown in Table 1.

3.2. System Model

3.2.1. Physical Model

As shown in Figure 2, our system model mainly includes RSU nodes and vehicle nodes. We suppose that the network involves N vehicle nodes. The set of vehicle nodes is represented by $V = \{V_1, V_2, ..., V_N\}$, where $V_i(i \in [1, N])$ represents the ith vehicle node. At the same time, there are M messages in the network, and $S = \{S_1, S_2, ..., S_M\}$ represents the set of messages. These M messages may be stored in RSU or vehicle nodes. To facilitate the discussion here, the copy of the same message $S_i(i \in [1, M])$ stored in different RSUs or vehicle nodes belongs to the same message.

Table 1. Mapping of loss aversion in VANETs.

	Amazon Online Bookstore	**VANETs**
Incentive object	Consumer	Vehicle node
Incentive threshold	Consumption amount reaches X dollar amount	Participate in cooperation Y times
Event	The consumer has bought the goods with a value of P_c dollars ($P_c < X$)	The number of nodes participating in cooperation reaches T_n ($T_n < Y$)
Incentive process	In order to get free shipping by d dollars, consumers choose to continue to consume p dollars, making $P_c + p \geq X$	In order to get additional bonus utility U, the node chooses to continue to participate in cooperation t times, making $T_n + t \geq Y$
Incentive results	The additional consumption of p dollars by consumers increases the profits of the bookstore	Nodes participate in cooperation t times, which improves the cooperation rate of nodes in the system

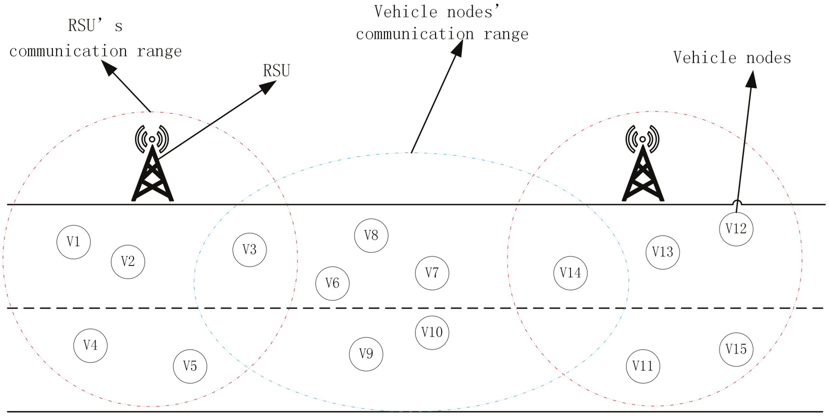


Figure 2. Physical model of VANETs.

When the vehicle node V_i wants to request the message S_i, if it is within the communication range of an RSU, then the node V_i can request to obtain the message S_i from the RSU. If the RSU stores the message S_i, the RSU will directly send the message S_i to the node V_i. If the RSU does not store the message S_i or the node V_i is outside the communication range of the RSU, it can request the message S_i from surrounding qualified nodes, such as the node V_8 in Figure 2. It can first request the message S_i from surrounding nodes, such as V_6 or V_7; if these nodes do not store the message S_i, these nodes can continue to request the message S_i from the nodes around them. Assuming that the node V_3 stores the message S_i, then the message S_i will be transmitted to the node V_8 through the communication link $V_3 \rightarrow V_6 \rightarrow V_8$.

After receiving the message S_i, the node V_8 will store the cooperation record $C = \{ID, L, Time, PK\}$ in the memory, where ID represents the ID of the cooperation record and L is the set of cooperation nodes in the cooperation record. $Time$ represents the time of the cooperation, and PK represents the private key of the node to verify the validity of the cooperation record. When the node moves to the RSU communication range, the cooperation record will be submitted to the RSU for storage, and for the convenience of discussion, the node will submit the cooperation record honestly.

3.2.2. Logical Model

The physical model of VANETs is discussed above, and then, the whole process of the incentive mechanism is discussed.

- As is shown in the logic diagram of Figure 3, in Step 1, the RSU determines the number of messages faced by all individual nodes by analyzing the number of messages Υ_{V_i}. Then, in Step 2, the RSU sets the incentive threshold Θ of the nodes. Only when the number of messages transmitted by the vehicle node satisfies $\Pi_{V_i} \geq \Theta$ can the nodes get the extra reward; when $\Pi_{V_i} < \Theta$, the nodes cannot get the extra reward, and they will regard the reward that cannot get as a loss. The incentive threshold set above is to change the nodes' selection behavior.
- In the third step, the nodes will determine the gain and loss balance point Ω_{V_i} according to the incentive threshold Θ determined by the RSU. After the node V_i calculates the gain and loss balance point Ω_{V_i}, the node V_i can hence get the relationship between the number of messages Π_{V_i} to complete transmission and the number of messages Υ_{V_i}, so that the nodes themselves can determine the number of messages Π_{V_i} to complete transmission. The incentive threshold Θ set by the RSU in Step 2 will cause the loss aversion of nodes, which will affect the choices made by nodes in Step 4.
- After determining the number of tasks chosen, the node will be in a random coalition $C^{V_{cur}} = C_i$ in Step 5, where $C^{V_{cur}}$ represents the current coalition the node will be in as a random coalition and C_i represents one of all those coalitions. Once in the coalition, the node will continuously adjust the strategies shown in Step 6 to maximize its utility. (1) The coalition merger strategy is adopted: if two coalitions merge, to be more specific, the first strategy in Step 6 is called the coalition merger strategy. When this strategy is adopted, the expected utility of the new coalition is less than the original coalition $\Lambda_{C_i \cup C_j} > \Lambda_{C_i} + \Lambda_{C_j}$, where $\Lambda_{C_i \cup C_j}$ represents the expected utility of the new coalition and Λ_C represents the expected utility of the original coalition, and the cost is higher than the original coalition $P_{C_i \cup C_j} < P_{C_i} + P_{C_j}$, where $P_{C_i \cup C_j}$ represents the cost of the new coalition and P_C represents the cost of the original coalition. (2) However, for the second strategy—the coalition separation strategy, once adopted, a coalition will be divided into several coalitions, then the sum of the expected utility of the new coalition is higher than that of the original coalition by $\Lambda_{C_i \cup C_j} < \Lambda_{C_i} + \Lambda_{C_j}$, and the transmission cost is lower than that of the original coalition by $P_{C_i \cup C_j} > P_{C_i} + P_{C_j}$. In Step 7, the node completes the task and obtains the corresponding utility. The main parameters used in this paper are shown in Table 2.

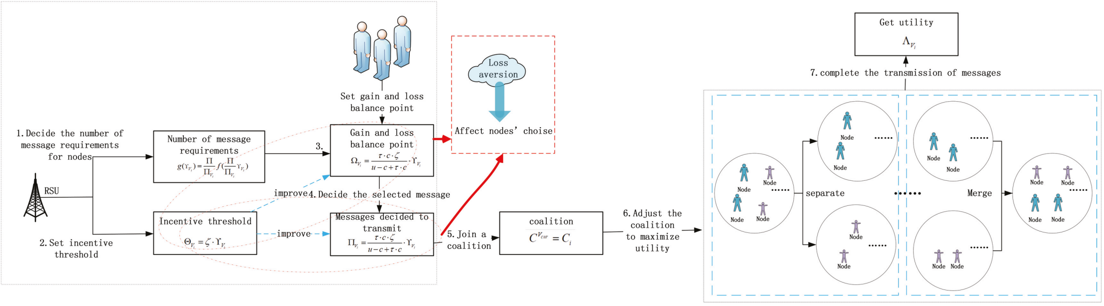


Figure 3. Logical model.

Table 2. Parameter table.

Parameter Name	Description of Parameters
Θ	Incentive threshold
Υ	Message demands
Π_{V_i}	Number of messages that the node V_i has completed
Ω_{Vi}	Gain and loss balance point of node V_i
ζ	Threshold factor
u	Transmission reward
c	Transmission cost
c_o	Threshold of participation
τ	Reward factor
P	Cost of coalition
Λ	The expected utility

3.3. Design of LAIM

In the model, each cooperation of the nodes will bring about consumption. Based on the mapping established in Section 3.1 and the utility function proposed in [37], the utility function of nodes based on loss aversion in VANETs is designed, and the incentive threshold is proposed to encourage nodes to participate in the cooperation. By evaluating the cost of the previous cooperation, additional rewards are given to the nodes who continue to participate in the cooperation. Therefore, the nodes are encouraged to choose to keep participating in the cooperation.

3.3.1. Design of Node's Utility Function Based on Loss Aversion

The primary purpose of this section is to design a utility function based on loss aversion. For the vehicle node V_i in the network G, whenever V_i helps to transmit a message S_i, V_i will obtain a utility function with a positive value. However, due to the consumption of the channel and energy for the transmission of messages, the transmission cost will be brought to the node, that is a negative utility. In order to facilitate the discussion, each time a node participates in the transmission of the message S_i, the node will get a reward u, and the transmission cost c satisfies $u \geq c$. The node will participate in the transfer only if the node's revenue is greater than the threshold c_o. In other words, without considering loss aversion, if $u - c - c_o > 0$, the node will think that participating in the transmission will bring benefits, then it will participate in the transmission; if $u - c - c_o < 0$, the node will think that participating in the transmission will bring loss, and hence will not participate in the transmission.

In this section of the network model, whenever a node needs to obtain messages from other nodes, a message demand will be generated. The number of messages will ultimately affect the overall utility of the nodes. Therefore, before designing the utility function of the node, the total messages Υ in the network G will be discussed here first.

1. Number of messages:

In a certain period T, assume that there are Υ messages in the network, that is to say the number of messages to be obtained from other nodes is Υ. All possible values of Υ obey the normal distribution at time T (since the normal distribution is the most common distribution in nature), that is $\Upsilon \sim N(\mu, \sigma^2)$, where μ represents the mathematical expectation of all possible values and σ is the standard deviation of all possible values. Then, it is easy to know that the probability density function $f(\Upsilon)$ of messages Υ satisfies Formula (1):

$$f(\Upsilon) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\Upsilon-\mu)^2}{2\sigma^2}} \tag{1}$$

At the same time, the probability distribution function $F(\Upsilon)$ of messages satisfies Formula (2):

$$F(\Upsilon) = \int_{-\infty}^{\Upsilon} f(\Upsilon) d\Upsilon = \int_{-\infty}^{\Upsilon} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\Upsilon-\mu)^2}{2\sigma^2}} d\Upsilon \tag{2}$$

In Formula (2) $\Upsilon \in R$, since the number of messages Υ in time T satisfies $\Upsilon \geq 0$, Formula (2) can be further simplified as Formula (3):

$$F(\Upsilon) = \frac{1}{\sqrt{2\pi}\sigma} \int_0^{\Upsilon} e^{-\frac{(\Upsilon-\mu)^2}{2\sigma^2}} d\Upsilon \tag{3}$$

In time T, for the node V_i, the number of messages that need to be transmitted by the node V_i is Υ_{V_i} and with $\Upsilon_{V_i} \leq \Upsilon$. Similarly, Υ_{V_i} satisfies the normal distribution, and the probability density function and the probability distribution function of Υ_{V_i} are $g(\Upsilon_{V_i})$ and $G(\Upsilon_{V_i})$ respectively. Suppose that the total number of messages that all nodes that choose to complete transmission at time T is $\prod$, the number of messages that the node V_i chooses to complete transmission at time T is $\prod_{V_i}$, and the sum of messages selected by other nodes to complete transmission at the same time is $\prod_{-V_i}$; since the number of messages is constant, there is $\prod = \prod_{V_i} + \prod_{-V_i}$. In the system model of this section, for the node V_i, the more messages Υ_{V_i} the node faces and messages Π_{V_i} it chooses to help complete, the more utility the node finally obtains. Therefore, Υ_i is directly proportional to Π_{V_i}, which satisfies Formula (4):

$$\Upsilon_{Vi} = \frac{\Pi_{V_i}}{\Pi} \Upsilon \tag{4}$$

According to Formulas (3) and (4), we have Formulas (5) and (6):

$$G(\Upsilon_{Vi}) = F\left(\frac{\Pi}{\Pi_{V_i}} \Upsilon_{Vi}\right) \tag{5}$$

$$g(\Upsilon_{Vi}) = \frac{\Pi}{\Pi_{V_i}} f\left(\frac{\Pi}{\Pi_{V_i}} \Upsilon_{Vi}\right) \tag{6}$$

The purpose of analyzing the number of messages Υ is to model the messages faced by the whole network and a single node. Furthermore, through analysis, it can provide a theoretical basis for the analysis of the possible value of the message number, the choosing of the cooperative behavior of the node, and the final utility.

2. Incentive threshold and threshold factor:

The incentive threshold Θ refers to the number of messages required for nodes to obtain additional rewards; in other words, nodes can only get additional rewards if they cooperate more than a few certain times. The reward factor is defined as τ, $\tau \in (0, 1)$, and the bigger τ is, the more additional rewards the node will get. Due to the loss aversion characteristic of nodes, according to the previous hypothesis, the perceived gain Γ_{V_i} of node V_i is defined as shown in Formula (7):

$$\Gamma_{V_i} = (u - c - c_o) \cdot \Pi_{V_i} + \tau \cdot (c + c_o) \cdot \left(\Pi_{V_i} - \Theta_{Vi}\right) \tag{7}$$

According to Formula (7), when $\prod_{V_i} < \Theta_{V_i}$, there is $\Gamma_{V_i} = (u - c - c_o) * \prod_{V_i} - \tau * c * (\Theta_{V_i} - \prod_{V_i})$. This is because according to the analysis in Section 3.1, the node will regard the additional reward that cannot be obtained as a loss under the influence of loss aversion, which is further explained by Lemma 1.

Lemma 1. *For the node V_i, when $u - c - c_o < 0$ and $\tau > 1 - \frac{u}{c+c_o}$, the node V_i will still choose to continue the cooperation.*

Proof of Lemma 1. When the loss utility is not considered, the profit of the node V_i is: $u - c - c_o < 0$, then nodes will not participate in the cooperation. When the loss utility is considered, the profit of the node V_i is $\Gamma_{V_i} = (u - c - c_o) + \tau * (c + c_o)$. As $\tau > 1 - \frac{u}{c+c_o}$, then $\Gamma_{V_i} > 0$, so the node V_i will choose to continue the cooperation. □

According to Lemma 1, Θ_{V_i} should be at least $\Theta_{V_i} \geq \prod_{V_i}$ in order to motivate nodes to choose to continue the cooperation. At the same time, one of the purposes of the mechanism proposed in this section is to promote the nodes to complete the messages of the surrounding nodes, as many as possible. Therefore, assume that the incentive threshold Θ_{V_i} corresponding to the node V_i satisfies $\Theta_{V_i} \propto \Upsilon_{V_i}$, and the relationship between Θ_{V_i} and Υ_{V_i} is defined as the following Formula (8):

$$\Theta_{Vi} = \zeta \cdot \Upsilon_{Vi} \tag{8}$$

In Formula (8), ζ is the threshold factor that represents the ratio of the incentive threshold Θ_{V_i} of the node V_i to the number of messages Υ_{V_i}, which is $0 < \zeta \leq 1$.

After bringing Formula (8) into Formula (7), we have Formula (9):

$$\Gamma_{V_i} = (u - c - c_o) \cdot \Pi_{V_i} + \tau \cdot (c + c_o) \cdot \left(\Pi_{V_i} - \zeta \cdot \Upsilon_{Vi}\right) \tag{9}$$

3. Expected utility of nodes:

According to Formula (9), the gain Γ_{V_i} of the node V_i is related to the messages faced by the node Υ_{V_i} at time T and the number of messages that the node chooses to complete the transmission $\prod_{V_i}$. Therefore, before analyzing the expected utility function of the node V_i, the balance point of the perceived gain and loss of the node V_i is defined as follows:

Definition 1 (The gain and loss balance point of node V_i (Ω_{V_i}))**.** *According to the analysis in the previous section, when the conditions are met, the node can choose the number of messages to complete the transmission at will. This means that the number of messages that the node chooses to transmit N and the number of messages Υ_{V_i} it faces satisfies $\prod_{V_i} \in [0, \Upsilon_{V_i}]$. If $\Omega_{V_i} \in (0, \Upsilon_{V_i})$ and $\prod_{V_i} \in (0, \Omega_{V_i})$, then we have $\Gamma_{V_i} < 0$; when $\prod_{V_i} = \Omega_{V_i}$, we have $\Gamma_{V_i} = 0$; when $\prod_{V_i} \in (\Omega_{V_i}, \Upsilon_{V_i}]$, we have $\Gamma_{V_i} > 0$, then Ω_{V_i} is called the gain and loss balance point of node V_i.*

According to the characteristics of loss aversion, the node's perception of equal loss and gain is different. Therefore, the definition of gain and loss balance point Ω_{V_i} is to distinguish the loss and gain part of the node V_i when analyzing the utility Λ_{V_i} of the node. The detailed analysis of Ω_{V_i} is shown in Theorem 1.

Theorem 1. *There is Ω_{V_i} that allows the node to distinguish between the gains and losses of its own utility.*

Proof of Theorem 1. According to Formula (9), when $\Pi_{V_i} \geq \Upsilon_{V_i} * \zeta$, we have $\Gamma_{V_i} = (u - c - c_o) * \prod_{V_i} + \tau * (c + c_o) * (\prod_{V_i} - \zeta * \Upsilon_{V_i})$, because $\tau * (c + c_o) * (\Pi_{V_i} - \zeta * \Upsilon_i) \geq 0$, $u > (c + c_o)$l therefore, in this case, $\Gamma_{V_i} > 0$. If $\prod_{V_i} < \zeta * \Upsilon_{V_i}$, $\Gamma_{V_i} = 0$ is possible. Therefore, when $\prod_{V_i} < \zeta * \Upsilon_{V_i}$, $\Gamma_{V_i} = (u - c - c_o) * \prod_{V_i} - \tau * (c + c_o) * (\zeta * \Upsilon_{V_i} - \prod_{V_i})$ can be calculated; let $\Gamma_{V_i} = 0$, then $(u - c - c_o) * \prod_{V_i} = \tau * (c + c_o) * (\zeta * \Upsilon_{V_i} - \prod_{V_i})$. By simplifying the formula, the following result can be calculated: $\prod_{V_i} = \frac{\tau * (c + c_o) * \zeta}{u - c - c_o + \tau * (c + c_o)} * \Upsilon_{V_i}$, according to Definition 1, when $\Omega_{V_i} = \prod_{V_i} = \frac{\tau * (c + c_o) * \zeta}{u - c - c_o + \tau * (c + c_o)} * \Upsilon_{V_i}$, the gain and loss balance point of the node is deduced. □

According to Theorem 1, after the gain and loss balance point Ω_{V_i} of node V_i is obtained, the user utility affected by the cost and benefit can be further discussed. The relationship between the number of messages $\prod_{V_i}$ chosen by the node V_i and the number of messages Υ_{V_i} that the node V_i faces satisfies Formula (10):

$$\Pi_{V_i} = \frac{\tau \cdot (c + c_o) \cdot \zeta}{u - c - c_o + \tau \cdot (c + c_o)} \Upsilon_{Vi} \tag{10}$$

According to Formula (10), the following Formula (11) is met when the balance point of gain and loss Ω_{V_i} is reached:

$$\Upsilon_{Vi} = \frac{u - c - c_o + \tau \cdot (c + c_o)}{\tau \cdot (c + c_o) \cdot \zeta} \Pi_{V_i} \tag{11}$$

According to Formulas (9) and (11), the expected utility Λ_{V_i} of the node V_i can be deduced as shown in Formula (12):

$$\begin{aligned} \Lambda_{Vi} =& \lambda_i \cdot \int_0^{\frac{u-c-c_o+\tau\cdot(c+c_o)}{\tau\cdot(c+c_o)\cdot\zeta}\Pi_{V_i}} \left[(u-c-c_o)\cdot\Pi_{V_i} - \tau\cdot(c+c_o)\cdot\left(\zeta\cdot\Upsilon_{Vi} - \Pi_{V_i}\right)\right] d\Upsilon_{Vi} \\ &+ \int_{\frac{u-c-c_o+\tau\cdot(c+c_o)}{\tau\cdot(c+c_o)\cdot\zeta}\Pi_{V_i}}^{\frac{\Pi_{V_i}}{\zeta}} \left[(u-c-c_o)\cdot\Pi_{V_i} - \tau\cdot(c+c_o)\cdot\left(\zeta\cdot\Upsilon_{Vi} - \Pi_{V_i}\right)\right] d\Upsilon_{Vi} \\ &+ \int_{\frac{\Pi_{V_i}}{\zeta}}^{+\infty} \left[(u-c-c_o)\cdot\Pi_{V_i} + \tau\cdot(c+c_o)\cdot\left(\Pi_{V_i} - \zeta\cdot\Upsilon_{Vi}\right)\right] d\Upsilon_{Vi} \end{aligned} \tag{12}$$

In Formula (12), λ_i is the loss aversion coefficient of the node V_i, indicating the degree of the node's loss aversion, and it satisfies $\lambda_i > 1$. Since the distribution of the number of messages that a node faces Υ_{V_i} is an uncertain value and we only know its distribution $\int_0^{+\infty} g\left(\Upsilon_{V_i}\right) d\Upsilon_{V_i} = 1$, this paper hence needs to calculate the expected value according to the distribution function of Υ_{V_i}. According to Formulas (10) and (11), the distribution function of Υ_{V_i} can be divided into three parts. The first part represents the probability that a node will lose when participating in the cooperation, that is to say, in the interval $\left(0, \frac{u-c-c_o+\tau*(c+c_o)}{\tau*(c+c_o)*\zeta} * \prod_{V_i}\right)$ calculated in Formula (11), and the utility of the node corresponding to this part of the probability is the first part of Formula (12). The second part represents the probability that the node participating in the cooperation will benefit, but fails to reach the threshold,;in other words, in the interval $\left(\frac{u-c-c_o+\tau*(c+c_o)}{\tau*(c+c_o)*\zeta} * \prod_{V_i}, \frac{\Pi_{V_i}}{\zeta}\right)$. The utility of the node corresponding to this part of the probability is the second part of Formula (12). The third part represents the probability that a node will benefit from cooperation and reach the threshold, that is in the interval $\left(\frac{\Pi_{V_i}}{\zeta}, +\infty\right)$. The utility of the node corresponding to this probability is the third part of Formula (12).

3.3.2. Design of the Node's Decision Model Based on Loss Aversion

This section uses the loss aversion of nodes to promote individual nodes to choose cooperation behavior and finally form the coalition group. Since the coalition formation game [55–57] is a common tool for analyzing the coalition group formed by the participants in the network, this section takes the coalition formation game as the analysis tool. The nodes in the network are considered as participants in the coalition game, and the nodes in the coalition can act as relay nodes to forward messages for the nodes outside the communication range of the source node. Based on loss aversion, the node's decision model is designed.

1. Node decision model based on loss aversion:

In the model proposed in this section, the coalition formation game is used as the analysis tool. Assume that the coalition i is represented by $C_i \in C$ and C is the coalition set of the current network, with $C = \{C_1, C_2, ..., C_i, ..., C_n\}$ and $n \in N$. Each coalition contains at least one node, and the node V_i can choose to join or leave a certain coalition C_i. Nodes cannot exist in two coalitions at the same time.

Suppose that the coalition game in this section is represented by $G = \{C, V, \Lambda, S, F\}$, where V is the set of nodes in the model, then there is $V = \{V_1, V_2, ..., V_i, ..., V_n\}$, where $n \in N$. Λ_{V_i} is the expected utility of nodes V_i, and S is the strategy set of all nodes, then we have $S = \{S_1, S_2, ..., S_i, ..., S_n\}$ and $n \in N$. Furthermore, S_i is the strategy combination of the node V, $S_i = \{s_i1, s_i2, ..., s_in\}$, and s_in is the single strategy of the node V_i. F is the decision function of the node, which is the decision-making basis that the node chooses whether to leave the current coalition or continue staying in the current coalition.

Definition 2 (The selection p of the node V_i ($\succ_i$))**.** *For the node V_i, when the following Formula (13) is true:*

$$\sum_{k=1}^{\Pi_{V_i}^{C_i}} c < \sum_{k=1}^{\Pi_{V_i}^{C_j}} c \wedge \Lambda_{V_i}^{C_i} > \Lambda_{V_i}^{C_i}, \tag{13}$$

then node V_i is inclined to prefer coalition C_i to coalition C_j, which is expressed as $C_i \succ_i C_j$. Among them, C_i is assumed to be the current coalition of the node, and C_j is a coalition that the node can choose to join or not. $\prod_{V_i}^{C_i}$ and $\prod_{V_i}^{C_j}$ represent the number of messages that the node V_i chooses to complete transmitting in coalitions C_i and C_j respectively. $\Lambda_{V_i}^{C_i}$ and $\Lambda_{V_i}^{C_j}$ represent the expected utility that the node V_i can require in coalitions C_i and C_j, respectively.

It can be seen from Definition 2 that when the node is in the coalition C_i, if the cost of transmitting messages in the coalition C_i is less than that in the coalition C_j and the expected utility of nodes in the coalition C_i is higher than that in the coalition C_j, then nodes will preferentially join or remain in the coalition C_i.

According to Definition 2, the F of the node V_i is defined as the following Formula (14):

$$F = \begin{cases} 0 & , C_i \succ_i C_j \\ 1 & , Other \quad situation \end{cases} \tag{14}$$

When the value of F is zero, this means that the node will continue staying in the current coalition C_i. When it is one, this means that the node will leave the current coalition and join the new coalition C_j.

One of the main purposes of the model proposed in this section is to promote nodes to join or form a coalition, to enhance the expected utility of nodes, to encourage nodes to participate in the message cooperation transmission. Different scales of coalitions can form a whole new bigger coalition while a bigger coalition can also be separated into several coalitions of different scales.

Definition 3 (Coalition merger strategy M)**.** *For any node in the coalition C_i, if the p for the new coalition after merging is better than that of the original one and the condition is also satisfied for the nodes in the coalition C_j, then the merger of the coalition C_i and C_j is a coalition merger strategy M.*

According to Definition 3, when Formula (15) is right between any two coalitions, these coalitions will form a new coalition:

$$\left[\forall V_m \in C_i, C_i \succ_m \left(C_i \cup C_j\right)\right] \wedge \left[\forall V_n \in C_j, C_j \succ_n \left(C_i \cup C_j\right)\right] \tag{15}$$

In Formula (15), $C_i \cup C_j$ represents the new coalition after the coalitions C_i and C_j are merged.

Definition 4 (Coalition separation strategy P)**.** *When there is at least one node in coalitions C_i or C_j and the node's p for coalitions C_i or C_j is higher than that for the coalition $C_i \cup C_j$, then the coalition $C_i \cup C_j$ is separated into coalitions C_i and C_j, which is a coalition separation strategy.*

According to Definition 4, when Formula (16) is true, the coalition will be separated into different coalitions:

$$\left[\forall V_m \in C_i, \left(C_i \cup C_j\right) \succ_m C_i\right] \wedge \left[\forall V_n \in C_j, \left(C_i \cup C_j\right) \succ_n C_j\right] \tag{16}$$

From Definitions 3 and 4, it can be seen that when a node joins or leaves a coalition, the merger and separation of the coalition will have an impact on the formation of the coalition game in the system model. Therefore, in the following summary, this paper will discuss and analyze these situations and evaluate the performance of the loss-averse node's decision-making model proposed in this section.

2. Analysis of model performance:

According to the previous analysis, the cost and expected utility of nodes participating in the message transmission in the system model will affect the cooperation degree of nodes. Therefore, the expected utility and cost of the coalition to evaluate the performance of the model is proposed in this section.

Definition 5 (Expected utility of coalition C_i (Λ_{C_i}))**.** *The expected utility of the coalition C_i is the sum of the expected utility of all nodes in the coalition.*

According to Definition 5, we have Formula (17):

$$\Lambda_{C_i} = \sum_{V_i \in C_i} \Lambda_{V_i}^{C_i} \tag{17}$$

Definition 6 (The transmission cost of coalition C_i (P_{C_i}))**.** *The transmission cost of the coalition C_i is the sum of the transmission costs of all nodes in the coalition.*

According to Definition 6, we have Formula (18):

$$P_{C_i} = \sum_{V_i \in C_i} \sum\nolimits_{K=1}^{\Pi_{V_i}^{C_i}} c \tag{18}$$

In the coalition formation game, one of the purposes of the nodes forming the coalition is to improve their expected utility and reduce their costs through cooperation. Therefore, one of the purposes of analyzing the expected utility and cost of the coalition is to evaluate the rationality of the formation of the coalition. If a new coalition is formed, the expected utility of the new coalition will be less than that of the original one, and the cost will be higher than that of the original one, then the coalition is unreasonable. The analysis of the coalition merger strategy is given by Theorem 2.

Theorem 2. *$\forall C_i$, C_j, $\forall V_i \in C_i$, $\forall V_j \in C_j$ of the coalition separation strategy M has $\Lambda_{C_i \cup C_j} > \Lambda_{C_i} + \Lambda_{C_j}$ and $P_{C_i \cup^{C_j}} < P_{C_i} + P_{C_j}$.*

Proof of Theorem 2. According to Formulas (17) and (18), the following formula can be used: $[\forall V_m \in C_i, (C_i \cup^{C_j}) \succ_m C_i] \wedge [\forall V_n \in C_j, (C_i \cup^{C_j}) \succ_n C_j]$, and $\forall V_m \in C_i, \forall V_n \in C_j$, satisfy $\Lambda_{V_m}^{C_i \cup^{C_j}} > \Lambda_{V_m}^{C_i}, \Lambda_{V_n}^{C_i \cup^{C_j}} > \Lambda_{V_n}^{C_j}, \sum\nolimits_{\kappa=1}^{\Pi_{V_m}^{C_i \cup^{C_j}}} c < \sum\nolimits_{\kappa=1}^{\Pi_{V_m}^{C_i}} c, \sum\nolimits_{\kappa=1}^{\Pi_{V_n}^{C_i \cup^{C_j}}} c < \sum\nolimits_{\kappa=1}^{\Pi_{V_n}^{C_i}} c$, so there are $\Lambda_{C_i} + \Lambda_{C_j} = \sum\limits_{V_i \in C_i} \Lambda_{V_i}^{C_i} + \sum\limits_{V_j \in C_j} \Lambda_{V_j}^{C_j} < \sum\limits_{V_i \in C_i} \Lambda_{V_i}^{C_i \cup^{C_j}} + \sum\limits_{V_j \in C_j} \Lambda_{V_j}^{C_i \cup^{C_j}} = \Lambda_{C_i \cup^{C_j}}$, and $P_{C_i} + P_{C_j} = \sum\limits_{V_i \in C_i} \sum\limits_{\kappa=1}^{\Pi_{V_i}^{C_i}} c + \sum\limits_{V_j \in C_j} \sum\limits_{\kappa=1}^{\Pi_{V_j}^{C_j}} c > \sum\limits_{V_i \in C_i} \sum\limits_{\kappa=1}^{\Pi_{V_i}^{C_i \cup^{C_j}}} c + \sum\limits_{V_j \in C_j} \sum\limits_{\kappa=1}^{\Pi_{V_j}^{C_i \cup^{C_j}}} c = P_{C_i \cup^{C_j}}$ □

It can be seen from Theorem 2 that when the coalition satisfying Formula (15) forms a new coalition, the expected utility of the new coalition will be higher than that of the original coalition, and the transmission cost is lower than that of the original coalition. In other words, the coalition merging strategy can allow each node to obtain higher expected utility and lower transmission cost in the new coalition. In this way, the nodes are facilitated to participate in the cooperation. The analysis of the coalition separation strategy is given by Theorem 3.

Theorem 3. $\forall C_i, C_j \in (C_i \cup^{C_j})$, $\forall V_i \in C_i$, $\forall V_j \in C_j$ *of the coalition separation strategy* P *has* $\Lambda_{C_i \cup^{C_j}} < \Lambda_{C_i} + \Lambda_{C_j}$ *and* $P_{C_i \cup C_j} > P_{C_i} + P_{C_j}$

Proof of Theorem 3. According to Theorem 2, it is known that: $[\exists V_m \in C_i, C_i \succ_m (C_i \cup^{C_j})] \wedge [\exists V_n \in C_j, C_j \succ_n (C_i \cup^{C_j})]$, and $\exists V_m \in C_i$, $\exists V_n \in C_j$ satisfy $\Lambda_{V_m}^{C_i \cup^{C_j}} < \Lambda_{V_m}^{C_i}$, $\Lambda_{V_n}^{C_i \cup^{C_j}} < \Lambda_{V_n}^{C_j}$, $\sum_{\kappa=1}^{\Pi_{V_m}^{C_i \cup^{C_j}}} c > \sum_{\kappa=1}^{\Pi_{V_m}^{C_i}} c$, $\sum_{\kappa=1}^{\Pi_{V_n}^{C_i \cup^{C_j}}} c > \sum_{\kappa=1}^{\Pi_{V_n}^{C_j}} c$, then $\Lambda_{C_i} + \Lambda_{C_j} = \sum\limits_{V_i \in C_i} \Lambda_{V_i}^{C_i} + \sum\limits_{V_j \in C_j} \Lambda_{V_j}^{C_j} = \sum\limits_{V_i \in \{C_i \backslash V_m\}} \Lambda_{V_i}^{C_i} + \sum\limits_{V_m \in C_i} \Lambda_{V_m}^{C_i} + \sum\limits_{V_j \in \{C_j \backslash V_n\}} \Lambda_{V_j}^{C_j} + \sum\limits_{V_n \in C_j} \Lambda_{V_n}^{C_j} > \sum\limits_{V_i \in \{C_i \backslash V_m\}} \Lambda_{V_i}^{C_i} + \sum\limits_{V_m \in C_i \cup^{C_j}} \Lambda_{V_m}^{C_i \cup^{C_j}} + \sum\limits_{V_j \in \{C_j \backslash V_n\}} \Lambda_{V_j}^{C_j} + \sum\limits_{V_n \in C_i \cup^{C_j}} \Lambda_{V_n}^{C_i \cup^{C_j}} = \sum\limits_{V_i \in C_i \cup^{C_j}} \Lambda_{V_i}^{C_i \cup^{C_j}} + \sum\limits_{V_j \in \{(C_i \cup^{C_j}) \backslash V_i\}} \Lambda_{V_j}^{C_i \cup^{C_j}} = \Lambda_{C_i \cup^{C_j}}$, $P_{C_i} + P_{C_j} = \sum\limits_{V_i \in C_i} \sum\limits_{\kappa=1}^{\Pi_{V_i}^{C_i}} c + \sum\limits_{V_j \in C_j} \sum\limits_{\kappa=1}^{\Pi_{V_j}^{C_j}} c = \sum\limits_{V_i \in C_i \backslash V_m} \sum\limits_{\kappa=1}^{\Pi_{V_i}^{C_i}} c + \sum\limits_{V_m \in C_i} \sum\limits_{\kappa=1}^{\Pi_{V_m}^{C_i}} c + \sum\limits_{V_j \in C_j \backslash V_n} \sum\limits_{\kappa=1}^{\Pi_{V_j}^{C_j}} c + \sum\limits_{V_n \in C_i} \sum\limits_{\kappa=1}^{\Pi_{V_n}^{C_i}} c < \sum\limits_{V_i \in C_i \backslash V_m} \sum\limits_{\kappa=1}^{\Pi_{V_i}^{C_i}} c + \sum\limits_{V_m \in C_i} \sum\limits_{\kappa=1}^{\Pi_{V_m}^{C_i \cup^{C_j}}} c + \sum\limits_{V_j \in C_j \backslash V_n} \sum\limits_{\kappa=1}^{\Pi_{V_j}^{C_j}} c + \sum\limits_{V_n \in C_i} \sum\limits_{\kappa=1}^{\Pi_{V_n}^{C_i \cup^{C_j}}} c = \sum\limits_{V_i \in C_i} \sum\limits_{\kappa=1}^{\Pi_{V_i}^{C_i \cup^{C_j}}} c + \sum\limits_{V_j \in C_j} \sum\limits_{\kappa=1}^{\Pi_{V_j}^{C_i \cup^{C_j}}} c = P_{C_i \cup^{C_j}}$. □

It can be seen from Theorem 3 that the coalition satisfying Formula (16) will be separated into multiple coalitions. It can be found that the sum of the expected utility of the new coalition is higher than that of the original one, and the transmission cost is lower than that of the original one. In other words, coalition separation can make at least one node obtain higher expected utility and lower transmission cost in the new coalition, thus promoting the nodes to participate in the cooperation.

From the analysis of Theorems 2 and 3, it can be concluded that the coalition merger strategy M and the coalition separation strategy P can bring higher utility and lower costs to nodes by merging or separating coalitions among nodes. Next, this paper will analyze whether there is an optimal expected utility in the coalition through Theorem 4.

Theorem 4. $\forall V_i \in C_i, \exists \Pi_{V_i}^{C_i *}$ *makes* $\Lambda_{V_i}^{C_i}$ *get the optimal value when* $\Pi_{V_i}^{C_i} = \Pi_{V_i}^{C_i *}$, *that is to say the node obtains the maximum utility.*

Proof of Theorem 4. The integral of Formula (12) by parts is as follows:

$$\begin{aligned}\Lambda_{V_i} = {} & \lambda_i \cdot \int_0^{\frac{u-c+\tau\cdot c}{\tau\cdot c\cdot\zeta}\cdot\Pi_{V_i}^{C_i}} (u-c)\cdot\Pi_{V_i}^{C_i}\cdot g(\Upsilon_{V_i})d\Upsilon_{V_i} - \lambda_i \cdot \int_0^{\frac{u-c+\tau\cdot c}{\tau\cdot c\cdot\zeta}\cdot\Pi_{V_i}^{C_i}} \tau\cdot c\cdot\zeta\cdot\Upsilon_{V_i}\cdot g(\Upsilon_{V_i})d\Upsilon_{V_i} \\ & + \lambda_i \cdot \int_0^{\frac{u-c+\tau\cdot c}{\tau\cdot c\cdot\zeta}\cdot\Pi_{V_i}^{C_i}} \tau\cdot c\cdot\Pi_{V_i}^{C_i}\cdot g(\Upsilon_{V_i})d\Upsilon_{V_i} + \int_{\frac{u-c+\tau\cdot c}{\tau\cdot c\cdot\zeta}\cdot\Pi_{V_i}^{C_i}}^{\frac{\Pi_{V_i}^{C_i}}{\zeta}} (u-c)\cdot\Pi_{V_i}^{C_i}\cdot g(\Upsilon_{V_i})d\Upsilon_{V_i} \\ & - \int_{\frac{u-c+\tau\cdot c}{\tau\cdot c\cdot\zeta}\cdot\Pi_{V_i}^{C_i}}^{\frac{\Pi_{V_i}^{C_i}}{\zeta}} \tau\cdot c\cdot\zeta\cdot\Upsilon_{V_i}\cdot g(\Upsilon_{V_i})d\Upsilon_{V_i} + \int_{\frac{u-c+\tau\cdot c}{\tau\cdot c\cdot\zeta}\cdot\Pi_{V_i}^{C_i}}^{\frac{\Pi_{V_i}^{C_i}}{\zeta}} \tau\cdot c\cdot\Pi_{V_i}^{C_i}\cdot g(\Upsilon_{V_i})d\Upsilon_{V_i} \\ & + \int_{\frac{\Pi_{V_i}^{C_i}}{\zeta}}^{+\infty} (u-c)\cdot\Pi_{V_i}^{C_i}\cdot g(\Upsilon_{V_i})d\Upsilon_{V_i} + \int_{\frac{\Pi_{V_i}^{C_i}}{\zeta}}^{+\infty} \tau\cdot c\cdot\Pi_{V_i}^{C_i}\cdot g(\Upsilon_{V_i})d\Upsilon_{V_i}\end{aligned}$$

$$- \int_{\frac{\Pi_{V_i}^{C_i}}{\zeta}}^{+\infty} \tau \cdot c \cdot \zeta \cdot \Upsilon_{V_i} \cdot g(\Upsilon_{V_i}) d\Upsilon_{V_i} = \lambda_i \cdot \tau \cdot c \cdot \zeta \cdot \int_0^{\frac{u-c+\tau \cdot c}{\tau \cdot c \cdot \zeta} \cdot \Pi_{V_i}^{C_i}} G(\Upsilon_{V_i}) d\Upsilon_{V_i}$$

$$+ \tau \cdot c \cdot \zeta \cdot \int_{\frac{u-c+\tau \cdot c}{\tau \cdot c \cdot \zeta} \cdot \Pi_{V_i}^{C_i}}^{\frac{\Pi_{V_i}^{C_i}}{\zeta}} G(\Upsilon_{V_i}) d\Upsilon_{V_i} - \tau \cdot c \cdot \zeta \cdot \int_{\frac{\Pi_{V_i}^{C_i}}{\zeta}}^{+\infty} G(\Upsilon_{V_i}) d\Upsilon_{V_i}.$$

The first derivative of $\Pi_{V_i}^{C_i}$ in the above formula can be obtained $\frac{\partial \Lambda_{V_i}}{\partial \Pi_{V_i}^{C_i}} = (\lambda_i - 1) \cdot (u - c + \tau \cdot c) \cdot G(\frac{u-c+\tau \cdot c}{\tau \cdot c \cdot \zeta} \cdot \Pi_{V_i}^{C_i}) + 2\tau \cdot c \cdot G(\frac{\Pi_{V_i}^{C_i}}{\zeta})$. The probability distribution function satisfies $0 \leq G(\Upsilon_{V_i}) \leq 1$, where $G(\Upsilon_{V_i})$ is a monotone non-decreasing function, and $\underset{\Upsilon_{V_i} \to -\infty}{lim} G(\Upsilon_{V_i}) = 0$. In this paper, the domain of $\Upsilon_{V_i} \in [0, +\infty)$, then $\frac{\partial \Lambda_{V_i}}{\partial \Pi_{V_i}^{C_i}} > 0$. In other words, Λ_{V_i} increases monotonically in the domain of $\Pi_{V_i}^{C_i}$ and gets the unique maximum value at the right endpoint of the definition domain. That means that the node V_i has a unique optimal choice $\Pi_{V_i}^{C_i *}$ to complete the transmission of messages, making the expected utility Λ_{V_i} of the node V_i optimized when $\Pi_{V_i}^{C_i} = \Pi_{V_i}^{C_i *}$. □

Through Theorem 4, it can be concluded that for any node in the coalition, there is always a unique choice to complete the transmission of messages, which makes the expected utility of the node maximum.

3. Algorithm of the incentive mechanism based on loss aversion:

Based on the above analysis of the decision-making model, it can be seen that the node will choose to join or leave the coalition, and the coalition will merge or separate to form a new coalition, which makes the nodes in the coalition able to obtain higher expected utility. Finally, it will urge the nodes to choose to cooperate. The algorithm of the incentive mechanism based on loss aversion is shown in Algorithm 1.

Algorithm 1: Algorithm of the incentive mechanism based on loss aversion.

```
Input :
        Set of nodes $V = \{V_1, V_2, ..., V_i, ..., V_n\}$;
        Set of coalitions $C = \{C_1, C_2, ..., C_i, ..., C_n\}$;
        The current node $V_{cur}$;
Output:
        The current coalition $C_{cur}$;
        The node's utility $\Lambda_{V_{cur}}^{C^{V_{cur}}}$;
Loss aversion-based coalition formation $i = 1, j = 1, k = 1, l = 1$;
while $i \leq n$ do
    if $C_i \succ_{cur} C^{V_{cur}}$ then
        $C^{V_{cur}} = C_i$;
Calculate incentive $\Lambda_{V_i}^{C^{V_i}}$;
while $j \leq n$ do
    while $k \leq n$ do
        if $\forall V_a \in C_j, (C_j \cup^{C_k}) \succ_a C_j$ and $\forall V_b \in C_k, (C_j \cup^{C_k}) \succ_b C_k$ then
            Merge coalition $(C_j, C_k)$;
while $l < n$ do
    $C_l = C_a \cup^{C_b}$ if $\exists V_a \in C_a, C_a \succ_a C_l$ and $\exists V_b \in C_b, C_b \succ_b C_l$ then
        Split coalition $(C_l)$;
```

4. Performance Evaluation

The free mobility model proposed in [58] is used to build the freeway mobile model scene. The expressway consists of two lanes, with a length of 3 km and a width of 300 m. At the initial time, vehicle nodes are distributed randomly in any position on the road, and their communication range is 300 m. They move from left to right. The minimum moving speed of the vehicle node is 10 m/s, and the maximum moving speed is 30 m/s. In practice, on the road section that vehicles often pass through, vehicles usually pass through the section from left to right or from right to left in different periods. In the experiment, in order to simplify the experiment, the time span of the vehicle on the road will be ignored, and the vehicle travels back and forth in a certain section in the experiment. The time of the experiment is 20 min. Due to the fact that the node cannot be the source node, the relay node, and the destination node at the same time, at the beginning of each round of the experiment, we set 50% of the randomly selected nodes to be the source nodes. The experimental data are all averaged after 1000 runs to eliminate the influence of some uncertain factors. See Table 3 for the specific experimental parameters.

Table 3. Parameters for simulation.

Parameter Name	Value or Range
Number of paths	2
Number of nodes N	[20, 80]
path length	3000 m
Path width	300 m
Node's maximum speed	30 m/s
Node's minimum speed	10 m/s
Node's communication range	300 m
Total messages Y	[400, 1600]
Threshold factor ζ	0.1, 0.3, 0.5, 0.7, 0.9
loss aversion coefficient λ	$(1, 3.5]$

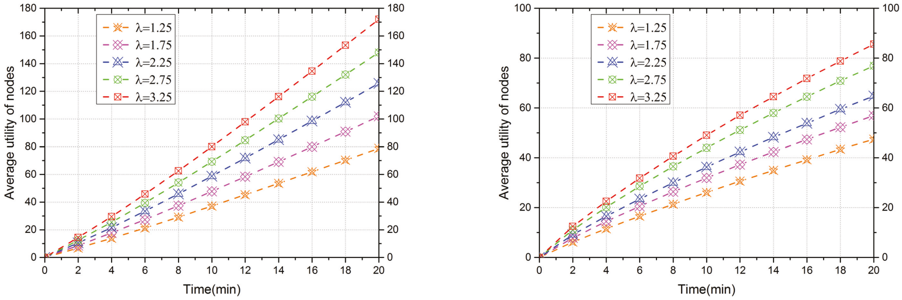
4.1. Influence of the Loss Aversion Coefficient on the Average Utility of Nodes

The loss aversion coefficient indicates the node's aversion to loss. Generally speaking, the higher the loss aversion coefficient is, the smaller the node's acceptance of loss will be, that is the more "averse" the node is to loss. According to the introduction of loss aversion in Section 2.2, $\lambda > 1$ is known, and according to [39], $\lambda = 2.25$ is what is usually set. However, in order to better analyze the impact of the loss aversion coefficient on the LAIM proposed in this section, we set $\lambda \in (1, 3.5]$ to observe the relationship between λ_i and the average node utility in the system.

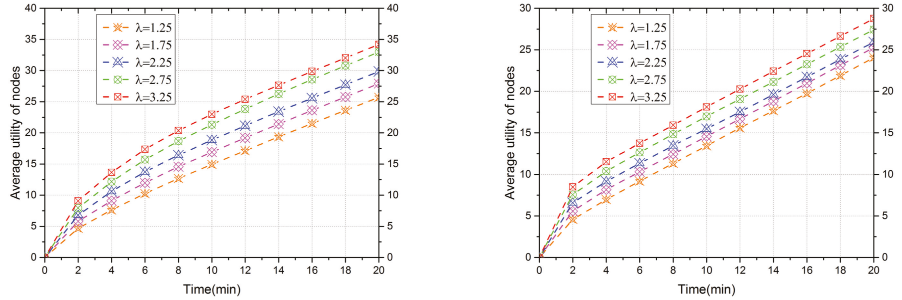
When $\mathrm{Y} = 400, N = 20$, as the value of λ_i changes, the trend of the average utility of nodes with time is shown in Figure 4.

It can be seen from Figure 4 that the average node utility increases with time, because with the increase of time, the nodes will have more time to participate in the message transmission. At this time, more and more nodes are selected to help complete the message transmission. The total utility obtained by the nodes will hence increase, and the average node utility will also increase.

It can also be seen from Figure 4 that when the value of λ_i increases from 1.25 to 3.25 and ζ from 0.3 to 0.9, the average node utility increases with the increase of λ_i, because when the value of λ_i increases, in other words, when the node's loss aversion increases, the node tends to choose cooperation behaviors. It can also be understood as the fact that it is more difficult for the node to bear the loss. Therefore, the final utility of the node will increase, and the average node utility will also increase. In the following experiment, $\lambda = 2.25$ is taken. At the same time, with the increase of ζ, the average node utility decreases. This is because the higher ζ is, the more messages the node needs to help complete the transmission to get additional rewards.



(**a**) $\Upsilon = 400, N = 20, \lambda = 1.25$ (**b**) $\Upsilon = 400, N = 20, \lambda = 1.75$



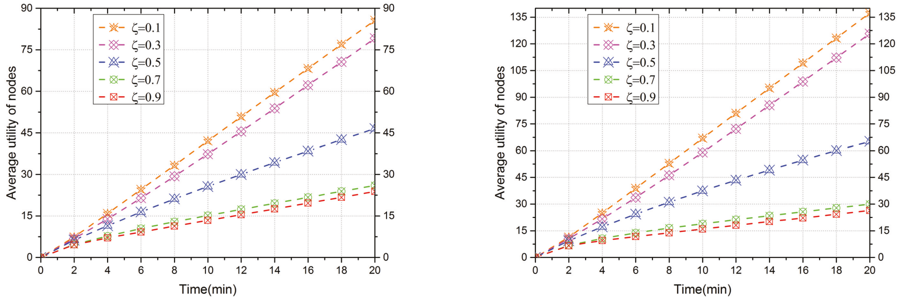
(**c**) $\Upsilon = 400, N = 20, \lambda = 2.25$ (**d**) $\Upsilon = 400, N = 20, \lambda = 2.75$

Figure 4. The influence of the λ value on the average node utility.

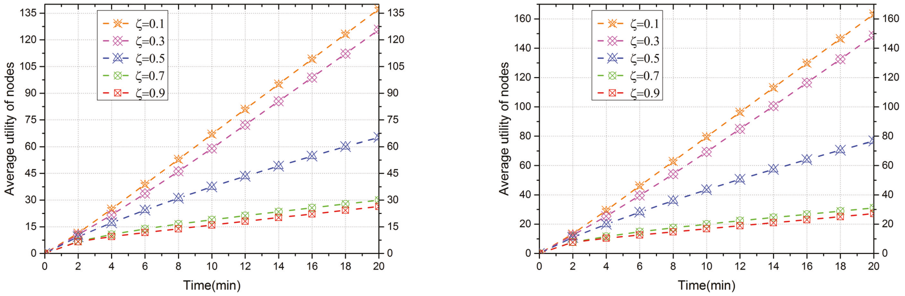
4.2. Effect of the Threshold Factor on the Average Utility of Nodes

The threshold factor ζ represents the proportion of the number of messages that need to be completed when the node wants to get additional rewards. Only when the number of messages that the node helps to complete the transmission reaches a specific proportion can the node get additional rewards.

Figure 5 shows that when $\Upsilon = 400, N = 20$ and the threshold factor ζ increases from 0.1 to 0.9, the average node utility decreases with the increase of ζ. This is because when ζ increases, the incentive threshold Θ will also increase. As a result, the number of messages that the node completes transmitting is difficult to meet the demand of Θ. Then, the node's utility decreases due to the lack of additional rewards. At the same time, it can be seen that when $\zeta = 0.1$, the average node utility is much higher than other conditions when $\zeta = 0.3$, 0.5, 0.7, and 0.9, respectively. This is because when $\zeta = 0.1$, it is easy for nodes to reach the incentive threshold Θ, so that more nodes get additional rewards. From Figure 4, it can also be seen that the average node utility at the point of 0.7 and 0.9 is relatively similar, as the number of completed message transmissions of nodes has difficulty reaching the incentive threshold in these two cases; the additional incentives cannot be obtained, so in the following experiment, $\zeta = 0.5$.



(**a**) $Y = 400, N = 20, \lambda = 1.25$ (**b**) $Y = 400, N = 20, \lambda = 1.75$



(**c**) $Y = 400, N = 20, \lambda = 2.25$ (**d**) $Y = 400, N = 20, \lambda = 2.75$

Figure 5. The influence of the ζ value on the average node utility.

4.3. Comparison with COMES and IMCS

This paper compares the LAIM with COMES [59] and IMCS [60]. COMES is comprised of a coalition formation algorithm which implements the peer-to-peer (P2P) approaches by introducing a coalitional graph game to model the cooperation among nodes. IMCS proposes a dynamic pricing incentive mechanism to solve the problem that users are unwilling to actively participate in content sharing. As the goal of the work is to improve the cooperation rate among vehicle nodes, this paper takes COMES and IMCSas a comparison. It mainly compares the LAIM and COMES from two aspects to analyze the performance of the LAIM: average node utility and average node proportion to acquire utility.

In addition to analyzing the growth of time, it also analyzes the changes in the number of messages and the number of nodes. The total number of messages represents the total number of messages faced by nodes in the system. In other words, the number of messages existing in the current system needs nodes as relay nodes to help the source node forward messages to the destination node. The higher the total message demand is, the more the average messages faced by each node are. In the case of the node choosing to cooperate, the more messages the node can help complete their transmission, the higher the utility of the node will be. Similarly, if there are more nodes in the system, the probability that a particular message demand will be completed at the same time T may also increase. Therefore, when comparing the LAIM and COMES from the two aspects of average node utility and average utility node proportion, in addition to the analysis of time growth, the impact of changes in total messages and the node number of the LAIM and COMES will also be analyzed.

4.3.1. Utility of Average Node

The average node utility refers to the average utility acquired by each node. The higher the average utility of the node, the more times the node participates in cooperation; otherwise, the fewer times the node participates in cooperation. Figure 6 compares the average node utility of the LAIM and COMES in terms of time.

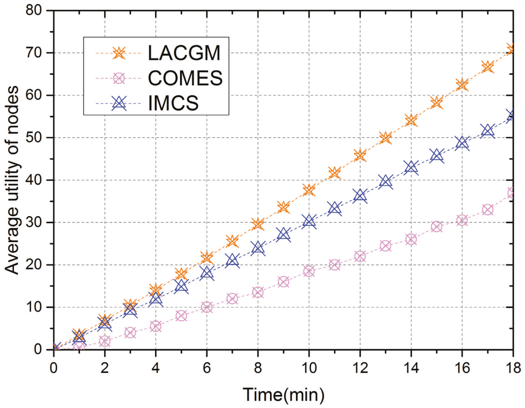
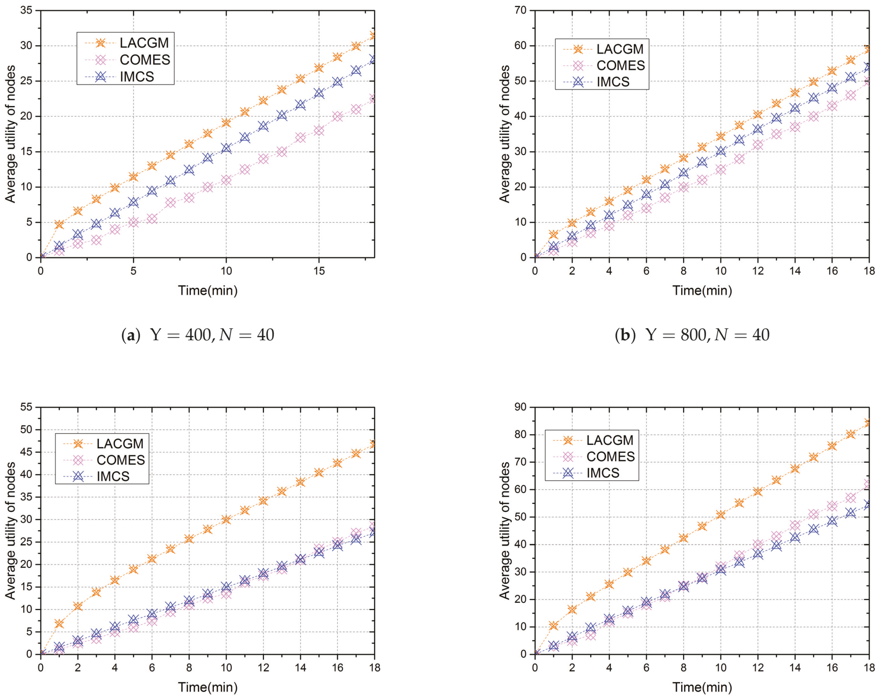


Figure 6. Average node utility changing with time ($Y = 400, N = 20$).

It can be seen from Figure 6 that the average node utility of the LAIM and COMES increases with time. This is because as time goes on, the times nodes participate in cooperation increases, and the final node utility and the average node utility will increase. In Figure 6, the average node utility of the LAIM is higher than that of COMES and IMCS. This is because, in the LAIM, the loss aversion of nodes makes it hard to bear the loss, and then, they will choose to cooperate, which hence leads to more cooperation times than COMES and IMCS. At the beginning, the average node utility of the LAIM is 591% higher than that of COMES at the 30th second, which gradually decreases with time, and finally decreases to about 112% at the 16th minute. Compared with IMCS, the average utility of LAIM users is only slightly higher than that of IMCS users, and the gap between the two gradually widens over time. This is because the LAIM has a significant promoting effect on the increase of utility due to the existence of loss aversion.

Figure 7 describes the relationship between the average node utility and both the number of messages and nodes. When the number of nodes and the number of messages have different values, the average node utility of the LAIM, IMCS, and COMES will increase with the increase of time, and the average node utility of the LAIM will be higher than that of the other two mechanisms. In Figure 7a,b, when the number of nodes remains unchanged and the number of messages increases, then the final average node utility will also increase, because when the number of nodes remains unchanged, the increase of messages will increase the average messages. Then, the number of messages that the node ultimately completes transmitting will also increase. As a result, the final average node utility will increase.

From Figure 7b,c, when the total number of nodes increases and the total number of messages remains unchanged, the utility of the average node will eventually decrease. This is because when the total number of messages remains unchanged and the number of nodes increases, the average number of messages faced by each node will decrease, and the average number of messages completed by each node will also decrease. Therefore, the utility of the final average node is reduced. By observing Figures 6 and 7a,c,d, the same situation as discussed above can be found. From Figure 7, it is easy to find that the average node utility of the LAIM is 34.35% higher than that of COMES and IMCS.



(**a**) $\Upsilon = 400, N = 40$ (**b**) $\Upsilon = 800, N = 40$

(**c**) $\Upsilon = 800, N = 80$ (**d**) $\Upsilon = 1600, N = 80$

Figure 7. Average node utility changes with the number of messages and nodes.

4.3.2. Utility of Average Node

The proportion of nodes acquiring utility refers to the proportion of the nodes that have acquired utility among the total number of nodes. The higher the proportion, the more nodes that have participated in cooperation in the system will be, and otherwise, the fewer nodes that have participated in cooperation in the system will be. First, this part needs to compare the proportion of nodes acquiring utility in the LAIM and COMES.

As is shown in Figure 8, with the increase of time, the node proportion of the LAIM, COMES, and IMCS also increases. This is because more and more nodes that have not participated in the cooperation participate in the cooperation over the time. At the same time, the node proportion increases rapidly before 8 min. However, the growth is slower, because if there are n nodes in the network, the nodes randomly send messages to each other, and the messages are sent from the source node to the destination node through one or more relay nodes. Suppose m nodes are participating in the message cooperation transmission after the (i)th random interaction; the proportion of nodes that do not get utility after the interaction is $(n-m)/N$. When the $(i+1)$th interaction starts, if the value is higher, then the proportion of nodes having participated in the $(i+1)$th cooperation will be higherand that of the nodes having not participated in any cooperation will hence be smaller. Therefore, the proportion of nodes acquiring utility in the latter half will grow slower than that in the previous half. It can also be seen from the figure that the proportion of nodes acquiring utility in the LAIM is higher than that in COMES and in IMCS since the loss aversion of the nodes is considered. As nodes are more likely to achieve cooperation behaviors in the LAIM, the proportion of nodes in the LAIM will be higher. It can be found that the gap in the average proportion of nodes acquiring utility among the LAIM, COMES, and IMCS is stable over time. The gap is within the interval [0.0409%, 0.0567%], with the average of 0.05409%.

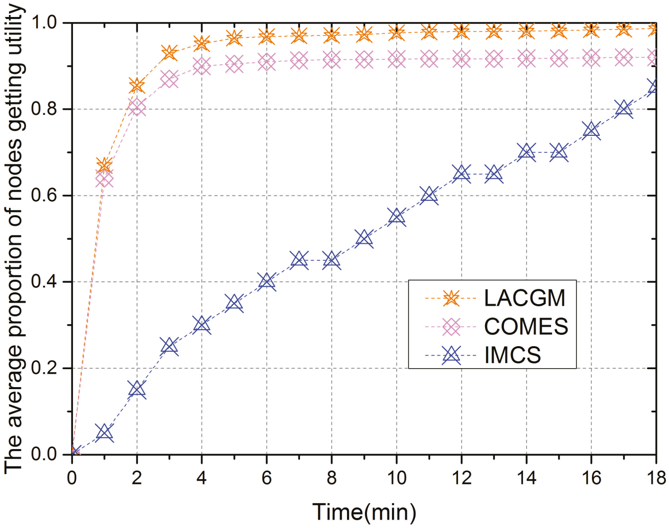
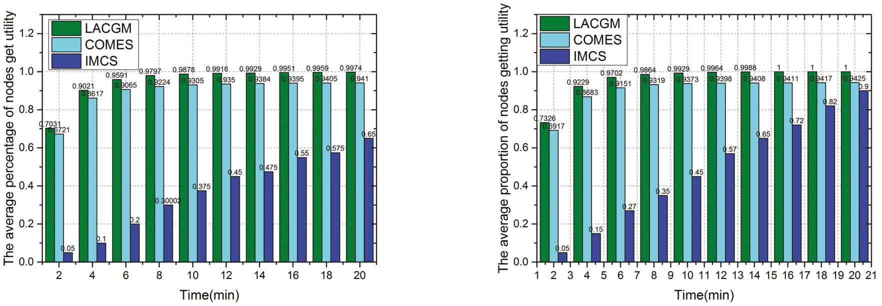
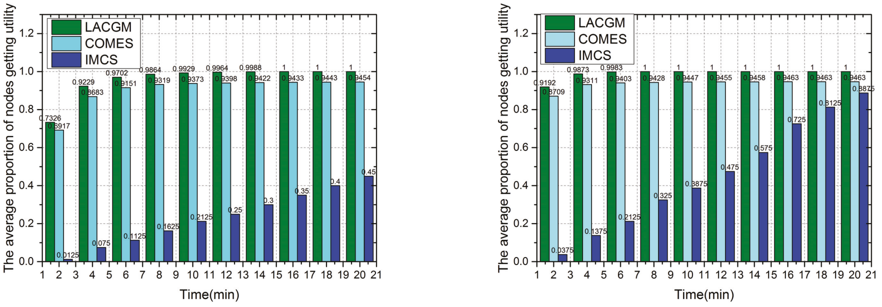


Figure 8. Average node utility changing with time ($Y = 400, N = 20$).

Figure 9 describes the relationship between the proportion of nodes and the number of messages and nodes. When the number of nodes and the number of messages have different values, the proportion of nodes in the LAIM and COMES will increase with time, and the proportion of nodes in the LAIM will be higher than that of COMES and IMCS. At the same time, it can be seen from Figure 9a,b that when the number of nodes remains the same and the number of messages increases, the proportion of nodes with utility will increase at the same time. This is because when the number of nodes remains the same, the increase of the number of messages will accordingly increase the average number of messages. Then, nodes without utility have a higher probability of getting utility by participating in cooperation. As a result, the proportion of nodes acquiring utility will increase. From Figure 9b,c, when the total number of nodes increases while the total number of messages remains unchanged, the proportion of nodes acquiring utility will eventually decrease, because when the total number of messages remains unchanged and the number of nodes increases, the average number of messages faced by each node decreases. Therefore, the probability of acquiring utility by participating in cooperation without acquiring utility will be also reduced. As a result, the proportion of nodes getting utility will be reduced. By observing Figures 8 and 9a,c,d, the same situation can be found as the discussion above.



(**a**) Y = 400, $N = 40$ (**b**) Y = 800, $N = 40$



(**c**) Y = 800, $N = 80$ (**d**) Y = 1600, $N = 80$

Figure 9. Proportion of nodes acquiring utility vs. the number of messages and nodes.

5. Conclusions

Inspired by the marketing strategy of Amazon's online bookstore, a new incentive mechanism considering loss aversion called the LAIM is constructed. By introducing loss aversion, the incentive threshold and the threshold factor are proposed based on the number of messages faced by the node. According to the cost of the message transmission, the utility function of the node is reconstructed. Based on the reconstructed utility function, the decision-making model of the node is designed by using the coalition formation game as an analysis tool to promote nodes to form coalitions. Through the simulation analysis, we find that the LAIM mechanism can play a role when the vehicle node participates in the transmission of the first message. Considering that the time of meeting among vehicles is short and limited, the LAIM mechanism can play an active role in reality. Moreover, when the vehicle is in operation, the speed, direction, and position of the vehicle nodes change, and the vehicle nodes will frequently be in different coalition ranges. Therefore, the strategy of changing the coalition proposed in this paper can effectively improve the effectiveness of vehicle nodes.

Simulation results show that the LAIM has a higher node utility and cooperation rate than the traditional VANETs cooperation guarantee mechanisms COMES and IMCS, which is based on the cooperation formation game.

In this paper, we focus more on the utility of vehicle nodes, and we encourage participants to cooperate based on this. Future research will be carried out to consider the impact of throughput and other related factors of VANETs.

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Smart Fuzzy Logic-Based Density and Distribution Adaptive Scheme for Efficient Data Dissemination in Vehicular Ad Hoc Networks

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Abstract: In vehicular Ad Hoc Networks (VANETs), smart data dissemination is crucial for efficient exchange of traffic and road information. Given the dynamic nature of VANET, the challenge is to design an adaptive multi-hop broadcast scheme that achieves high reachability while efficiently utilizing the bandwidth by reducing the number of redundant transmissions. In this paper, we propose a novel intelligent fuzzy logic based density and distribution adaptive broadcast protocol for VANETs. The proposed protocol estimates the spatial distribution of vehicles in the network employing the Nearest Neighbor Distance method, and uses it to adapt the transmission range to enhance reachability. To reduce packet collisions, the protocol intelligently adapts the contention window size to the network density and spatial distribution. Bloom filter technique is used to reduce the overhead resulting from the inclusion of the neighbor IDs in the header of the broadcast message, which is needed in identifying the set of potential rebroadcasting vehicles. Our simulation results confirmed the effectiveness of the proposed scheme in enhancing reachability while efficiently utilizing bandwidth.

Keywords: fuzzy logic; bloom filter; nearest neighbor; contention window size; transmission range; VANET broadcast; intelligent transportation systems

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1. Introduction

Vehicular Ad Hoc Network (VANET) is an advanced wireless communication technology which potentially enhances Intelligent Transportation Systems (ITS) safety and efficiency. VANET is a subclass of Mobile Ad-hoc Network (MANET) that has high mobility and very dynamic topology. VANET can have a larger number of nodes, and scalability is one of the challenges that needs to be addressed in designing VANET protocols. VANET has potentially many safety and non-safety applications. Since both safety and non-safety related message dissemination is necessary in VANET, multi-hop broadcast is an important communication scheme to propagate the messages [1,2].

Flooding is the most straightforward broadcast system, in which each receiving node will rebroadcast the message. This inconsiderate rebroadcast method exponentially increases the number of transmissions leading to a broadcast storm which will waste a notable portion of the bandwidth [3]. There is also a trade-off between successful message delivery ratio and bandwidth consumption in broadcast systems. Considering the distribution of vehicles, when the network is sparse, the main issue is to overcome the potential disconnection between vehicles. In other words, reachability is the main issue in a sparse network. On the other hand, when the network is dense, more consideration should be given to efficient bandwidth utilization.

Thus, in order to facilitate a reliable message dissemination scheme, we need to design an efficient broadcast scheme, which avoids the broadcast storm problem by reducing the number of redundant transmissions and at the same time reaches a higher number of vehicles.

Based on how the next rebroadcasting vehicle will be selected, VANET broadcast schemes can be categorized into three classes: cluster-oriented, transmitter-oriented, and receiver-oriented. In cluster-oriented broadcast methods [4–6], the next relay is an identified node (either mobile or fixed). In transmitter-oriented broadcast systems, the transmitting vehicle selects the next relay based on exchanged information of neighbors [7–14]. In reciever-oriented broadcast systems, each receiving vehicle decides how to behave, rebroadcast the received message, or remain silent [15–22].

To be able to improve reachability in sparse networks, transmission range adaptation is one of the possible strategies. However, increasing transmission range can increase the interference which leads the network to experience more packet loss. One of the possible solutions can be density-based transmission range adaptation. When the density of vehicles in the network is low, increasing the transmission range causes slight increase in interference. In addition, to reduce interference, the transmission range can be reduced when the network is very dense. In this work, we use Point Pattern Analysis technique to estimate the spatial distribution of vehicles and adapt the transmission range by dynamically adjusting the transmission power.

According to the IEEE 802.11p standard, which is a revision of the IEEE 802.11 to support Wireless Access in Vehicular Environments (WAVE) [23], each vehicle uses the Distributed Coordination Function (DCF), or an Enhanced Distributed Channel Access (EDCA) function to deal with channel access. Each transmitting vehicle checks if the wireless medium is idle before transmission. If it finds that the medium is idle for longer than DCF Inter-Frame Space (DIFS) or Arbitration Inter-Frame Space (AIFS), it can instantly transmit. Otherwise, it has to postpone the transmission until the medium becomes idle. After this period, the transmitting vehicle needs to wait for an additional deferral time (backoff). This random period is an integer that is randomly picked from a uniform distribution over the interval of [0, CW], where CW is the current size of the contention window. The size of CW is a value depending on aCW_{min} and aCW_{max} subject to the access category. When two or more neighboring transmitting vehicles select the same value of backoff period, we expect packet collisions. Therefore, in a dense network, with a higher number of neighboring vehicles, a larger CW can prevent the packet collisions. This happens because a larger CW reduces the probability that two or more neighboring vehicles pick the same value of backoff period. On the other hand, in a sparse network, a smaller size of CW decreases the delay.

Fuzzy logic attracts the attention of researchers because of its effectiveness to direct the problem solving path in the systems with rapid changes. Fuzzy logic-based systems can intelligently analyze different metrics even if they are inexact and opposing to one another, improve the decision-making process, and reduce the computation delays [24]. Recently, it comes as no surprise that fuzzy logic has been shown to be effective for VANET broadcast [25–29].

Our work is motivated by the observation that the majority of existing schemes use a static transmission range for vehicle to vehicle communication [4,5,7–16,19–22]. The existing schemes that use transmission range adaptive protocols, to the best of our knowledge, consider only the vehicle density to adjust the transmission power and they do not take spatial distribution of vehicles into account [30,31]. The spatial distribution is more important as it reflects how far apart the vehicles are.

The primary contribution of this work is the proposed density and distribution self-adaptive scheme with transmission range adaptation broadcast (TRAB). TRAB is a smart receiver-oriented broadcast scheme which adapts the transmission range by dynamically adjusting the transmission power considering the spatial distribution of vehicles to increase reachability, especially in sparse networks. In order to characterize the spatial distribution of vehicles in the network, we use Nearest Neighbor Distance method, which is one of the Point Pattern Analysis (PPA) techniques. The calculated nearest neighbor index (NNI) is the main factor used to adapt the transmission range. We also use Fuzzy logic to adjust the contention window size at the MAC layer to prevent packet collisions. We use the spatial distribution and similarity of density as inputs to the fuzzy logic system. The Bloom filter technique is used to reduce the overhead resulting from the inclusion of the neighbor IDs in the header of the broadcast message, which is needed in identifying the set of a potential rebroadcasting vehicle.

The rest of the paper is organized as follows: In Section 2, some related work on broadcast schemes in VANETs is presented. We present our proposed broadcast cross-layer scheme in Section 3. In Section 4, we provide the simulation results and discussion. Finally, Section 5 concludes the paper.

2. Related Work

Multi-hop broadcast is the main communication method to disseminate messages for VANET safety and non-safety applications. In this paper, we focus on VANET multi-hop broadcast methods for non-safety applications such as traffic data dissemination, where delay requirements are not as strict. In this case, protocols are required to disseminate data to large regions while efficiently consuming bandwidth. As mentioned in the previous section, based on how the next rebroadcasting vehicle will be selected, we categorize broadcast protocols into three main classes:

- Cluster-oriented
- Transmitter-oriented
- Receiver-oriented

In this paper, we focus on adaptive receiver-oriented broadcast schemes. In receiver-oriented broadcast protocols, each receiving vehicle determines whether or not to rebroadcast. In these types of broadcast methods, since the receiving vehicle is the one that determines the status of rebroadcasting, the probability of packet loss is lower than the other types. In statistical receiver-oriented broadcast methods, in order to decide whether to rebroadcast, each receiving vehicle measures a local value and compares that to a predefind threshold. Thus far, five fundamental statistical broadcast methods have been introduced: stochastic, counter-based, distance-based, location-based, and distance-to-mean-based [15].

In [15], the Distance-to-Mean (DTM) broadcast protocol, which is based on the distance-to-mean method, is introduced. In DTM, each receiving vehicle uses the position information (exchanged by hello messages) to calculate the spatial mean of its transmitting neighbors. Then, the receiving vehicle calculates its distance to the spatial mean (distance-to-mean). Finally, the receiving vehicle decides to rebroadcast if its distance-to-mean exceeds a predefined threshold. This threshold is a function of the number of neighbors.

In [16], the Distribution-Adaptive Distance with Channel Quality (DADCQ) broadcast protocol is proposed. DADCQ is a distance-based statistical broadcast protocol in which each receiving vehicle determines whether to rebroadcast based on a threshold. In DADCQ, the threshold is simultaneously adaptive to the vehicular traffic density, the spatial distribution pattern, and the wireless channel quality. In order to analyze the distribution of vehicles, DADCQ uses a quadrat method.

In [17], based on game theory, a distance-based stochastic broadcast method is proposed. In this protocol based on the QRE equilibrium and, using a symmetric version of volunteer dilemma game, the VANET broadcast protocol is modeled.

A vehicle density-based forwarding protocol (VDF) for VANET is proposed in [18]. In VDF, the rebroadcasting vehicle is chosen based on the vehicle density. The protocol will assign different waiting times between reception and rebroadcasting of the message. The waiting time is established according to the computed current contention window of the vehicle.

The Fuzzy Logic-based Broadcast (FLB) protocol, proposed in [20], employs fuzzy logic techniques to check receiving vehicles' qualification to rebroadcast the message. FLB performs well in terms of reachability in various traffic densities.

The Bandwidth Efficient Fuzzy Logic Assisted Broadcast (BEFLAB) protocol, presented in [21], aggressively suppresses the number of rebroadcasts. Thus, achieving high bandwidth efficiency while still enjoys an acceptable level of reachability. Deploying a fuzzy logic system, each receiving vehicle dynamically determines a set of candidate forwarders and decides to rebroadcast according to the distance-to-mean value of each vehicle in this set.

In [22], an Intelligent Hybrid Adaptive Broadcast (IHAB) protocol is introduced. To design a bandwidth efficient multi-hop broadcast scheme with a high level of reachability, IHAB brings the advantages of FLB and BEFLAB together. Since FLB is a reliable smart broadcast scheme with shown high level of reachability, IHAB takes advantage of FLB in sparse networks, where, in dense networks, it deploys BEFLAB to perform efficiently in terms of bandwidth usage.

As part of GeoNetworking, Contention-Based Forwarding (CBF) provides communication for both unicast and broadcast purposes [32]. Based on the CBF algorithm used for GeoBroadcast, each receiving vehicle uses a timer to decide whether to forward the message or not. The timer defines a timeout with respect to the distance between the receiving vehicle and the neighbor message transmitter. The message will be rebroadcast if the receiving vehicle does not overhear the message within the timeout. The performance of the broadcast component of CBF (CBF-broadcast) is compared to that of the protocol proposed in this paper.

Non-homogenous distribution of vehicles and rapid topology changes affect the vehicle connectivity in VANETs. This issue is much more noticeable in sparse networks which can cause a significant reachability reduction. Dynamic transmission range is one possible strategy to achieve high level of network connectivity. In [30], a dynamic transmission range assignment (DTRA) algorithm is proposed. First, based on traffic-flow models, a local density estimation is formulated. In this estimation model, traffic density is a function of vehicle mobility pattern. In [33], based on traffic pattern measures, a transmission range adjustment method is introduced. In this method, for varying traffic densities, traffic dynamics are analyzed as a result of stop-and-go waves. In [34], a beamforming-based receiver-oriented broadcast protocol is introduced in which, considering local density and distance between source and destination, vehicles set their transmission range.

In order to reduce packet collisions, contention window size adjustment mechanisms are proposed in [13,35–37]. In [13], a transmitter-oriented broadcast protocol is proposed. Q-learning technique is employed to adjust CW size in VANET. In this method, the reception of a broadcast message is checked at the network layer. In order to adaptively adjust the contention window size, a Q-learning-based method is deployed at the MAC layer which decides to keep, reduce, or increase the previous contention window size for the new transmission. In [35], the contention window size adjustment is performed based on an estimated number of transmitting vehicles in the network. Authors in [36] propose a backoff algorithm which takes the estimated number of active nodes into consideration. The protocols proposed in [35] and [36] are not evaluated for multi-hop broadcast communications. Moreover, due to the nature of VANET, it is difficult to predict the data traffic patterns. Ref. [37] introduces a partitioning-based CW assignment method for a transmitter-oriented VANET broadcast scheme. To meet shorter delays, a smaller contention window is used by vehicles in the farthest partition from the sender.

3. Proposed Scheme

In this paper, we propose a Bloom filter-assisted smart cross-layer broadcast scheme. The proposed scheme features spatial distribution-based transmission range adaptation and distribution and density-based contention window size adjustment. Figure 1 shows the cross-layered architecture of our proposed broadcast scheme.

The proposed scheme assumes that all the vehicles in the network know their own position and velocity by using a Global Positioning System (GPS). In addition, periodic hello messages are exchanged between the neighboring vehicles. These broadcast hello messages provide position, velocity, and ID information. Thus, each vehicle is able to create and update its own neighboring information table.

In addition, each vehicle is going to include the IDs of its neighboring vehicles in the header of the message. Since this may introduce high overhead, we propose to use the Bloom filter technique to mitigate this overhead, as explained in the following subsection. Based on IEEE 1609.2, all communications and data exchanging are secured.

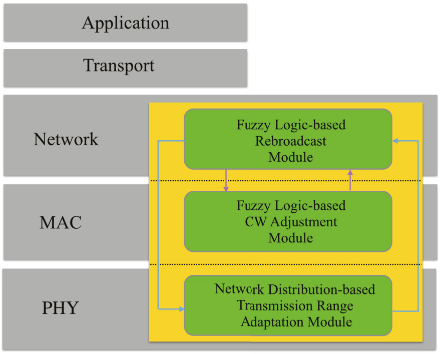


Figure 1. Cross-layer architecture of TRAB.

3.1. Fuzzy Logic-Based Rebroadcast Module

The protocol uses Bloom filter technique to mitigate the overhead resulting from the inclusion of neighbors IDs in the header of the broadcast message. A Bloom filter is a space and time efficient data structure which is used to check whether an element is present in a set [38]. This probabilistic data structure shows that the element either definitely is not a member of the set or might be a member of the set. As shown in Figure 2, each Bloom filter is made up of two basic parts: an $m - bit$ array and k hash functions $h_1(.), h_2(.)... h_k(.)$. Initially, all the m bits of the Bloom filter are set to 0.

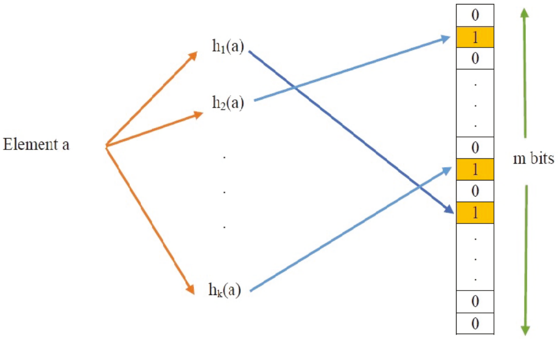


Figure 2. A basic Bloom filter with m bits and k hash functions.

To map an element a into a Bloom filter, first the hash functions are applied on a, which generates k indexes within the range $[1, m]$. Then, all the array's bits at the location of these generated indexes will be set to 1.

To search for an element b in a Bloom filter array, the first step is again to apply the hash functions to produce k indexes. If all the bits that are located at these indexes have been set to 1, then element b can be considered a member of the set.

Here, the only type of error that can be named is false positive, which reports a non-member element b as a member of the set.

The proposed rebroadcast scheme inserts the neighbors IDs of a broadcasting vehicle into a Bloom filter and adds it to the header of the broadcast message. Then, each receiving vehicle checks whether its neighbors belong to the array of the received broadcast message and determines the common (shared) neighbors with the transmitting neighbor. Bloom filter-based overhead reduction is shown in Figure 3. Based on the proposed Bloom filter technique, the system achieves up to 80% overhead reduction for both highway and urban environments as the number of vehicles increases. In addition, the accuracy of determining the common (shared) neighbors based on the Bloom filter is shown in Figure 4.

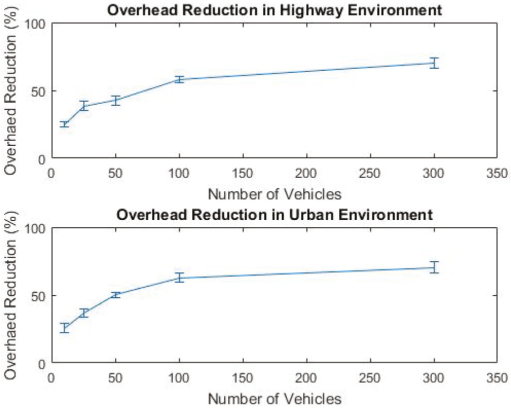


Figure 3. Overhead Reduction using a Bloom Filter.

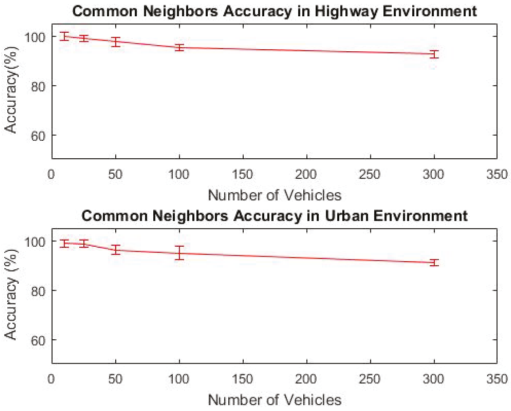


Figure 4. Common neighbors accuracy.

When Vehicle r receives a new broadcast message with a unique sequence number, the protocol uses a random assessment delay technique to identify the transmitting neighbors of vehicle r from which the message has been successfully received [39].

Based on the random assessment delay technique, when a message is received from one of the neighbors at distance l, vehicle r records the message along with the neighbor ID and sets a backoff timer to a maximum value multiplied by $1 - \frac{l}{R}$, where R is the transmission range. It means that messages received from farther neighbors will have shorter backoff times. If vehicle r receives the same message from other neighbors, it resets the timer before the timer expires. After the timer expires, vehicle r will have a record of the received messages and their transmitting vehicles, and we call them the transmitting neighbors.

We consider a set of potential rebroadcasting vehicles (SPR) as the common (shared) neighbors between vehicle r and its transmitting neighbor(s), which are assumed to receive the message and proceed whether to rebroadcast. In order to identify SPR, the protocol determines if the IDs of the neighbors of vehicle r belong to the Bloom filters received from these transmitting neighbors.

Given that false negative of a Bloom filter is 0, the uncommon neighbors between vehicle r and its transmitting neighbors are predicted correctly. Then, the protocol can estimate the common (shared) neighbors between them by eliminating the uncommon neighbors from vehicle r's set of neighbors. These common (shared) neighbors form SPR have the potential to rebroadcast the message.

To achieve high bandwidth efficiency, a fuzzy logic system is designed to determine the qualification of vehicle r to rebroadcast the broadcast message. This proposed fuzzy logic system is fed with mobility and coverage factors as inputs [21]. Vehicle r calculates the mobility factor (MF) using Equation (1):

$$MF = \frac{v_i - v_{min}}{v_{max} - v_{min}} \tag{1}$$

where v_i denotes the velocity of vehicle i and v_{min} and v_{max} are the minimum velocity and maximum velocity of the potential rebroadcasting vehicles including vehicle r. Vehicles with a lower velocity will have a lower mobility factor. Vehicles with lower mobility factors are more qualified to rebroadcast the message.

To obtain the coverage factor (CF), the distance-to-mean method is used [15]. The distance-to-mean method determines the distance from the vehicle to the spatial mean of the potential rebroadcasting vehicles. The spatial mean of a set of n points, (x_i,y_i), is calculated as:

$$(\bar{x}, \bar{y}) = (\frac{1}{n}\sum_{i=1}^{n} x_i, \frac{1}{n}\sum_{i=1}^{n} y_i) \tag{2}$$

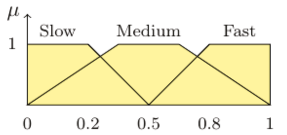
If the position of vehicle r is at (x,y), then the normalized distance to mean variable, CF, is measured using Equation (3):

$$CF = \frac{1}{TR}\sqrt{(x-\bar{x})^2 + (y-\bar{y})^2} \tag{3}$$

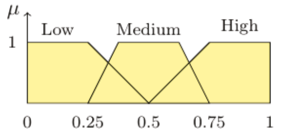
where TR is the current transmission range of vehicle r. A small value of CF indicates that the potential rebroadcasting vehicles are distributed evenly around vehicle r, which means that vehicle r should not rebroadcast.

As shown in Figure 5, we use the trapezoidal membership functions for mobility and coverage factors, and also for the membership functions of the output. Based on the mobility membership function, vehicle r calculates the degree of mobility $\{slow, medium, fast\}$.Similarly, it determines the degree of coverage $\{low, medium, high\}$. We use Max-Min fuzzy inference method, in which the fuzzy operator AND takes the minimum value of the antecedents [24]. Considering the fuzzy values of the input variables and applying If-Then, rules (as given in Table 1), the status of the vehicle, either rebroadcasting or non-rebroadcasting, is determined. In this work, we use the most popular defuzzification technique, Center of Gravity (COG), which is widely used in actual applications.

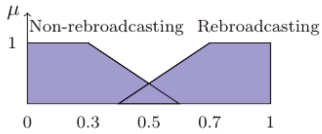
The qualification of vehicle r to rebroadcast will be checked based on the proposed fuzzy module. If the status of vehicle r is determined as non-rebroadcasting, it drops the broadcast message. Otherwise, the protocol uses the fuzzy logic system to establish the set of candidate rebroadcasting vehicles (SCR). SCR includes vehicle r and the vehicles in the set of potential rebroadcasting vehicles which are recognized as qualified to rebroadcast by the fuzzy system. SCR is formed to check if vehicle r is the best candidate (based on the distance-to-mean parameter) among the set to rebroadcast the message.



a) Mobility Factor



b) Coverage Factor



c) Status

Figure 5. Rebroadcast module fuzzy membership functions.

Table 1. Fuzzy Rules of Rebroadcast.

Mobility	Coverage	Status
slow	low	non-rebroadcasting
slow	medium	rebroadcasting
slow	high	rebroadcasting
medium	low	non-rebroadcasting
medium	medium	rebroadcasting
medium	high	rebroadcasting
fast	low	non-rebroadcasting
fast	medium	non-rebroadcasting
fast	high	rebroadcasting

Vehicle r rebroadcasts the message if it has the largest value of distance-to-mean in SCR. Otherwise, it waits for a t_{wait} time. If, after this time, it does not hear the message being broadcast by other vehicles, it rebroadcasts. This is to avoid the situation where the message is not rebroadcast by any of the candidate rebroadcasting vehicles. t_{wait} is given by Equation (4):

$$t_{wait} = T_{max}(1 - \frac{d_{min}}{TR}), \tag{4}$$

where d_{min} denotes vehicle r's distance to its nearest neighbor. The closer vehicle r is to the nearest candidate rebroadcasting vehicle, the longer it should wait, (the larger the t_{wait} is). Based on simulation results shown in [21], we use the optimal value, 100 ms, for T_{max}. The proposed rebroadcast process in the network layer is described in Algorithm 1.

Algorithm 1: TRAB rebroadcast method.

```
if Vehicle r receives a message with a seq. number, which was previously received;
then
    Drop the message.
else
    Use a random assessment delay mechanism to find the transmitting neighbors to
      determine common neighbors;
    Determine if the ID of vehicle r's neighbors belong to the Bloom filter of its transmitting
      neighbors;
    Determine SPR and calculate the MF and CF;
    Use the fuzzy logic system to check the rebroadcasting status;
    if Vehicle r is not qualified to rebroadcast then
        Drop the message.
    else
        Determine SCR;
        if Vehicle r has the highest dtm in SCR;
        then
            Consider vehicle r as a rebroadcasting vehicle and perform Algorithms 2 and 3.
        else
            wait for $t_{wait}$ time;
            if Vehicle r hears the rebroadcast message during $t_{wait}$;
            then
                Drop the message.
            else
                Consider vehicle r as a rebroadcasting vehicle and perform Algorithms 2 and 3.
```

3.2. Spatial Distribution-Based Transmission Range Adaptation

3.2.1. Point Pattern Analysis

Point Pattern Analysis (PPA) is the arrangement evaluation of a set of points on a surface, which reports the actual spatial or time-related location of points. In a numerical data set, Complete Spatial Randomness (CSR) refers to the spatial model of a random process or a Poisson distribution. Nearest Neighbor Distance and quadrat techniques are specifically introduced for pattern analysis of point data. Our protocol utilizes the Nearest Neighbor Distance method to estimate the spatial distribution of vehicles in the network.

In the Nearest Neighbor Distance analysis method, as one of the PPA models, the distance of each point (here vehicles) to its nearest neighbor (in the transmission range) is determined and the average nearest neighbor distance for all vehicles is calculated. Nearest Neighbor Index (NNI) is a unit-less statistical metric that determines the distribution. NNI is defined as the ratio of the observed average distance to the expected average nearest distance (Equation (5)):

$$NNI = \frac{\bar{D_o}}{\bar{D_E}} \tag{5}$$

where $\bar{D_o}$ is the observed mean distance between each vehicle and its nearest neighbor:

$$\bar{D_o} = \frac{\sum\limits_{i=1}^{n} d_i}{n} \tag{6}$$

and $\bar{D_E}$ is the expected mean distance for the vehicles given a uniform random pattern in area A:

$$\bar{D_E} = 0.5\sqrt{\frac{A}{n}} \tag{7}$$

where n denotes the number of vehicles.

Generally, for uniform patterns, the value of NNI is expected to be around 1. In addition, clustered patterns are considered to have an NNI close to 0. Finally, NNI of sparse patterns is expected to have a value greater than 2.

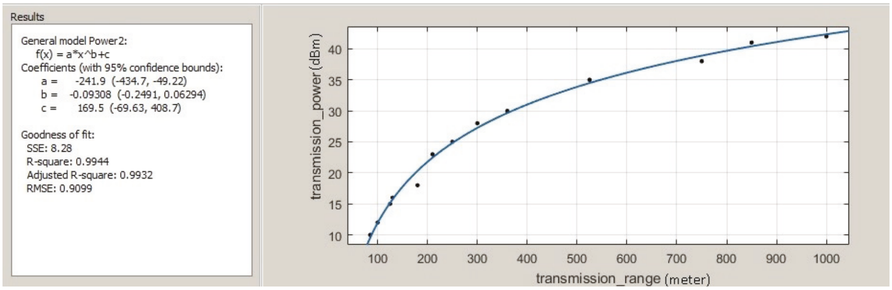
3.2.2. Transmission Range Adaptation Algorithm

In this work, based on the Nearest Neighbor Distance method, the distribution of vehicles on the road will be established. The protocol calculates NNI and uses it in the proposed algorithm (Algorithm 2) to dynamically adjust the transmission range of each rebroadcasting vehicle. When a rebroadcasting vehicle is in a locally sparse area ($NNI > 2$), a maximum transmission range of 1000 m will be assigned to reach more vehicles. If the rebroadcasting vehicle is in a locally dense neighborhood (area) ($NNI \approx 0$), the transmission range will be adapted to 250 m. When the rebroadcasting vehicle is in a random pattern area ($NNI \approx 1$), the transmission range will be assigned to approximately 500 m.

To obtain the proper transmission power as a function of transmission range, as Figure 6 shows, we use ns-3 simulation experimentation for an environment with the Nakagami propagation model. Then, using MATLAB Curve Fitting Tool, we obtain the best fitting function with 95% confidence bounds and root mean squared error (RMSE) of 0.9, as given in Equation (8):

$$P_{tr} = -241.9(TR)^{-0.93} + 169.5 \tag{8}$$

where P_{tr} and TR are the transmission power and transmission range, respectively.



```
General model Power2:
    f(x) = a*x^b+c
Coefficients (with 95% confidence bounds):
      a =      -241.9  (-434.7, -49.22)
      b =    -0.09308  (-0.2491, 0.06294)
      c =       169.5  (-69.63, 408.7)

Goodness of fit:
  SSE: 8.28
  R-square: 0.9944
  Adjusted R-square: 0.9932
  RMSE: 0.9099
```

Figure 6. Transmission power function.

Transmission range adaptation process is stated by Algorithm 2.

Algorithm 2: Transmission range adaptation.

```
Input: NNI
Output: TR
if $NNI \geq 2$;
 then
    $TR \leftarrow TR_{max}$;
else
    $TR \leftarrow 0.25 * TR_{max} * (1 + NNI)$;
```

3.3. Distribution and Density-Based CW Size Adjustment

According to IEEE 802.11p MAC specification, the back off time is calculated by:

$$backoff = SlotTime * Rand() \tag{9}$$

where $Rand()$ is a number randomly drawn from a uniform distribution over the interval of $[0, CW]$. CW is defined as:

$$CW = 2^n - 1; n \in \{4, 5, 6, ..., 10\} \tag{10}$$

The initialized contention window size is considered aCW_{min}, which is equal to 15. However, since at the MAC layer there is neither reception acknowledgment nor retransmission of broadcast frames, the contention window size does not change. In a dense network, there is a high probability to have a high data traffic load, so a small contention window causes a high probability of collision. This issue inefficiently affects the network data dissemination. In addition, when the number of vehicles in the network is small, a large contention window could increase end-to-end delay. Thus, due to these issues, in this work, we propose a contention window size adjustment algorithm which considers both the local density and the distribution information. It is assumed that the protocol will include the broadcasting vehicle's current contention window size and number of neighbors in the header of the broadcast message. When vehicle r receives a new broadcast message and aims to rebroadcast the message, its transmitting neighbors from which the message is successfully received will be checked. The transmitting vehicle, vehicle t, which has the smallest contention window CW_t^s in the set of transmitting neighbors will be selected. In addition, the number of neighbors of vehicle t (K_t) will be captured. In the neighboring set, if multiple transmitting vehicles have the same value of CW_t^s, the neighbor that has the largest number of neighbors will be considered. Since vehicle r successfully received the message from vehicle t, the value of CW_t^s will be a reliable candidate for the contention window base value of CW_r. We propose a fuzzy logic-based contention window size adjustment system based on the information of spatial distribution and similarity of density. This system is utilized by the protocol to decide to keep, reduce, or increase the base value to adjust CW_r. For the first input of the fuzzy logic, the normalized value of NNI (spatial distribution measure) is used:

$$NNI_{normalized} = \frac{NNI}{NNI_{max}} \tag{11}$$

where, in our proposed network, NNI_{max} can be defined as:

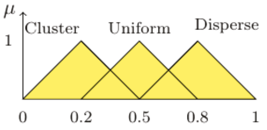
$$NNI_{max} = 1.2\sqrt{n} \tag{12}$$

As the second input of the fuzzy system, the $Similarity\ of\ Density\ (Den - Sim)$ metric described in Equation (13) is used:

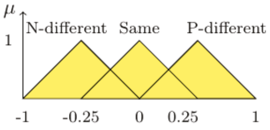
$$Den - Sim = \frac{K_r - K_t}{max\{K_r, K_t\}} \tag{13}$$

where K_r denotes the number of neighbors that vehicle r has. $Den - Sim$ will take on the values between –1 and 1. When K_r is less than K_t, $Den - Sim$ will get a negative value and, for K_r greater than K_t, $Den - Sim$ will be positive. The larger $\mid K_r - K_t \mid$ is, the smaller the similarity of density is. In this case, if $Den - Sim$ has a negative value $(N - different)$, the contention window size will be reduced, and, if it has a positive value $(P - different)$, the contention window size will be enlarged. Figure 7 shows the membership functions of the fuzzy input parameters and Table 2 states the fuzzy IF-THEN rules.

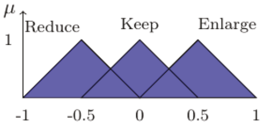
Algorithm 3 describes the proposed contention window size adjustment method. Table 3 shows the reduction of packet loss due to collisions, when the proposed fuzzy logic-based contention window size adjustment is applied. In addition, Figure 8 shows the TRAB system flowchart.



a) Spatial Distribution



b) Similarity of Density



c) Status

Figure 7. CW adjustment fuzzy membership functions.

Table 2. *CW* size adjustment rules.

Spatial Distribution	Similarity of Density	Status
Cluster	Negative-different	Keep
Cluster	Same	Enlarge
Cluster	Positive-different	Enlarge
Uniform	Negative-different	Reduce
Uniform	Same	Keep
Uniform	Positive-different	Enlarge
Disperse	Negative-different	Reduce
Disperse	Same	Reduce
Disperse	Positive-different	Enlarge

Algorithm 3: Size adjustment for contention window.

```
Select the transmitting neighbor $t$ which has the smallest $CW$
  Consider vehicle $t$'s number of neighbors ($K_t$)
  Consider vehicle $t$'s contention window size ($CW_t^s$)
  Initialize the current $CW$ of vehicle $r$ as $CW_r$=$CW_t^s$
  Calculate the metrics $NNI_{normalized}$ and $Den-Sim$
  Use the proposed fuzzy logic system to determine the Status
if Status is Decrease;
 then
   $CW_r$=$((CW_t^s+1)/2)-1$;
if Status is Keep;
 then
   $CW_r$=$CW_t^s$;
if Status is Increase;
 then
   $CW_r$=$((CW_t^s+1)*2)-1$;
```

Table 3. Packet loss reduction.

Number of Vehicles	Packet Loss Reduction in Highway	Packet Loss Reduction in Urban
10	10%	12%
25	13%	15%
50	14%	16%
100	17%	19%
300	19.5%	21%

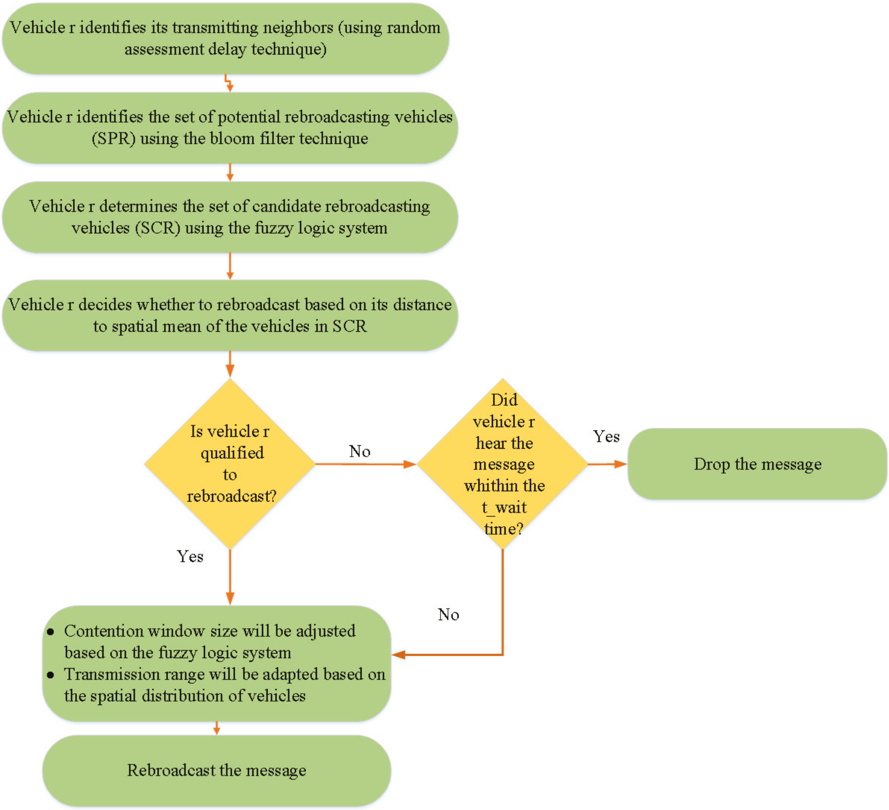


Figure 8. TRAB system flowchart.

4. Evaluation and Results

In this section, we evaluate the efficiency of our proposed intelligent self-adaptive broadcast scheme and discuss the results. We use ns-3, which is one the most reliable and scalable network simulators, with the stated parameters in Table 4.

The duration of network simulation is set up to 1200 s and the initial communication range is 250 m. We use “ns-3 Range Propagation Loss Model” in which only the distance of transmitter to receiver is considered to cause the propagation loss.

Table 4. The simulation parameters.

Parameter	Value
Number of vehicles	10, 25, 50, 100, 300
Duration	1200 s (20 min)
Max speed (Highway)	25 m/s
Max speed (Urban)	14 m/s
T_{max}	100 ms
Hello message period	1 s
Hello message size	64 bytes
Message period	20 s
Message size	512 bytes
Signal propagation model	Nakagami
MAC/PHY protocol	IEEE 802.11p
Layer 3 addressing	IPv4
Simulation area scenarios	$3 * 3$ Manhattan grid (urban), straight line (highway)

The path loss is determined based on the MaxRange (in meter). In addition, we consider "ns-3 Nakagami Propagation Loss Model" to address the signal strength variation caused by multipath fading. We use the ns-3 WAVE model [40], as the system architecture of vehicular communications. The WAVE model supports 802.11p MAC and PHY layers and uses the 5.9 GHz frequency band. The bandwidth is 10 MHz while the data rate is 6 Mbps. The PHY layer controls the process of frame decoding considering the received signal strength-to-noise ratio (SINR). We also use layer 3 IPv4 addressing.

To evaluate the performance of TRAB, we use seven other adaptive receiver-oriented broadcast protocols: CBF-broadcast [32], DADCQ [16], QRE [17],VDF [18], FLB [20], BEFLAB [21], and IHAB [22].

In our simulations, we assume, in all the protocols, that vehicle position and speed information is obtained from the vehicle's GPS.

We present the results based on four different metrics:

- Reachability
- Rebroadcasts per covered vehicle
- Bytes sent per covered vehicle
- Per-hop delay

We define reachability as the average portion of vehicles in the network which successfully receives the source message. The second metric, the number of rebroadcasts per covered vehicle, represents the average number of retransmissions per receiving vehicle ignoring beaconing.

To get the bytes sent per covered vehicle, we obtain the ratio of the total number of bytes sent by a receiving vehicle (including beacons) to the total number of receiving vehicles.

Finally, we define the per-hop delay as the time it takes to deliver the message to the last covered vehicle divided by the number of hops traversed.

We also run the simulation for different scenarios of traffic density (low, medium, and high).

4.1. Simulation Results

In this section, we evaluate the proposed broadcast scheme and compare it with other broadcast protocols. We use the same simulation environments and parameters used by the other protocols. To assess scalability, we run the simulation for different traffic density scenarios. For each scenario, the results are based on the average of the five simulation runs. We present plots that show the results for both highway and urban areas including the 95% confidence intervals indicated by the error bars.

4.1.1. Highway Environment

In order to simulate a highway environment, we use the ns-3 rectangle position model to place the vehicles randomly on a straight line. Then, using the ns-3 constant speed mobility model, we generate the vehicles' mobility.

As stated in Table 4, we run the simulations for various numbers of vehicles in the network. Figure 9 shows that TRAB is the best scheme to deliver the message in terms of reachability compared to the other schemes. The reachability of TRAB is around 93% when the network is sparse and increases up to 98.5% when the network begins to be dense. This is because the scheme can adapt the transmission range and the contention window size.

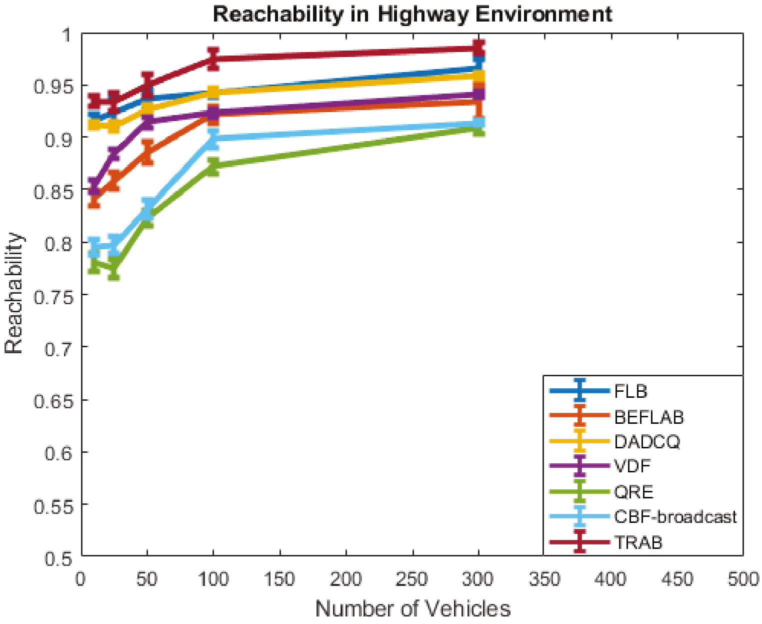


Figure 9. Highway reachability.

From Figures 10 and 11, we observe that, with increasing number of vehicles, the number of rebroadcasts and the bytes sent per covered vehicle reach a plateau. This proves that the proposed algorithm is scalable and can control the bandwidth usage in dense networks. In addition, it can be seen from Figures 10 and 11 that TRAB outperforms DADCQ, FLB, IHAB, VDF, and QRE protocols in terms of bandwidth consumption. It significantly reduces the number of retransmissions and also the number of bytes for all traffic densities compared to those protocols while it has slightly better results than CBF-broadcast and BEFLAB. This is because TRAB is more aggressive in determining the rebroadcasting vehicles. In addition, its adaptive transmission range reduces the number of redundant transmission hops, especially in sparse networks.

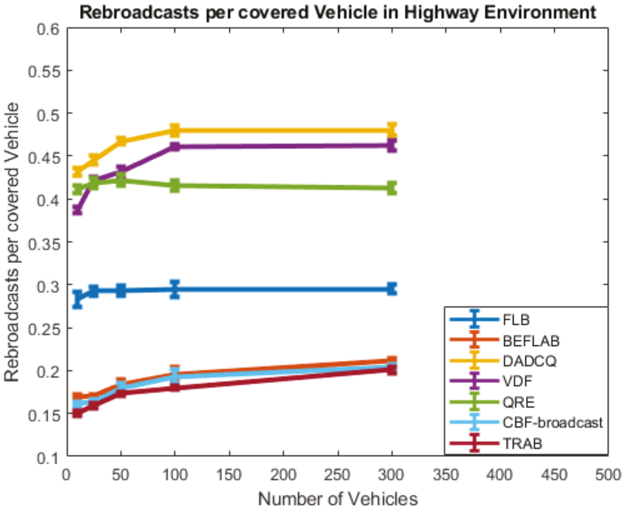


Figure 10. Highway rebroadcasts per covered vehicle.

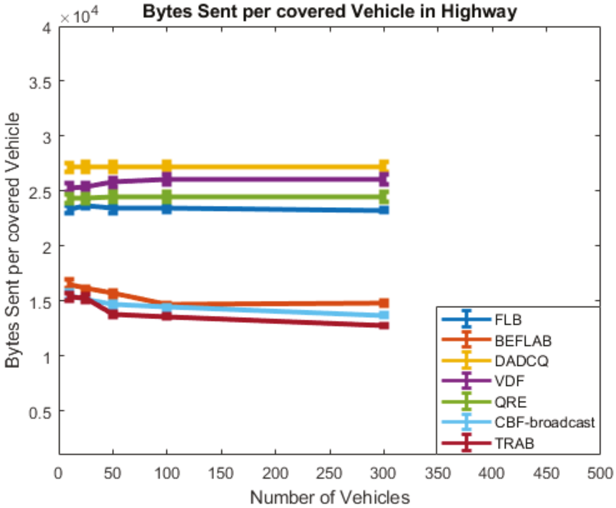


Figure 11. Highway bytes sent per covered vehicle.

Figures 12 and 13 indicate the per-hop delay and average total delay of TRAB, FLB, BEFLAB, IHAB, DADCQ, VDF, QRE, and CBF-broadcast. As can be seen from these two figures, TRAB experienced slightly higher value of delay (per-hop and total delay) compared to the other protocols (for per-hop delay around 54 ms and for total delay 165 ms in dense networks). This could be attributed to the computational and communication complexity of TRAB.

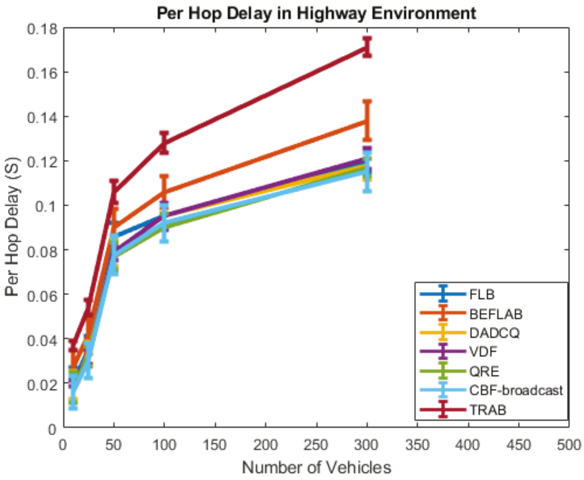


Figure 12. Highway per-hop delay.

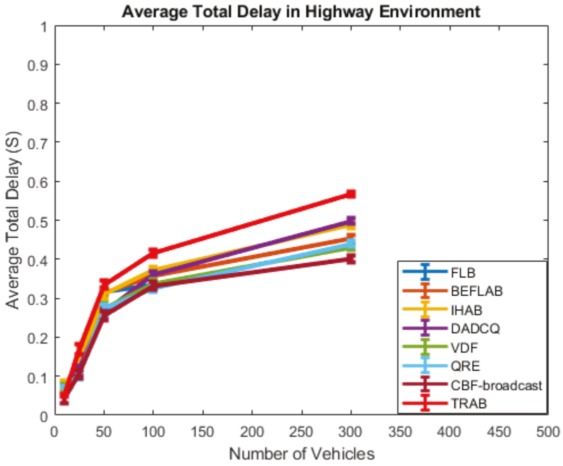


Figure 13. Highway average total delay.

4.1.2. Urban Environment

We consider a 3 ∗ 3 Manhattan grid, which has an edge length of 1 Km and an equal distance of 0.5 Km between neighboring intersections. We also employ Simulation of Urban MObility (SUMO) to generate mobility of vehicles and utilize the car-following model, in which each vehicle adjusts its velocity based on the velocity of the leading vehicle. Using "randomTrips.py" in SUMO, we randomly generate the distribution of vehicles and routes. Finally, in order to generate node mobility, we use the Ns2MobilityHelper class to import the generated mobility traces into ns-3.

The simulation results for urban environment are shown in Figures 14–17. Based on Figure 14, it is clear that TRAB enhances the reachability for various numbers of vehicles. On the average, the reachability of TRAB is almost 75% when the network has a few number of vehicles, and it increases up to 94% when the network has 300 vehicles. As we mentioned for the highway environment, the reachability enhancement is the result of the transmission range adaptation and the contention window size adjustment.

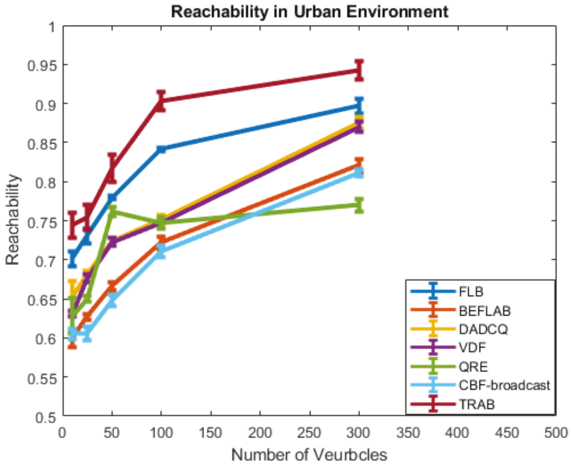


Figure 14. Urban reachability.

From Figures 15 and 16, similar to the simulation results for the highway environment, we can see that TRAB outperforms almost all the other protocols in terms of reducing the number of retransmissions and bytes sent. Again, this is due to its aggressive behavior in determining the rebroadcasting vehicles. In addition, its ability to adapt the transmission range suppresses redundant transmissions. Figure 17 shows the per-hop delay for TRAB and the other protocols. Similar to the highway results, the computational and communication complexity of TRAB brings on a bit higher per-hop delay compared to the other protocols (around 41 ms in dense networks). Finally, Figure 18 indicates the total delay. As can be seen from Figure 18, when the density of vehicles is low (up to 50 vehicles in the network), TRAB experiences a moderate amount of total delay which could be due to its ability to adapt (increase in this case) the transmission range. It is likely to reduce the number of hops to cover all the vehicles in the network. With increased number of vehicles, TRAB has the highest total delay.

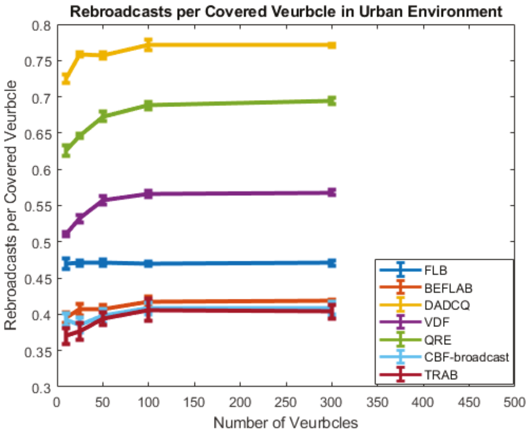


Figure 15. Urban rebroadcasts per covered vehicle.

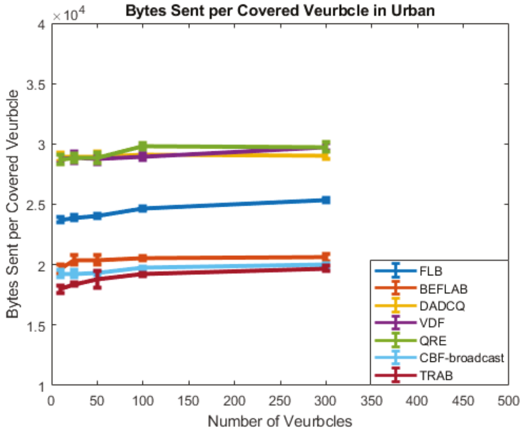


Figure 16. Urban bytes sent per covered vehicle.

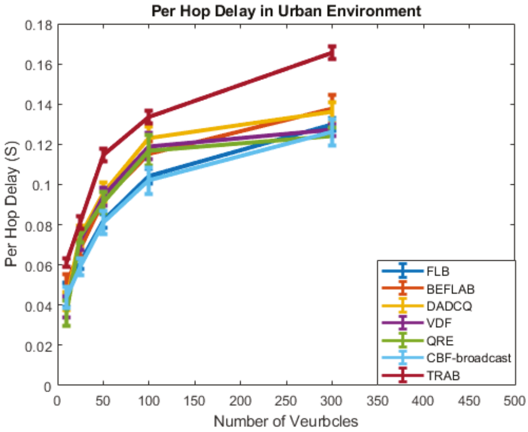


Figure 17. Urban per-hop delay.

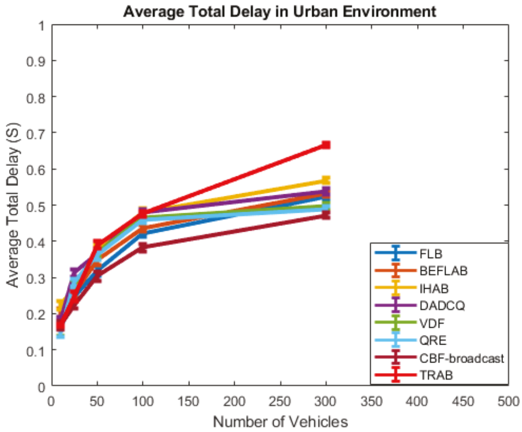


Figure 18. Urban average total delay.

5. Conclusions

In Vehicular Ad Hoc Networks (VANETs), smart data dissemination is crucial for efficient exchange of traffic and road information. Given the dynamic nature of VANETs, the challenge is to design an adaptive multi-hop broadcast scheme that achieves high reachability while efficiently utilizing the bandwidth by reducing the number of redundant transmissions. In this paper, we propose a novel intelligent fuzzy logic-based density and distribution adaptive broadcast protocol for VANETs. The proposed protocol estimates the spatial distribution of vehicles in the network, employing the Nearest Neighbor Distance method, and uses it to adapt the transmission range to enhance reachability. To reduce packet collisions, the protocol intelligently adapts the contention window size to the network density and spatial distribution. The Bloom filter technique is used to reduce the overhead resulting from the inclusion of the neighbor IDs in the header of the broadcast message, which is needed in identifying the set of potential rebroadcasting vehicles. For increased number of vehicles, the Bloom filter technique results in up to 80% overhead reduction for both highway and urban environments.

Our simulation results confirmed the effectiveness of the proposed scheme in enhancing reachability while efficiently utilizing bandwidth. While the reachability enhancement can be attributed to the adaptive transmission range and adjustable size of the contention window, the efficient bandwidth consumption performance of TRAB comes as a result of its aggressive behavior in reducing the number of rebroadcasts. The per-hop delay and average total delay results show a very slight disadvantage of TRAB compared to the other protocols. This could be attributed to the computational and communication complexity of TRAB. As future work, in addition to spatial distribution and density adaptation, we plan to incorporate interference-aware transmission range adaptation to further improve the performance of TRAB.

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Article

Epidemic and Timer-Based Message Dissemination in VANETs: A Performance Comparison

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Abstract: Data dissemination is among the key functions of Vehicular Ad-Hoc Networks (VANETs), and it has attracted much attention in the past decade. We address distributed, efficient, and scalable algorithms in the context of VANETs adopting the paradigm. We introduce an epidemic algorithm for message dissemination. The algorithm, named EPIC, is based on few assumptions, and it is very simple to implement. It uses only local information at each node, broadcast communications, and timers. EPIC is designed with the goal to reach the highest number of vehicles "infected" by the message, without overloading the network. It is tested on different scenarios taken from VANET simulations based on real urban environments (Manhattan, Cologne, Luxembourg). We compare our algorithm with a standard-based solution that exploits the contention-based forwarding component of the ETSI GeoNetworking protocol. On the other hand, we adapt literature based on a connected cover set to assess the near-optimality of our proposed algorithm and gain insight into the best selection of relay nodes as the size of the graph over which messages are spread scales up. The performance evaluation shows the behavior of EPIC and allows us to optimize the protocol parameters to minimize delay and overhead.

Keywords: vehicular networks; data dissemination; epidemic algorithms

1. Introduction

In the framework of smart cities and environments, a fundamental role will be played by VANETs (Vehicular Ad-Hoc Networks). These networks are set up in an ad-hoc fashion by vehicles and provide direct communication among them, without the support of external infrastructure. Originally conceived essentially for vehicular safety, VANETs are also used for road monitoring and infotainment applications in the framework of the intelligent transportation system paradigm.

VANETs are designed to increase safety and driving efficiency and make the driving experience more comfortable. As for safety, it has been demonstrated that about 60% percent of accidents can be avoided by sufficient warnings. This can be pursued by using direct vehicular message dissemination in emergency situations. VANETs will also be used to gather Floating Car Data (FCD) for urban sensing and vehicular traffic control.

In all cases, Vehicle-to-Vehicle (V2V) communication systems provide a 360 degree view of similarly-equipped vehicles within communication range, and multi-hop dissemination messages can be spread or collected in different Regions of Interest (RoI). In this case, VANET vehicles themselves act as the relay nodes of the network, giving the possibility to forward the time-critical (e.g., emergency) messages, independently of the availability of external network infrastructures.

Many challenges are posed by the implementation of VANETs, which should provide first of all a high quality of services able to guarantee, with a very high probability, the correct forwarding of a message through the network. Another challenge is to achieve a minimum latency in the dissemination of information over an RoI. This is especially important in the case of critical messages, e.g., for emergency situations. When dealing with broadcast-based dissemination, also efficiency is a concern, i.e., the minimization of the number of replicas of the same message that are transported by the network to cover the RoI.

The VANET is a, particular type of "ad-hoc" [1] network; hence it is self-configuring and designed to operate autonomously. Each mobile node is free to move independently while communicating. The protocols used to communicate are specified in the standard IEEE 802.11p [2], which is an amendment of IEEE 802.11. On top of the IEEE 802.11p stack, one of the most important goals is to define and implement an efficient dynamic routing algorithm that can help disseminate a message to all vehicles roaming in a given RoI. Defining a simple, distributed, efficient routing algorithm is challenging because of the highly dynamic topology of the network, where each node is in constant movement. The challenge is to reduce the delay associated with passing the information from a node to another and making the algorithm as fast, reliable, and efficient as possible, while requiring the least possible local control information and overhead.

Epidemic paradigms can represent a valid model to follow. These models have been studied to analyze the behavior of infectious diseases and to model their spreading in the population, but they have turned out to be relevant and useful also for technological fields, e.g., to model the propagation of malware or, like in our specific case, to model the dissemination of a message in an ad-hoc network. There are different types of epidemic models. The simplest is the Susceptible-Infected (SI) model. In this model, each node can assume only two states: (i) susceptible, if it has not been infected yet; (ii) infected, if the node has got the disease. In terms of message dissemination in a VANET, infection consists of getting a message; hence, a vehicle is susceptible as long as it has not received a copy of the message yet. In this simple model, we assume that a vehicle remains in the status "infected" for the rest of the time after receiving the message. Another model is SIS (Susceptible-Infected-Susceptible), similar to SI, but with the difference that the "infected" state only lasts for a given time period. After that time, the node returns to a 'susceptible" state. Yet another variant, which is the one that inspired our protocol, is Susceptible-Infected-Recovered (SIR) [3]. Recovered means that a node cannot be infected any more (it is immune), nor does it contribute to the spreading of the disease. In the VANET application, this means that a vehicle that has received the message (thus turning its state from susceptible to infected) has to decide whether to relay the message or not. Once the decision is made, either way, the vehicle will not take part in the dissemination of the same message any more (it becomes recovered). The contribution of this paper is threefold: (i) we introduce EPIC, a protocol for disseminating messages in VANETS with the aim of being based on few assumptions and very simple to implement in a distributed fashion; (ii) we compare EPIC with a theoretical bound derived form the literature on the connected cover set that allows us to assess the near-optimality of our proposed algorithm; (iii) we compare EPIC with the Contention-Based Forwarding (CBF) approach, which is defined by the ETSI standardization bodies, and with an evolution of it (named CBF+); we show, in real urban scenarios, the performance gain of our approach both in terms of capability to reach a great number of vehicles and in the reduced number of involved relay nodes to attain this satisfactory result. The rest of the paper is structured as follows. Section 2 discusses key related works on epidemic dissemination in VANETs. The EPIC model and algorithm are presented in Section 3, while the relevant performance assessment is in Sections 4 and 5. Finally, conclusions are given in Section 6.

2. Related Work

A VANET dissemination logic is used to select a sub-set of vehicles that are situated along the road, to act as relay nodes. Message dissemination in VANETs has been discussed in several papers in the last few years, where different challenging aspects have been highlighted [4]. Data dissemination is fundamental to transport information to intended receivers while meeting certain design objectives, e.g., high delivery ratio. In pure ad-hoc VANETs, where a network infrastructure does not exist, messages move from one vehicle to another in order to reach the indented receivers. While flooding is a possibility to disseminate data in a VANET, it may result in being very inefficient due to the high load generated in the system. The dissemination logic has to select only a sub-set of vehicles to act as relay nodes to avoid the broadcast storm problem [5]. As an example, the paper [6] aimed at selecting as relaying vehicles those that were located at preferred positions, while inhibiting others. The protocols in this category can be identified as cluster-based relay where the dissemination logic operates by identifying clusters and cluster heads for an efficient dissemination. The paper [7] proposed different solutions to collect real-time FCD information efficiently in Dedicated Short-Range Communication (DSRC)-enabled VANETs. The goal was to improve the efficiency of the FCD collection operation while keeping the impact on the DSRC communication channel as low as possible. We do this by exploiting a slightly modified version of a standardized data dissemination protocol to create a backbone of relaying vehicles that, by following local rules, generate a multi-hop broadcast wave of collected FCD messages. The proposed protocols are evaluated via realistic simulations under different vehicular densities and urban scenarios.

Another way to face the dissemination problem is to rely on probabilistic approaches. One branch of these approaches is represented by the epidemic models that were proposed in the past to solve the probabilistic communication and information dissemination in ad-hoc networks [8] and in distributed systems [9]. In [10], M.Nekovee et al. showed the benefits of using epidemic algorithms in vehicular ad-hoc networks. One key advantage that epidemic algorithms offer is that they do not need any information about the network topology. This perfectly fits the requirements of VANETs because of their dynamic topology and the absence of an infrastructure to which to refer. An epidemic algorithm, as explained in [11], mimics the spread of a contagious disease: Each vehicle relays the information it has received to randomly chosen peers, rather than to a specific node. Each node decides if it has to re-transmit the message or not, according to some infection rules. The simplest epidemic example is flooding, where each node rebroadcasts all messages it receives. Many variations have been proposed to minimize the redundancy of flooding, for example probabilistic, distance-based, and location-based algorithms. An adaptive bio-inspired epidemic dissemination protocol for wireless sensor-actuator networks was presented in [12]. An analytical model of message dissemination optimal control to minimize the accumulated network cost was provided in [13], with applications to mobile and social networks. Epidemic modeling has been also applied extensively to malware spreading in networks (e.g., see [14]).

In [15], it was shown how the performance of a VANET degraded as the packet flow increased, and the authors proposed a probabilistic algorithm as a solution to reduce the overload. One fundamental issue during flooding is the spurious forwarding, that is when multiple vehicles are committed to forward the same packet when it is not necessary, i.e., when a vehicle forwards a message even if all its neighbors have already received it. Situations like this have a catastrophic impact on the network in the case of a high density of nodes and channel congestion, limiting performance and functionality. With probabilistic approaches, the impact of spurious forwarding is reduced by introducing a parameter p (decimation probability), so that a node gives up forwarding with probability p and becomes a forwarder with probability $1 - p$.

Furthermore, the work in [16] addressed probabilistic dissemination algorithms, defining an analytical model to infer optimal re-broadcast probabilities. Our approach is based instead on timers, rather than probabilistic forwarding. Reliable message broadcast was the focus of [17]. The authors aimed at providing a reliable broadcasting of messages in a vehicular network. The potential of non-orthogonal multiple access for V2V message dissemination was explained in [18]. The paper in [19] targeted reliable delivery of emergency messages. The authors focused on coding and the optimal number of repetitions of the message to combat the unideal vehicular radio channel. In [20], the authors defined a message dissemination protocol suited for urban environments. It exploited knowledge of the street layout, e.g., adapting its behavior to the presence of intersections.

In this paper, we present EPIC, as the preliminary proposed in [21], and we provide an extensive performance evaluation by comparing it with both a theoretical bound provided by leveraging the graph theory and with an algorithm, Contention-Based Forwarding (CBF), defined by the ETSI standardization bodies [22].

Epidemic approaches applied to the data dissemination in VANETS can be found also in [23]. In [23], the proposed algorithm was based on the SIR approach enhanced with a selection of the relay only among the ones sending back a passive acknowledgment message and at the farthest distance. Compared with this approach, EPIC, does not use control messages, apart from the beaconing service, which is used by the vehicles to update the positions of neighbors, since all the metadata needed for the algorithm to work are contained in the short header of the message being disseminated. Moreover, another important aspect is that EPIC is evaluated in real urban scenarios.

3. EPIC Model and Algorithms

The leading idea of EPIC is as follows. A vehicle A, which receives a message, estimates if one or more of its neighbors have already received a copy of the same message, broadcast by other relay nodes. If the majority of the neighbors of A are believed to have already received the message, then A will not relay the message itself. A can estimate the coverage of its neighbors thanks to: (i) a list of previous relays carried in the header of the message; (ii) the knowledge of the position of its neighbors. The execution of the algorithm does not require any dedicated control message. Each vehicle executes the algorithm autonomously, i.e., based only on: (i) events that it observes at its network interface; (ii) information stored in the vehicle node; (iii) information contained in the disseminated message.

In the following, we assume that each vehicle is equipped with GPS (hence knows its position) and maintains an updated database of its neighbor vehicles, the so-called Local Dynamic Map (LDM) [24]. The LDM is updated thanks to beaconing [25] (notice that the LDM includes only the neighbors of a vehicle, so it gives no knowledge about the overall network topology).

3.1. Message Structure

The dissemination protocol header carried by the message contains the following main fields:

1. ID (four bytes), a message identifier;
2. $EMITTERS$ (variable size), a list of records, one for each previous relay node of the message;
3. TTL (one byte), the number of remaining hops before stopping the dissemination at $TTL = 0$. TTL is decremented by one by each relay node and set to a given initial value by the application at the originator of the message.

Each record in the $EMITTERS$ list is comprised of: the MAC address of the previous relay node (*ADDR* = 6 bytes), its GPS coordinates (*COORD* = 12 bytes), a timestamp of when the relaying took place (*TS* = 4 bytes). The $EMITTERS$ list is completed by a one byte field carrying the current number of records listed. The first element in the list corresponds to the message originator, the lest one is the last relay node from which the message has been received.

Table 1 lists the data type and size of the message fields. The parameter h indicates the number of nodes that have already relayed the message whose coordinates are stored in the $EMITTERS$ message header. The maximum value of h is denoted as N_{eml}. As a consequence, the message length is $L = 4 + 1 + 1 + (12 + 6 + 4) \cdot h + \ell = 6 + 22 \cdot h + \ell$, where ℓ is the length of the message payload.

To reduce the overhead, it is possible to shorten the list of relay nodes ($EMITTERS$) recorded in the message header to $N_{eml} < TTL$ nodes, trading off the performance of the dissemination protocol in terms of efficiency (reduced number of redundant copies of the message) with the overhead carried by each relayed message.

Table 1. Message header: field, type, and size.

Field	Type	Size (Bytes)
ID	Integer	4
EMITTERS	List	1+(12+6+4)$\cdot h$
TTL	Integer	1

3.2. EPIC Algorithm

The EPIC algorithm is conceived of as the spreading of an "infection", given the analogy of message dissemination to a population of vehicles roaming in the RoI with the spreading of a disease in a population of susceptible individuals. This spread follows the SIR model described in [3]. EPIC uses the same states and transitions of the SIR model, as shown in Figure 1, and these states refer to each vehicle for a given message M. This means that for two different messages, M and M^*, i.e., $M^* \neq M$, the same vehicle can be in different states. On the contrary, for the same message M, a vehicle is in exactly one state at any given time. The time spent in a state depends on the events described in the caption of Figure 1.

Figure 1. States and transitions of the Susceptible-Infected-Recovered (SIR) model. The same are used in EPIC, and they refer to a specific message. Let us identify it as M, which is sent in the VANET. Each vehicle that never received the message M is in the susceptible state. When it receives the message M, it makes a transition to the infected state, setting a timer Δt. Once the timer expires, the vehicle decides whether to rebroadcast a message or not (this is part of the EPIC algorithm and is described in the following) and makes a transition to the recovered state. When a vehicle is in this latter state, it discards all the next copies of M.

Algorithm 1 describes the behavior of a vehicle every time it receives a message. For the sake of simplicity, we will consider the dissemination of a single message.

Each vehicle starts in the *SUSCEPTIBLE* state, meaning that it has not yet received a copy of the message. Let us consider a tagged vehicle A. Once a copy of the message arrives at A, the procedure is executed, changing A's state from *SUSCEPTIBLE* to *INFECTED* and starting a timer of duration Δt:

$$\Delta t = \max\left\{T_{min}, T_{max}\left(1 - \frac{d}{R_{max}}\right)\right\} \tag{1}$$

where:

- T_{max} and T_{min} are respectively the maximum and minimum waiting time before sending a message in broadcast.
- R_{max}: the maximum communication range, i.e., the maximum range within which message delivery is successful with a high probability.
- d: distance between the receiver and transmitter of the message.

An additional parameter is used in the EPIC procedure, *EvaluatePositions*, namely R_{min}. R_{min} is the minimum communication range considered by the Algorithm 2, i.e., it is assumed that two nodes within distance R_{min} can communicate successfully with probability one.

The timer value depends on the distance d between A and the vehicle node B from which A has received the message. The coordinates of B are known to A, since they are carried in the message header (last element of the $EMITTERS$ list).

Algorithm 1 Procedure to be executed upon message receipt.

```
procedure OnMessageReceipt
    input:
    msg ← received message
    state ← vehicle state, can be SUSCEPTIBLE, INFECTED, or RECOVERED

    main:
    if state = RECOVERED then
        return
    else if state = SUSCEPTIBLE then
        rcv_messages ← empty list
        state ← INFECTED
        timer ← new timer($\Delta t$)
        rcv_messages.append(msg)
    else if state = INFECTED then
        rcv_messages.append(msg)

    on timeout:
    do_relay ← EvaluatePositions
    if do_relay and msg.TTL > 0 then
        msg ← updateMessage(msg)
        relayMessage(msg)
    state ← RECOVERED
```

While the timer is running, *A* remains in the *INFECTED* state. In that state, *A* collects all other possibly received copies of the same message (*A* can recognize that a received packet contains a copy of a previously received message by looking at the message *ID* and originator source address). *A* appends all received copies in the "rcv_messages" list.

Upon timer expiry, *A* uses the content of the "rcv_messages" list to understand whether it should relay the message. For that purpose, *A* runs the procedure *EvaluatePositions* described in Algorithm 2. If this evaluation returns TRUE and if the current hop counter of the message is less than *TTL*, then *A* updates the message header fields and broadcasts the message. If instead, the outcome of the procedure *EvaluatePositions* returns FALSE (i.e., relaying the message is not needed, since all neighbors of *A* should have already received it), node *A* does not relay the message and drops it (after having delivered the data to the upper layer).

After the decision about whether to relay the message or not, the protocol state machine of *A* moves to the *RECOVERED* state. Once in this state, the vehicle will ignore all further copies of the message.

Algorithm 2 uses a heuristic to identify whether or not a vehicle has to relay a message. The heuristic is based on the knowledge of the position of the previous emitters. This position is used to infer whether the message has been or not received by the neighbors of the current vehicle. Notice that being a heuristic, it may return a result that does not always match the reality. In the following, we present more detail of the steps performed to implement this heuristic. In the initialization step, the current vehicle creates a set of all emitters found in the headers of all received copies of the message (in case *EMITTERS.ADDR* is duplicated, the emitters list picks only the emitter with the recentest *TS*field). Then, in the main phase, the heuristic iterates over each emitter *E* in the set and checks whether any neighbor *V* of *A* is within $R_{\min}$ of *E*. If this is the case, the heuristic infers that *V* has already received the message from *E*. Hence, *A* removes *V*'s position from the "not_reached" list that it had initialized with the full list of *A*'s current neighbors. The algorithm returns TRUE if, at the end of the execution, the number of unreached neighbors is greater than a threshold fraction α of all the neighbors of *A*. Otherwise, it returns FALSE. It is apparent that, if we increase/decrease $R_{\min}$, a neighbor has more/less chances to be removed from the list; thus, it is more/less likely that the vehicle relays the message. We notice again that, EPIC being a heuristic, Algorithm 2 can declare that: (i) a neighbor of A has received the message, while in fact it has not, or that (ii) a neighbor of A has not received the message, while in fact, the message was received by it. In the former case, there is a possibility that the EPIC node A does not act as the relay, while on the contrary, it is important to relay the message to reach some unreached nodes. In the second case instead, the EPIC node A may relay a message, and this relay is not necessary. If we set a limit on the *EMITTERS* list, the whole procedure's execution has a time complexity that is linear with respect to the number of neighbors of a vehicle node.

Algorithm 2 *EvaluatePositions*

Returns whether or not a vehicle node should re-broadcast a message (*dist* is the Euclidean distance).

```
procedure EvaluatePositions
    input:
    rcv_messages ← list of msgs received during timer
    neighbor_pos ← list of positions of my neighbors

    initialization:
    not_reached ← neighbor_pos
    emitters = ∅
    for msg in rcv_messages do
        emitters = emitters ∪ msg.EMITTERS

    main:
    for emitter in emitters do
        for pos in neighbor_pos do
            if dist(emitter.COORD, pos) < $R_{min}$ then
                not_reached.remove(pos)
    if not_reached.length > $\alpha$·neighbor_pos.length then
        return True
    else
        return False
```

Figure 2 illustrates an example of the execution of EPIC. Node A is *INFECTED* (EPIC vehicle, in red), waiting for the timer to expire, and receives copies of the message from two emitter nodes (yellow ones in the figure). Once the timer expires, the EPIC node has to decide whether or not to relay. It knows the positions of the emitters, retrieved from the *EMITTERS* field of each received message, and the positions of its neighbors from the LDM (*Neighbor* 1, *Neighbor* 2, and *Neighbor* 3 in the figure). The EPIC node gives up relaying the message since all of its neighbors are within R_{min} of at least one emitter node. In Figure 2a, the distance of *Neighbor* 3 from the closest emitters is greater than R_{min}; thus, the EPIC node decides to relay the message. On the other hand, in Figure 2b, all of EPIC's neighbors are within the R'_{min} range ($R'_{min}>R_{min}$) of a previous emitter node; thus, the node gives up relaying.

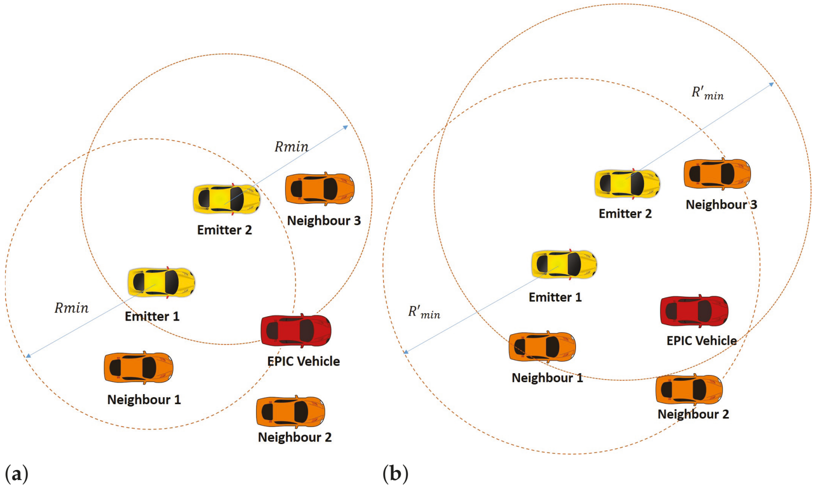


Figure 2. The red vehicle is the node currently running EPIC: (**a**) In this case, EPIC decides to relay, because one of the three neighbors (Neighbor2 in the figure) is not in the R_{min} range of any emitter; thus, the EPIC vehicle, from its perspective, considers it as not reached by the message. (**b**) The EPIC vehicle does not relay because the new R_{min} (R'_{min} in the figure) is such that all three of its neighbors are assumed to be reached by the message sent by the other two emitters.

4. Performance Evaluation Setting

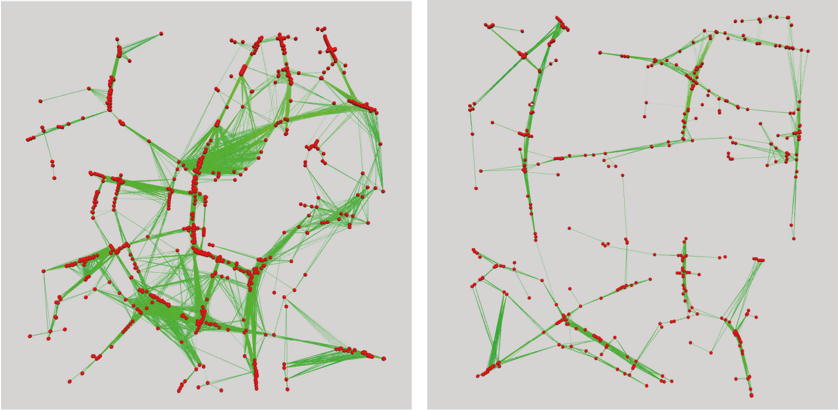
To assess the performance of EPIC and compare it to other approaches, we set up simulations of vehicular networks using VEINS [26] and three different scenarios. The considered scenarios refer to three urban maps of Cologne, Luxembourg, and Manhattan in New York. For each of these three scenarios, we defined vehicle flows feeding the maps, with a square RoI having a side of a few km. VEINS allowed an accurate simulation of the micro-mobility of a vehicle through the road map, thanks to all the metadata that describe the road lanes, traffic lights, the right of way, and vehicle routing. Simulation of the radio channel and of the communication stack was taken care of by OMNET++. The considered radio channel was the two-ray ground with the additional attenuation due to obstacles (the description of obstacles was included in the metadata of the urban maps).

For each scenario, we ran simulations where vehicles sent hello messages in the broadcast. Once all vehicles had sent their hello message, we recorded the LDMs of vehicles. In the LDM of vehicle i, we found the list of neighbors of i, i.e., those vehicles from which i received a message successfully. This allowed us to build a connectivity graph of the vehicular network. If vehicle i was reachable from vehicle j, we set $a_{ij} = a_{ji} = 1$. We forced the connectivity matrix to be symmetric, since the radio channel was reciprocal (time-division duplexing). The elements a_{ij} defined the adjacency matrix $\mathbf{A}$ of the connectivity graph. Table 2 shows the main characteristics of the considered graphs.

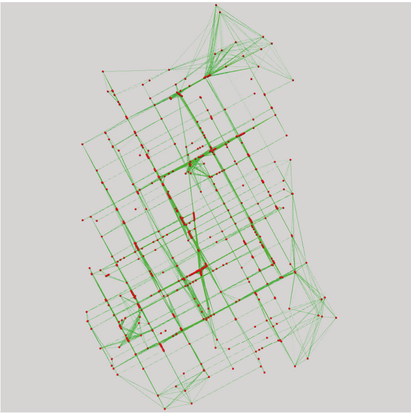
Figure 3a–c contains an overview of the geographical distribution of the network nodes (in red) and the connections between them (in green) derived by running simulations on the wireless communication via VEINS. We selected these graphs since they provide heterogeneous test settings for EPIC. Luxembourg (Figure 3a) had a high number of nodes, a high number of edges, and a very high average degree. Cologne (Figure 3b) had a low number of nodes, a low number of edges, and a high diameter. New York (Manhattan) (Figure 3c) had a high number of nodes, a relatively high number of edges, and a very low average number of hops between nodes.

Table 2. Metrics of connectivity graphs. In order from top to bottom: number of nodes, number of edges, average node degree, standard deviation of the degree, average distance between any two nodes (measured as the number of hops), standard deviation of the distance, diameter.

Scenario	**Luxembourg**		**Cologne**		**New York**	
Density	*High*	*Low*	*High*	*Low*	*High*	*Low*
# of Nodes	790	787	436	220	672	432
# of Edges	17,316	4589	3766	1217	12,462	4447
Avg. degree	43.84	11.66	17.27	11.06	37.09	20.59
Degree std. dev.	24.13	7.34	9.62	5.99	22.51	10.22
Avg. distance	4.07	7.10	8.11	6.25	3.29	3.45
Distance std. dev.	0.82	1.13	1.37	1.35	0.49	0.50
Diameter	10	16	21	15	8	9



(**a**) Luxembourg, 790 nodes (**b**) Cologne, 436 nodes



(**c**) New York (Manhattan), 672 nodes

Figure 3. Overview of the network graphs. They will provide heterogeneous test settings for EPIC.

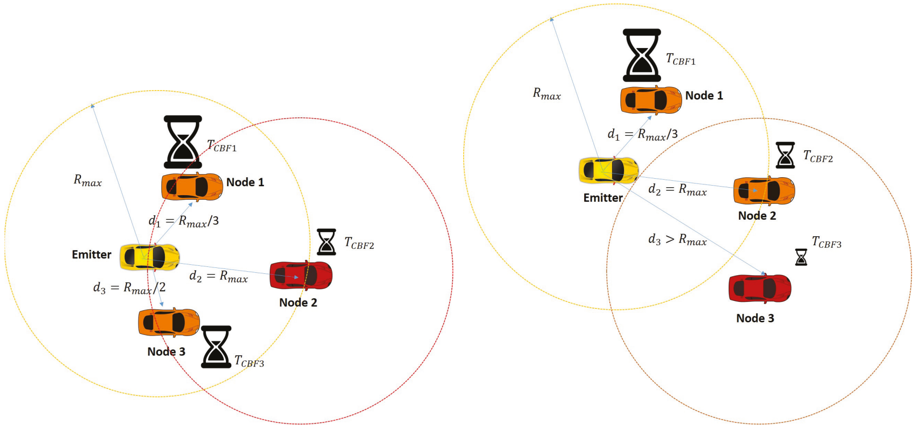
The evaluation of EPIC's performance was carried out on those graphs. The simulation experiments consists of picking an initial node at random and making it start message dissemination. The EPIC algorithm was run in each node of the network. To account for the effect of the underlying radio network, we defined a delay θ required for the transmission of the message, which was the sum of the overhead implied by lower layers plus the time to transmit the data. Since the packet size variation as it propagated was minor, we set θ equal to a fixed value, namely $\theta = 2.5$ ms. This time stemmed from the following calculation. Accounting for back-off slot count down (in the worst case), frame overhead in IEEE 802.11p amounts to 0.386 ms. If we assumed a node transmitted a payload of 800 bytes at air bit rate 3 Mbit/s (the most robust modulation and coding set of IEEE 802.11p), it turned out that $\theta = 0.386 \text{ ms } + 8 \cdot 800 \text{ bytes } / 3000 \text{ kbit/s } \approx 2.519$ ms.

According to the message passing model, if a node started transmitting a message at time t_0 (upon its timer expiry), its neighbors received that message only at time $t_0 + \theta$. This implied that a neighbor whose timer expired after time t_0, but before time $t_0 + \theta$, would not be inhibited, thus realizing a so-called "spurious forwarding" [27].

As a comparison, we considered the Contention-Based Forwarding (CBF) algorithm of the ETSI GeoNetworking protocol [22]. CBF is a simple forwarding scheme based on timers. Each node receiving a new message starts a timer given by:

$$T_{CBF} = \begin{cases} T_{min} + (T_{max} - T_{min}) \left(1 - \frac{d}{R_{max}}\right) & d < R_{max} \\ T_{min} & d \geq R_{max} \end{cases} \tag{2}$$

where the meaning of the parameters is the same as for EPIC. If the tagged node receives a new copy of the same message while the timer is running, it gets inhibited. It deletes the timers and gives up forwarding it. If instead, the timer expires and no new copy of the message has been received, the message is forwarded. A qualitative representation of this mechanism is reported in Figure 4.



(**a**) (**b**)

Figure 4. Example of the Contention-Based Forwarding (CBF) behavior where the emitter is the yellow vehicle and its transmission range is R_{max}. Cases: (**a**) There are three nodes receiving the message. The timers are set in accordance with Equation (2), and the first forwarder is the red vehicle (Node 2). The transmission of Node 2 will be received for the second time by Node 1 and Node 3, who are inhibited from forwarding the message again. (**b**) In this case, Node 3 receives the original message (being at a distance greater than R_{max}), and its timer is the lowest, so it re-transmits. The transmission by Node 3 inhibits Node 2, but not Node 1, which is no longer in the area of Node 3.

The version of CBF described above is the one specified as an ETSI standard. We introduced a modified version, with a new parameter that could be tuned to improve performance trade-offs, namely the fraction of vehicles reached by a disseminated message against the number of relay vehicles.

The modification affected the inhibition rule. During the timer count-down, a vehicle node was inhibited and canceled message forwarding, if it received at least $K \geq 1$ copies of the same message.

The standard corresponded to the special case $K = 1$. For the sake of clarity, we called the extended algorithm with a general parameter $K > 1$ CBF+ and reserved the name CBF for the standard one ($K = 1$).

5. Performance Results

We present the numerical results of the EPIC algorithm in the three scenarios described in the previous section. The presentation of the numerical results is organized as follows. In Section 5.1, we introduce the performance indicators and list the main parameters of the considered protocols. In Section 5.2, we give an exhaustive evaluation of the message delivery and message delays of EPIC, from which we derive an optimized setting of the EPIC parameters. In Section 5.3, we briefly examine CBF/CBF+'s performance, to derive the optimized setting of the parameter K and select the best configuration of CBF+ to compare with EPIC.

5.1. Metrics

We define the following performance metrics:

- PDR, the Packet Delivery Ratio, i.e., the fraction of the network nodes in the considered graph that were reached by at least one copy of the message. This was also the probability that a node received the disseminated message.
- NR, the Number of Relays, i.e., the number of network nodes that forwarded the message.
- RR, the Ratio of Relays, i.e., the ratio of NR over the number of network nodes, reported in Table 2.
- D, the Delay, that is the time elapsing between the beginning of the dissemination process and the and the last message reception (including duplicates). This was a measure of the time required for the dissemination process to die out. Thanks to the inhibition rule and to the finite number of nodes belonging to a graph, D was bounded above to a finite value.

Each metric was obtained by running several dissemination experiments, each one by selecting a random initial node that triggered message dissemination.

The result for each metric was obtained by taking the average of the obtained values over the different simulations.

Results were produced for three scenarios (Luxembourg, Cologne, and New York) and for two levels of vehicular density (high and low).

In the ensuing analysis, we removed all isolated graph nodes, so that the considered graphs were fully connected. This way, an ideal message dissemination algorithm should reach 100% of the nodes.

5.2. EPIC Performance

Figure 5a,b plot the PDR (dark colored/blue bars) and RR (light colored/orange bars) as percentages vs. R_{min} for the Luxembourg scenario with high and low vehicle densities, respectively.

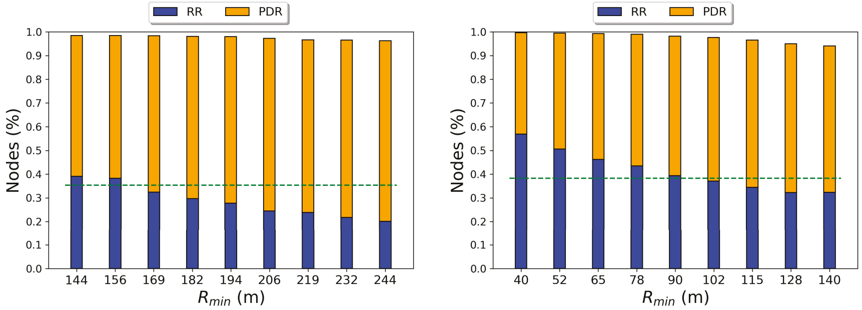
The horizontal dashed line represents the number of relay nodes estimated according to a heuristic algorithm [28] to compute the cardinality of the minimum connected cover set of a graph, given that it is comprised of a given node (the node that starts the dissemination).

Several remarks are in order.

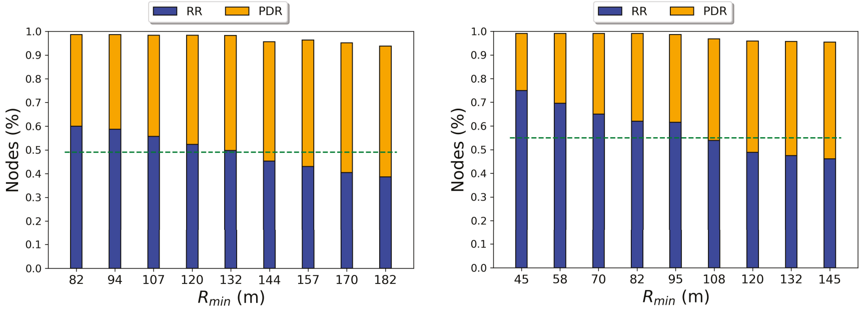
As for the effect of the parameter R_{min}, the bigger it was, the fewer the number of relay nodes. Correspondingly, also the coverage of the disseminated message exhibited a slight decrease, decreasing from about 99% to about 95%. Sizing R_{min} meant finding a good compromise between coverage (PDR close to 100%) and overhead (number of relay nodes). A sensible value appeared to be $R_{min} \approx 190$ m for high density and $R_{min} \approx 90$ m for low density.

The fact that the achieved number of relay nodes became smaller than the bound predicted by the heuristic algorithm for the minimum connected cover set should not be a surprise. First, it was a heuristic algorithm, not giving the exact minimum. Second, the algorithm found the connected cover set comprising all nodes belonging to the graph, while EPIC only reached part of the nodes of the graph (even if it was the vast majority).

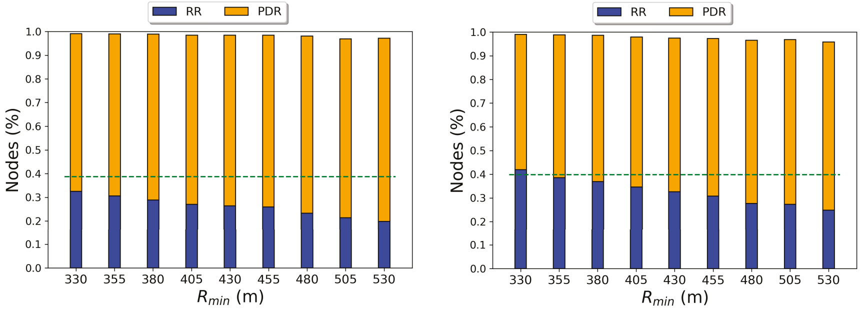
Finally, the percentage of required relay nodes was quite high, ranging between 30% and 40%. As expected, it was higher for the low density scenario.



(**a**) Luxembourg high density (**b**) Luxembourg low density



(**c**) Cologne high density (**d**) Cologne low density



(**e**) New York high density (**f**) New York low density

Figure 5. Comparison between network nodes reached by the disseminated message and nodes that broadcast the message, as a function of R_{min}. The overall bar reports the PDR ratio and the blue part is the Ratio of Relays (RR), as described in Section 5.1. The horizontal green line represents the RR using the heuristic connected set cover algorithm described in [28].

Figure 5c,d plot the PDR (dark colored/blue bars) and RR (light colored/orange bars) as percentages vs. R_{min} for the Cologne scenario with high and low vehicle densities, respectively. New York scenario is plotted in Figure 5e,f, according to the same color scheme as for the other scenarios.

Similar comments apply to the Cologne and New York scenarios as for Luxembourg.

The right choice for R_{min} appeared to be $R_{min} \approx 130$ m and $R_{min} \approx 95$ m for the high and low density Cologne scenario. As for New York, we found $R_{min} \approx 450$ m and $R_{min} \approx 380$ m, respectively, for high and low density.

We see that the best choice of the parameter R_{min} depended on the considered urban scenario. A marked difference could be noticed between Luxembourg and Cologne on one side and New York on the other side. In the first case, the right value for low density was slightly below 100 m, while it should be between 100 m and 200 m for high density. In the case of New York, the best R_{min} value was much bigger. The main reason was the regularity of the road pattern of New York (Manhattan) with respect to Luxembourg and Cologne. The average length of open, straight streets is much bigger for New York. The effect of this higher regularity was a low diameter and a low average number of hops between nodes in the connectivity graph, as shown in Table 2, which in turn was also a performance improvement both for the coverage (PDR) and the number of relay nodes (RR).

Figure 6a–f show respectively PDR and RR as a function of the ratio T_{max}/θ, for the three considered scenarios and two levels of vehicular density.

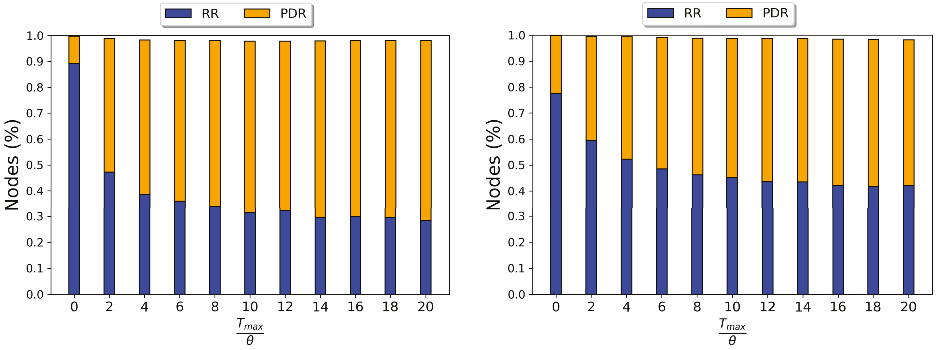
Since R_{min} was set in an optimal way for each scenario, the percentage of covered nodes was quite high. The percentage of relay nodes decreased monotonously with T_{max}/θ, tending to an asymptotic stable value, which was essentially reached for $T_{max} \approx 10 \cdot \theta$.

This set of results gave indications to set a proper maximum timer level T_{max}, once we had an estimate of the amount of time θ required to transmit the packet carrying the message.

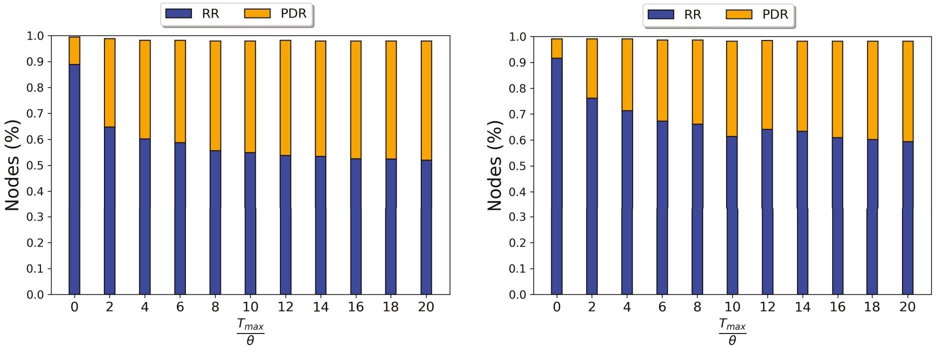
Figure 7a,b plot the normalized dissemination delay D/θ as a function of the normalized maximum value of the forwarding timer T_{max}/θ, for all urban scenarios and high and low vehicular density, respectively.

The average dissemination delay increased with T_{max}/θ, as expected. We saw that we needed to set $T_{max}/\theta \approx 10$ to reduce the number of forwarders to the lowest level achievable by EPIC, so as to limit the number of redundant forwarded messages copies.

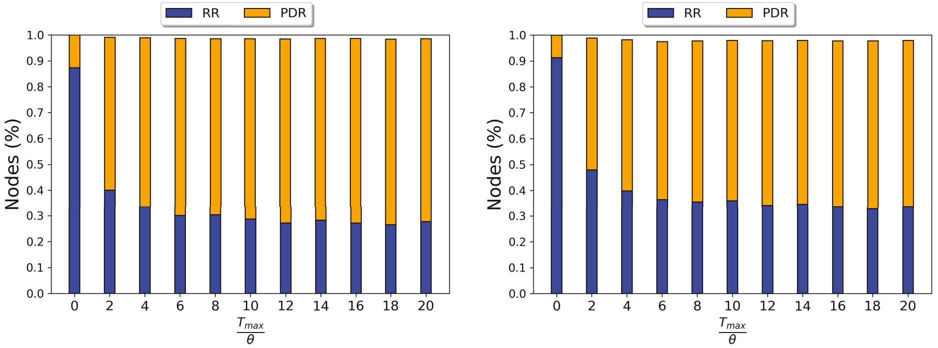
Going from high to low density, we saw that the performance in the New York scenario did not change, since the considered road topology was highly regular and the communication graph of vehicles was connected in both cases. The irregular road topology of the other two scenarios had contrasting effects. In Luxembourg, we observed a significant increase of dissemination delay when the density was lower. This was due to the reduced effectiveness of the inhibition rule, so that forwarding actions lasted longer to explore the whole vehicle graph. On the contrary, delay in the Cologne scenario become slightly lower with lower density. This correlated with the lower PDR of this last scenario, i.e., dissemination delay was somewhat shorter only because fewer vehicles (in percentage) were reached. Those that were left out were just those that had few connections, i.e., those at which would take more time to arrive.



(**a**) Luxembourg high density (**b**) Luxembourg low density

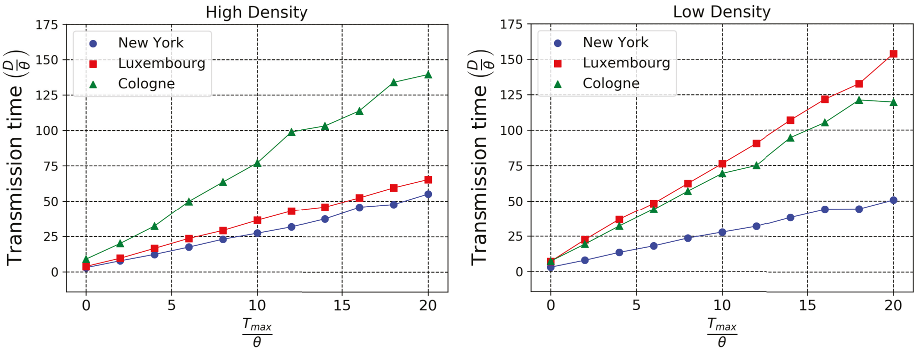


(**c**) Cologne high density (**d**) Cologne low density



(**e**) New York high density (**f**) New York low density

Figure 6. Comparison between network nodes reached by the disseminated message and nodes that broadcast the message by varying T_{max}/θ. If $T_{max} \approx \theta$, network nodes did not have time to receive transmissions from neighbors, and they relayed the message themselves with high probability, making RR reach unnecessary high values. This effect was mitigated if T_{max} was at least approximately ten times θ, achieving high values of PDR with a lower RR.

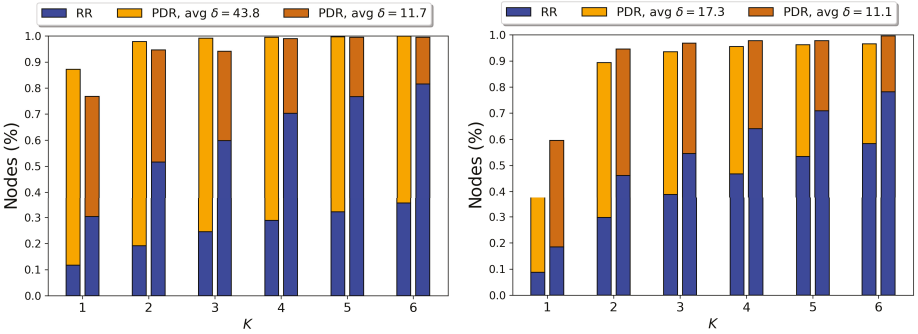


(**a**) High density scenarios (**b**) Low density scenarios

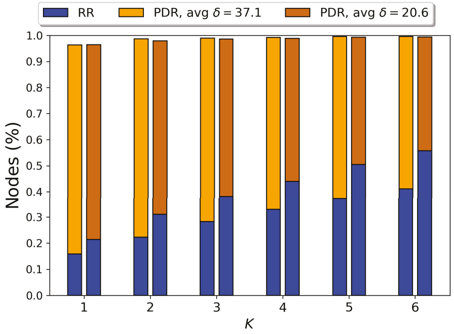
Figure 7. The increase of the transmission time D as a function of T_{max}. If T_{max} is set too low, the overall performance may be degraded, as shown in Figure 6.

5.3. CBF Performance and Parameter Tuning

Figure 8a–c plots the PDR and RR ratios for the Luxembourg, Cologne, and New York scenarios achieved by the CBF+ algorithm vs. the parameter K described in Section 4.



(**a**) Luxembourg (**b**) Cologne



(**c**) New York

Figure 8. Performance of CBF/CBF+ in terms of PDR and RR as a function of K (standard CBF with $K = 1$). As K increases, the probability that a network node relays a message becomes higher, thus increasing the number of relay nodes and the overall coverage alongside.

The plain CBF algorithm ($K = 1$ in the figures) worked well in the New York scenario (Figure 8c), both in the high density and low density case, achieving high coverage with few relay nodes. As we said previously, the low diameter and low average distance between nodes in the New York graph had the effect of increasing the performance of both PDR and RR.

On the other hand, CBF had poor performance in the Luxembourg (Figure 8a) and Cologne (Figure 8b) scenarios, achieving a ratio of covered nodes of $\approx 87\%$ and $\approx 38\%$ in the high density case and $\approx 86\%$ and $\approx 60\%$ in the low density case, respectively.

To improve CBF's performance, we could use the CBF+ generalization with $K > 1$. By the definition of K given in Section 4, the bigger K was, the higher the probability that a node relayed a message. This had the effect, in turn, of increasing the number of covered network nodes.

In order to perform the comparison between EPIC and CBF+, we chose an optimal value for K, which meant finding a good compromise of covered nodes and relay nodes for each scenario. We saw that K depended heavily on the scenario and on the density setting. A reasonable choice seemed to be $K = 3$ and $K = 4$ for Luxembourg, $K = 5$ and $K = 5$ for Cologne, and $K = 2$ and $K = 3$ for New York, for the high and low density cases, respectively.

5.4. Comparison of EPIC and CBF/CBF+

In Table 3, we report the values of the parameters that were optimized for each scenario (R_{min}, R_{max}, α for EPIC and K for CBF+). All the simulations were executed by using these parameters and with a packet drop rate of 1%.

Table 3. Parameters used during the simulations.

Scenario	**Luxembourg**		**Cologne**		**New York**	
Density	*High*	*Low*	*High*	*Low*	*High*	*Low*
R_{min}	194 m	90 m	132 m	95 m	430 m	430 m
R_{max}	500 m	500 m	500 m	500 m	1000 m	1000 m
α	5%	0%	5%	0%	10%	10%
K	3	4	5	5	2	3

In Tables 4–6, we report the simulation results, using both EPIC and CBF+ as the dissemination algorithm, for the scenarios of New York Luxembourg, and Cologne, respectively. In each table, we report the number of relay nodes, the ratio of relay nodes, the transmission delay, and the PDR.

Table 4. Results obtained for the New York scenario. NR, Number of Relays.

Algorithm	**CBF+**	**EPIC**	**CBF+**	**EPIC**
Density	*High*		*Low*	
NR	150	176	171	139
RR	22.32%	26.19%	39.58%	32.17%
D	335 ms	247 ms	301 ms	252 ms
PDR	98.14%	98.59%	98.61%	97.69%

Table 5. Results obtained for the Luxembourg scenario.

Algorithm	**CBF+**	**EPIC**	**CBF+**	**EPIC**
Density	*High*		*Low*	
NR	207	228	547	320
RR	26.20%	28.86%	69.50%	40.66%
D	403 ms	313 ms	791 ms	736 ms
PDR	99.05%	98.23%	98.98%	98.28%

Table 6. Results obtained for the Cologne scenario.

Algorithm	**CBF+**	**EPIC**	**CBF+**	**EPIC**
Density	*High*		*Low*	
NR	202	215	155	129
RR	51.95%	49.31%	70.45%	58.64%
D	692 ms	765 ms	627 ms	621 ms
PDR	96.01%	98.17%	97.73%	98.18%

As for New York (Table 4), we noticed that both EPIC and CBF+ achieved a satisfactory ratio of covered network nodes, with a PDR close to 100%. As for RR, EPIC used about 4% more relay nodes than CBF+ in the high density scenario, while in the low density case, EPIC used about 7% less than CBF+. Both algorithms worked well in the New York scenario, mainly due to its low diameter and low average number of hops between network nodes.

For Luxembourg (Table 5), we observed similar values of PDR and RR across the high density case. Instead, for the low density case, the relay ratio dropped from 69.50% for CBF+ to 40.66% for EPIC, a relative decrease of more than 40%.

This high number of relay nodes of CBF+ was due to the high value of K, which was set in order to have a PDR ratio comparable to EPIC.

In EPIC, the inhibition rule indicated to a node whether or not to act as a relay based on the geographical coordinates of the previous broadcasts. This was not possible using CBF+, which simply counted the number of received copies of the same message, independently of from which the position they were broadcast.

The power of the inhibition rule designed in EPIC was measured by achieving a high coverage while maintaining a low number of relay nodes.

As for the Cologne scenario (Table 6), EPIC and CBF+ achieved in the high density case similar values of covered and relay nodes, with EPIC showing slightly higher coverage (98.17% vs. 96.01%) and a slightly lower relay ratio (49.31% vs. 51.95%). In the low density scenario, the RR ratio went from 70.45% for CBF+ to 58.64% for EPIC, a relative decrease of more than 15%.

As for the dissemination delay, we observed that in most of the scenarios, EPIC needed less time to disseminate the message. While only for Cologne, high density CBF+ was faster (692 ms vs. 765 ms), for Luxembourg, high density EPIC was $\approx$ 25% faster than CBF+ and more than 15% faster for New York, both high and low density.

6. Conclusions

We defined an epidemic algorithm, EPIC, for message dissemination in vehicular networks with direct V2V communications. The EPIC algorithm was completely distributed and executed autonomously by each vehicle node, based on proper parameter settings and events collected at the network interface. We provided a simulation-based performance analysis to tune EPIC's parameters. Simulations were based on accurate modeling of the radio path, physical layer, and vehicular environment, obtained by means of VEINS and three different urban scenarios.

We compared EPIC with the ETSI standard algorithm for message dissemination, Contention-Based Forwarding (CBF), and a heuristic performance bound on the number of relay vehicle nodes, based on the minimum connected cover set cardinality on the vehicle connection graph.

Performance analysis showed that EPIC offered a good performance trade-off between the coverage of message dissemination (which reached more than 98% of nodes in high density scenarios with the number of relay nodes below 30–40%, depending on the analyzed city), overhead due to multiple forwarding nodes/message copies, and dissemination delay. Extension of this work may address adaptive self-tuning of protocol parameter, to adapt to the specific vehicular scenario (e.g., vehicle density, pattern of roads).

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electronics

Review

Survey on Power-Aware Optimization Solutions for MANETs

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Abstract: Mobile ad hoc networks (MANETs) possess numerous and unique characteristics, such as high channel error-rate, severe link-layer contentions, frequent link breakage (due to node mobility), and dissimilar path properties (e.g., bandwidth, delay, and loss rate) that make these networks different from the traditional ones. These characteristics seriously interfere with communication and hence, ultimately degrade the overall performance in terms of end-to-end delay, packet delivery ratio, network throughput, and network overhead. The traditional referenced layered strict architecture is not capable of dealing with MANET characteristics. Along with this, the most important apprehension in the intent of MANETs is the battery-power consumption, which relies on non-renewable sources of energy. Even though improvements in battery design have not yet reached that great a level, the majority of the routing protocols have not emphasized energy consumption at all. Such a challenging aspect has gained remarkable attention from the researchers, which inspired us to accomplish an extensive literature survey on power-aware optimization approaches in MANETs. This survey comprehensively covers power-aware state-of-the-art schemes for each suggested group, major findings, crucial structures, advantages, and design challenges. In this survey, we assess the suggested power-aware policies in the past in every aspect so that, in the future, other researchers can find new potential research directions.

Keywords: MANET; energy-efficient routing; transmission power control; power-aware routing metrics; power-aware optimization; cross-layer optimization; hybrid optimization

1. Introduction

Mobile ad hoc networks (MANETs) have gained increasing popularity for a range of applications [1], such as emergency/rescue operations, military sector applications (e.g., battlefield), health monitoring of civil structures, homeland monitoring, and ubiquitous computing. A MANET consists of mobile nodes that communicate with each other without any infrastructure. These mobile radio autonomous nodes are arranged in a mesh topology and form a dynamic, multi-hop radio network in a decentralized way [1]. The impression of forming a MANET came from the Defense Advanced Research Projects Agency (DARPA) packet radio network [2,3]. In the past few decades, several researchers [4,5] have purely focused on the issue of selecting and managing the optimum set of ad hoc routers, whereas some researchers [6–8] have suggested other effective techniques to deal with routing issues, leveraging existing features of accessible Internet routing algorithms.

Recently, MANETs have been developed promptly in the wireless communication arena due to their active features of rapid mobility, fast deployment capability, higher spatial multiplexing rate, and self-organizing nature [9–14]. Despite these fascinating and striking features of MANETs, these networks last with many constraints and challenges that certainly necessitate profound investigation before their widespread implementation and deployment. MANET devices operate with limited CPU processing capabilities, constrained battery life, inadequate bandwidth support, limited storage, etc. In MANETs, the nodes are also free to roam in any random direction and can only interact with their direct neighbor nodes (i.e., the nodes which are in its transmission range). Nevertheless, this random motion can undeniably cause frequent breakage in communication links. This leads to the issue of dynamic network topology changes and hence, ultimately makes forwarding more difficult. Along with this, all the nodes have to communicate via highly error-prone, limited capacity, and exceedingly bandwidth-constrained wireless channels. In MANETs, the wireless channel is highly utilized as the transmissions by each node are broadcast in nature, and the Medium Access Control (MAC) layer algorithm tries to control access to the shared broadcast channel. Additionally, the wireless links have the interference of signals, a higher error-rate, fading, etc. Undoubtedly, such a highly constrained environment has a profound impact on network performance. Furthermore, in MANETs, all the nodes are attached to low-powered battery devices. The energy of the battery needs to be efficiently utilized to the dodge prompt cessation of wireless nodes. The network designers should keep such battery constrained operation issues in mind while designing any forwarding scheme. This consideration is vital, since node shutdown (due to energy exhaustion) ultimately confines the capability of the dead node to forward packets, and thus it reduces the lifetime of the network as well [15–25]. Consequently, in the dynamic environment of MANETs, we cannot implement the communication system via protocols of a conventional network with infrastructure (i.e., cellular network). Rather, we have to separately implement protocol policies that can work on the fly.

In summary, MANETs have unique characteristics that impose a variety of challenges in the design of the routing protocol and complicate Quality of Service (QoS) provision. In the early stages, many routing policies were instructed to continuously update the routing information amongst nodes, since, in such an environment, the network topology changes a lot. Although the suggested schemes were doing their job well to some extent, still, if we talk about the case of dense network environment then all these schemes failed significantly in offering performance. Meanwhile, in such policies, the process of updating the routing table for each and every node increases the network overhead to a great extent and that makes such schemes highly infeasible for large dense network environments [26]. Additional traffic intensity is also generated if intense heterogeneous multimedia data (i.e., video, audio, images, etc.) are transmitted over MANET, while such multimedia data traffic can significantly increase the energy exhaustion of mobile devices. In particular, when an application sends multimedia data, such as video over a MANET, the network traffic intensity level is greater than before. Therefore, a large increase in energy consumption takes place [27], while new challenges are imposed for video streaming over MANETs [28]. This quick growth in heterogeneous traffic causes higher packet losses and excessive network delays, hence, it ultimately increases energy consumption and reduces QoS performance [27]. Indeed, congestion ensues when the total amount of transmitted load over the network exceeds the entire obtainable capacity. Such a condition causes escalated buffer usage over the available network path, leading to higher packet losses during the case of unavailability of network resources.

In MANETs, higher network congestion occurs than that of a wired network due to its unique characteristics [29]: (1) problems related to exposed and hidden terminals; (2) constraints on resources; (3) error-prone shared broadcast channel; (4) node mobility. Congestion control for MANETs requires extra demands (except efficiency of bandwidth usage and fairness in network traffic) because network congestion is not only due to the traffic of the network, but it can also be due to other factors, such as wireless signal noise, interference node, mobility, and contention [30]. Meanwhile, each node in a MANET is a relay for routing packets to other nodes [1]. When the node mobility increases, the Packet Loss Ratio (PLR) also increases, resulting in increased energy consumption during dynamic routing. The intermediate node that becomes the network relay often experiences network traffic overloading. Dynamic routing in the MANET must be energy efficient as this feature resolves the extension of how the network is practically valuable [31]. In MANETs, the routing algorithm and the congestion control scheme must be energy efficient and must reduce packet loss retransmission as much as possible to reduce energy consumption on each node. Energy conservation improves the lifespan of a MANET and ensures that the communication process is effective [32]. In MANETs, the most significant energy consumer is employed for wireless communication rather than the computing tasks from the mobile device microprocessor. Indeed, energy consumption for computation is at least 50% lower than energy consumption for communication [33,34]. As a result, energy consumption can be reduced by saving the transmission (energy) power of nodes. Over the years, researchers have focused on investigating how to reduce energy consumption in MANETs. Most of their studies have considered the energy efficiency of routing and tried to prolong the lifetime of nodes and the network. The majority of these studies [15,35–45] have introduced single-path energy-efficient routing protocols. However, in single-path routing, the nodes in the selected path quickly deplete their batteries. In light of this evidence, we understand that single-path routing schemes are incomplete. Moreover, in single-path routing, some nodes are highly congested, as they transmit most of the network traffic. As a result, single-path routing does not distribute the load among the nodes in a fair and balanced way. This, in turn, can lead to the significant degradation of network performance. The disadvantages of single-path routing protocols have led to intelligent multipath routing algorithms that address the problem of energy consumption at the network layer.

Multipath routing algorithms aim to find novel techniques for power-efficient route setup and reliably, relaying data packets between source–destination pairs in the direction of maximizing the network lifetime. To address the various constraints of MANETs, many power-efficient routing schemes [20] have been developed. Many other studies [46–51] have proposed energy-efficient cross-layer optimization solutions for MANETs. Some of these studies have reconsidered the impact of energy efficiency, but also other performance metrics, such as scalability, fairness, and delay in the presence of energy flow into the network. Moreover, in some cross-layer studies, the Physical (PHY), MAC, and routing protocols are re-designed using a cross-layer design (CLD) to optimize the rate at which the energy is consumed, rather than just minimizing the total energy expenditure.

Motivation and Scope of this Survey

The goal of this survey article is to synthesize the existing power-aware optimization solutions for MANETs from diverse viewpoints and to present a classification of them. This article extends the work done by previous surveys, presenting recent power-aware optimization solutions for MANETs. We present new techniques that do not just consider power-aware routing metrics and energy-efficient routing protocols, but we also consider other power-aware optimization solutions for MANETs. This survey analyzes state-of-the-art power-aware optimization solutions for MANETs. To the best of our knowledge, a comprehensive survey of such solutions for MANETs does not exist and is the goal of this article. This survey article comprises as follows:

- It analyzes key-issues on power-aware optimization solutions for MANETs;
- It surveys the existing power-aware optimization solutions for MANETs;
- It discusses open research areas in MANETs, such as: (1) cross-layer designs; (2) hybrid optimization algorithms for topology management in cluster-based MANETs; (3) design of cooperative MAC protocols; (4) multipath routing based on hybrid modeling; (5) fuzzy-logic support in multicast routing schemes.

The remainder of this article is structured as follows: Section 2 presents previous surveys that summarize research into energy-efficient routing in MANETs and its related power-aware routing metrics;

Section 3 delineates the leading energy-efficiency related issues unsettling numerous routing-based proposals. It analyses all the categories of power-aware optimization solutions for MANETs, such as cross-layer optimization approaches for energy conservation in MANETs; Section 4 reflects upon some lessons that we have learnt to date from this research; The survey article presents design challenges and future research opportunities in Section 5.

2. Related Work

Several studies, as shown in Table 1, have analyzed the existing energy-efficient routing schemes for MANETs. Some surveys have focused only on PHY layer methods for energy-efficient wireless communication. For instance, Feng et al. [52] reviewed only PHY layer techniques for energy-efficient wireless communication, such as orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO), cognitive radio (CR), network coding, cooperative communication, etc. Pantazis et al. [53] surveyed and analyzed energy-efficient routing protocols for Wireless Sensor Networks (WSNs). Ehsan and Hamdaoui [54] discussed the design challenges of routing protocols for Wireless Multimedia Sensor Networks (WMSNs) and classified current techniques with their limitations. Zuo et al. [55] considered diverse routing schemes, investigating the benefits of multi-antenna assisted relay nodes, the number of MAC retransmissions, and the number of hops on the performance energy consumption. Kanellopoulos [26] summarized state-of-the-art solutions on QoS routing and resource reservation mechanisms to provide multimedia communication over MANETs. The author considered the limitations of existing QoS models concerning satisfying QoS in serving multimedia over MANET. Jabbar et al. [20] discussed the challenging factors in MANETs by highlighting issues in power-based routing metrics. They classified existing power-efficient routing algorithms in MANETs into six categories and compared the routing techniques of each category using their merits and limitations. Muchtar et al. [23] exposed the critical view on why the Host-Centric Networking (HCN)-based MANET is not energy-efficient by indicating the incompatibility of the HCN paradigm with the MANET itself. They recommended a new solution for improving energy efficiency in MANETs by shifting from the HCN paradigm to the Information-Centric Networking (ICN) paradigm. Kanellopoulos [56] presented various types of scheduling techniques for MANETs. The author also analyzed load-based queue scheduling techniques and presented various cross-layer schedulers for power control. Most of the presented techniques are related to power-efficient routing. Rahman et al. [57] presented and evaluated energy-based clustering algorithms for cluster-based MANETs. Such as, clustering algorithms electing a node as a Cluster-head (CH), based on its node energy level. A CH performs cluster management and this activity causes too much energy consumption, which affects network performance. Consequently, the energy constraint of a node is a vital parameter for electing a CH because it directly impacts the overall lifetime of the network. Finally, Mendes and Rodrigues [58] presented cross-layer solutions for WSNs.

2.1. Energy-Aware Routing Protocols in MANETs

Even though improvements in battery design have not yet reached that great a level, where a device can be able to operate for a longer period, the majority of the proposed routing protocols have not emphasized energy consumption at all. In MANETs, energy-efficient routing is one of the important problems that must be considered. Keeping this issue in mind, many researchers have suggested very efficient policies. Specifically, in MANETs, energy-aware routing is undeniably the utmost design benchmark, since all the nodes are attached and operated with low-powered battery devices. The shutdown of an intermediate node, due to power failure, not only affects the node's system itself but also its capability of relaying packets on the behalf of others, and hence it ultimately reduces the lifetime of the network [15,59,60]. With the untimely shutdown of a node, the entire network system suffers a burn, since, as soon as a node stops due to power failure, forwarding packets on the route will get completely disconnected. However, the preceding node keeps on unnecessarily re-transmitting the same packets up to a certain threshold, and thus the power of that preceding node is also needlessly wasted. Then, that preceding node knows that the path is disconnected, and it ultimately notifies the source about it. Finally, the source node again performs route discovery, and this process also consumes a significant amount of energy in the network.

Table 1. Previous surveys that summarize research into power-efficient routing in mobile ad hoc networks (MANETs).

Year	Ref.	Focus
2020	[57]	It presents energy-based clustering algorithms. It proposes a cross-layer clustering framework and a hybrid self-organization clustering model that improves QoS in cluster-based MANETs.
2019	[56]	It presents various types of scheduling techniques for MANETs. It analyses load-based queue scheduling and presents cross-layer schedulers for power control. Most of these techniques are related to power-efficient routing.
2018	[23]	It exposes the critical view on why a HCN-based MANET is not energy-efficient by explaining the incompatibility of the HCN paradigm with the MANET itself.
2017	[26]	It presents existing solutions on QoS routing and resource reservation methods to support multimedia communication over MANETs. It considers the limitations of existing QoS models.
2017	[20]	It discusses the challenging factors in MANETs by focusing on power-based routing metrics. It classifies existing power-efficient routing algorithms in MANETs into six categories. It compares the routing schemes in each category, based on their merits and limitations. It also highlights their main features.
2015	[55]	It considers diverse routing schemes investigating the benefits of multi-antenna aided relay nodes, the Frame Error Ratio (FER), the number of MAC retransmissions, and the number of hops on the performance energy consumption.
2013	[53]	It classifies energy-efficient routing protocols in WSNs into four main categories. It surveys and analyses energy-efficient routing protocols for WSNs.
2012	[54]	It presents energy-efficient routing techniques for WMSNs. It discusses the design challenges of routing protocols for WMSNs and classifies current methods with their limitations.
2012	[52]	It reviews only the PHY layer techniques for energy-efficient wireless communication, such as MIMO and OFDM, cognitive radio, network coding, cooperative communication, etc.
2011	[58]	It presents cross-layer solutions for WSNs, including cross-layer energy-efficient routing protocols.

Many authors [61–67] have proposed energy-aware routing schemes for the dynamic environment of MANETs. All these schemes have conveyed a new aspect for the unnecessary consumption of the battery energy of a node. What they have suggested is that the node's battery energy can not only be consumed during its active participation in forwarding and receiving packets (active state) but also when it stays in energy preserving and idle medium (wireless) listening mode (in-active state). As a result, some of the energy-aware routing schemes consider active and in-active energy consumption states. Bearing in mind the active energy consumption state, energy-aware routing schemes reduce energy consumption, while nodes are forwarding and receiving packets. In this direction, researchers have suggested a method that regulates each node's radio (i.e., transmission) power just enough to reach the neighboring node and not more than that. On the other hand, in energy-aware routing schemes that consider the inactive energy consumption state, the researchers have recommended the optional feature of actively adapting the operation mode of radio state (i.e., either to switch the operational mode into active/idle/sleep or simply shut the radio state off). Nevertheless, we cannot simply switch the operational modes blindly; instead, it involves efficient coordination and complex synchronization to guarantee efficient delivery. In conclusion, routing schemes based on the active and in-active energy consumption states focus on minimizing the individual node's energy consumption.

In the next subsection, we analyze power-aware routing that can be used for determining optimum routes in energy-efficient MANETs.

2.2. Power-Aware Routing Metrics

The conventional forwarding (routing) protocols for wireless networks instinctively consider minimum-hop and shortest-delay forwarding as a metric to assess optimal paths. Such protocols are Destination-Sequenced Distance Vector (DSDV) [68], Wireless Routing Protocol [69], Temporally-Ordered Routing Algorithm (TORA) [8], Ad hoc On-Demand Distance Vector Routing (AODV) [70,71], and Dynamic Source Routing (DSR) [72]. While, Dube et al. [73] have suggested the Signal-Stability based Adaptive (SSA) forwarding scheme, which utilizes the steadiness of the distinguishable host, location permanence, and signal strength as forwarding metrics. The SSA scheme suggests that picking the most suitable stable links will lead to strongly connected network paths. Understandably, some of these well-known orthodox metrics have a harsh consequence on network lifetime, since such metrics unintentionally over-utilize the power resources of the nodes (i.e., no consideration of power at all had been done). Singh et al. [61] have effectively shown that none of the abovementioned forwarding metrics (currently deployed in many routing protocols) can achieve the goal of carefully utilizing power resources.

In general, energy-aware forwarding policies can be categorized based on their adjusted route selection procedures (or routing metrics used) [20,36]:

1. Induced power-cost from the transmission.
2. Residual power capacity of the node.
3. Probable node lifetime.
4. Hybrid energy-aware metrics.

Energy-aware forwarding policies often utilize more than one set of energy-allied metrics to estimate and determine the optimum routes, depending on the conditions, briefly defined as:

- *Reducing the Energy Exhaustion per Packet Transmission and Reception*: This metric shows how the overall average power consumption per packet transmission and reception can be reduced. According to [61], under lighter traffic conditions, if we utilize this metric to assess the paths then there is the possibility (in most cases) that the chosen path will be equivalent to paths that get selected by the minimum-hop forwarding metric. So, in such a case, we cannot expect much change in power consumption performance. Nevertheless, under heavy traffic conditions, the path selected via such a metric may be different from the path chosen via the minimum-hop forwarding metric. Subsequently, if a node (or more than one node) on the selected path (i.e., it may or may not be the shortest route) suffers from severe congestion, then per-packet power consumption at each congested node will also differ because there may be a case of higher variations in contention level at each congested node, hence, per-packet power consumption will also get vary. Consequently, this metric may tend to forward packets in highly congested network areas. Nevertheless, taking this metric blindly without examining the individual residual energy of nodes may lead to the problem of unfair energy residual distribution in the network. We conclude that this metric does not assist in increasing network lifetime in any case.

- *Maximizing Period to Network Segregation*: According to [61], the set of critical nodes in the network must be identified. If critical nodes detach from the network for any reason, the entire network will divide into many parts. The paths between such partitions must pass through one such crucial mobile node. The forwarding process has to be modified in such a way that the load is evenly distributed over all such critical nodes via a "load-balancing" scheme. Nevertheless, trouble will arise if multiple network parts are connecting with a single node, as shown in Figure 1—for instance, in the network topology node "0", depicted in Figure 1, is a critical node. If node "0" stops working for any reason, then this entire network will be separated into many small parts. Here, the main idea is to ensure that the rate of power consumption should be similar in all critical nodes if we want to maximize the network lifetime. Nonetheless, the idea of ensuring a similar power drain rate metric amongst critical nodes is a tough task, because such a metric is directly dependent on the packet size. Therefore, we cannot blindly choose an optimal path without having all the information about the size of future arriving data packets. However, if we assume that all the future arriving data packets have the same size, we can ensure an equivalent rate of power consumption amongst such crucial mobile nodes. However, maximizing network segregation time is challenging, especially when we expect high throughput and high performance by reducing end-to-end delay.
- *Minimize High Variance in Mobile Node Battery Energy Level*: The basis of this metric is that all mobile nodes are highly essential in the network and the untimely shut-down of any node is not good for the network's throughput and delay performance. Along with that, while designing any forwarding scheme, we have to take full care that no one mobile node is overloaded more than any of the others [61]. This metric tries to ensure that all the available mobile nodes can live and work for a longer period. Nevertheless, again, the idea of ensuring a similar power drain rate metric amongst nodes is a challenging task, since such a metric is directly dependent on the packet size. Nonetheless, if we assume that all the future inward data packets are of the same size, we can unquestionably guarantee an equivalent rate of power consumption amongst mobile nodes. Although, we cannot make such an infeasible assumption while designing any forwarding strategy.
- *Minimizing Price-Per-Packet (PPP)*: According to [61], if we need to prolong the lifetime of all the nodes, then we need to utilize the PPP metric, other than the power disbursed per packet metrics. The PPP metric is the total price of transmitting a packet along some selected routes. The main advantages of the PPP metric are: (1) it can commendably assist in integrating the battery-related features unswervingly in designing part of the routing scheme; (2) it directly reflects the congestion level along a selected path.

Singh and Raghavendra [74] effectively instigated the Energy Exhaustion per Packet Transmission and Reception and the PPP metric in their proposed scheme, called Power-Aware Multi-Access Protocol with Signalling (PAMAS). Specifically, the authors believe that incorporating the suggested PPP metric in PAMAS directly reflects the optimization in other metrics (i.e., Period to Network Segregation and Battery Energy-level Variance metric, respectively, as well). Furthermore, it is noteworthy that such metrics for forwarding do not need to be utilized constantly. Rather, initially, when the nodes are configuring and have an ample amount of battery power in the network, we can stick with a conventional forwarding scheme (i.e., minimum hop-count). Nevertheless, after a certain time, when battery power starts going down by a certain amount, nodes can switch to these mentioned power-aware metrics.

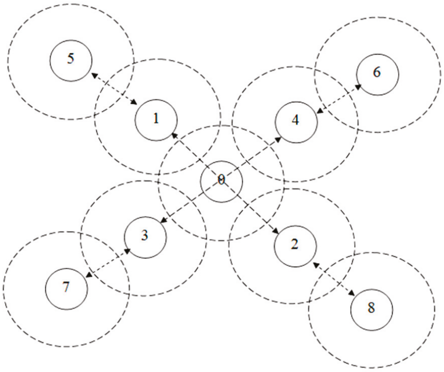

Figure 1. A mobile ad hoc network (MANET) topology illustrating the problem of network segregation.

3. Analysis of Power-Aware Optimization Solutions in MANETs

In this section, we delineate the leading energy-efficiency-related issues unsettling numerous routing-based solutions. Along with this, we introduce the problems related to such energy-efficiency related issues. Furthermore, we also apprehend the way through which research works have been made to resolve all such issues.

Power-efficient approaches for MANETs can be classified into eight categories, according to their basic operation:

1. Approaches based on adaptations of the radio state operational mode.
2. Routing protocols based on adaptive load balancing.
3. Location-based routing protocols.
4. Multicast-based routing protocols.
5. Energy-efficient proactive (link state-based) routing protocols.
6. Energy-efficient reactive (source-initiated-based) routing protocols.
7. Transmission power control-based routing protocols.
8. Cross-layer based routing protocols.

In the following subsections, we describe these categories of power-aware optimization solutions for MANETs.

3.1. Approaches Based on Adaptations of the Radio State Operational Mode

The exchange of packets consumes a significant amount of the power of a node in the network. In a MANET, the transmission from one wireless node to another is potentially overheard by all of its possible neighbors. All of these neighboring nodes consume a significant amount of power, even though such transmission is not related to them. For instance, in the small MANET topology, shown in Figure 2, the transmission from node "1" to node "2" is overheard by node "3" since it is an immediate neighbor of node "1". Now, node "3" consumes a significant amount of power, even though such transmission is not directed to it. A solution to this problem in node "3" to turn its radio state shut off (sleep-mode) during the entire duration of such transmission to conserve battery energy. This idea of such radio state adaptation was adopted in the PAMAS routing protocol [74].

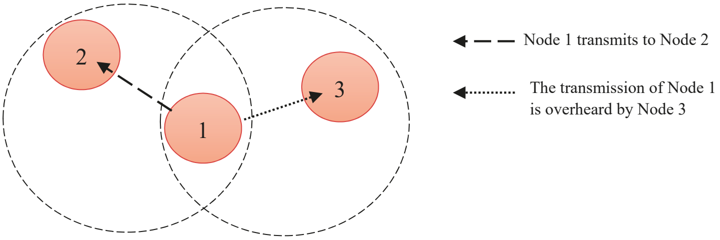

Figure 2. Simple MANET topology.

The idea of such radio state adaptation (termed "sleep mode" or "power-save mode") is highly suitable in large dense MANETs. Based on this idea, topology control routing protocols can reduce the energy consumption of mobile nodes [75]. Inactive nodes are placed in sleep (very low energy consumption) mode for a maximum duration (i.e., they do not accept packets as they automatically become slave nodes). On behalf of the slave nodes, qualified master nodes communicate with other nodes to permit slave nodes to stay in sleep mode and to save more energy. A mobile node is put in sleep mode via a wireless scheduler algorithm that takes into account the need to prolong the battery life of the mobile device. To conserve energy, the node transmits/receives in contiguous time slots and then goes into a sleep mode for an extended period rather than to rapidly switch among transmit, receive, and sleep modes. This preference is balanced against the need to maintain the QoS requirements of the current application. For instance, the sleep and awake scheduler [76] activates the channel during the data transmission only. Based on efficient scheduling, inactive nodes can be placed in sleep mode for a definite period through the use of Geographic Adaptive Fidelity (GAF) [77] and Spanning Tree (SPAN) [78] techniques. It is noteworthy that any intermediate node in an energy-inefficient routing path cannot be set in sleep mode, because the goal is to improve network capacity whilst totally reducing energy consumption [79].

The "sleep mode" control is only performed in the MAC layer. In the preceding literature, especially for the case of WSNs, the low-duty cycle, associated with contention-based MAC design, has been logically classified into two rudimentary categories: asynchronous and synchronous. Synchronous schemes synchronize the awake and sleeping slots of the neighboring nodes. On the other hand, asynchronous schemes do not need to make any synchronization between nodes and let the nodes to operate autonomously.

Ye et al. [80] and Ye et al. [81] have recognized the major reasons for energy consumption in a dynamic environment. The reasons can be transmission overhearing, routing control packets transmission overhead, collisions, and idle listening. Based on identifying such possible sources of inefficiencies, Ye et al. [80] presented a synchronous MAC design, called the Sensor-MAC (S-MAC) protocol. The main motivation of S-MAC is to reduce such unnecessary energy consumption. The scheme ideally relies on the basic problem of unnecessary power consumption due to overhearing, originally inspired by the PAMAS protocol. The S-MAC protocol, in contrast PAMAS, does not utilize any out-of-channel signaling. Along with this, S-MAC addresses the problem of idle listening power consumption as well, in contrast to PAMAS. S-MAC significantly reduces the problem of idle listening overhead by actively utilizing a periodic awakening and sleeping scheme. Nevertheless, S-MAC experiences certain degradation in both latency and fairness (per-hop) performance. Indeed, S-MAC experiences reduced throughput performance, since only the active slot of the frame is utilized for actual data communication. Meanwhile, latency, in S-MAC, escalates because data generation (from upper-layer) events may happen during the sleeping slot of the frame. Subsequently, these generated messages during the sleeping slot are unnecessarily queued and they have to wait for the next active slot of the frame. Van Dam and Langendoen [82] improved the performance of the S-MAC design and suggested another synchronous MAC protocol, called Timeout-MAC (T-MAC). T-MAC improves

S-MAC by making adaptations in the active and sleep slots of the frame. T-MAC radically abridges the active slot of the frame when the channel is idle. For a shorter instance, T-MAC senses the channel and, if no data are received during this shorter slot, the radio state turns awake to sleep mode. Otherwise, the node's radio state remains active (awake) in anticipation that either the active slot ends or no additional data are received. Additionally, T-MAC, under variable or heterogeneous load, suggested improved performance in terms of power consumption. However, as S-MAC, T-MAC experiences certain degradation in both throughput and latency performance. Similarly, RMAC [83] and DW-MAC [84] contention-based synchronous low-duty cycle-based schemes were presented in the past. These schemes significantly assist in reducing idle listening power consumptions. Still, such schemes typically require an additive synchronization, which further introduces complexity and overhead in the system. Afterwards, if we talk about contention-based asynchronous low-duty cycle schemes, such as WiseMAC [85], B-MAC [86], and X-MAC [87], these schemes incorporate the concept of low energy consumption listening. In particular, such schemes let the sender transmit a preamble, whose size is sufficiently large enough as long as the sleep instance of a receiver is activated before actual transmission. Afterwards, when the receiver turns from the sleep to awake state and subsequently senses the preamble, it stays in the awake state to accept the data. The asynchronous low-duty cycle schemes effectively assist in eradicating the problem of the complex synchronization overhead required in the synchronous low-duty cycle-based schemes and also suggested improved performance in terms of lower power consumption. Nevertheless, Sun et al. [88] have extensively discussed that asynchronous low-duty cycle schemes only achieve good performance in lighter traffic conditions. There is a serious decline in packet delivery, energy efficiency, and latency performance of such a policy as soon as traffic intensity increases. Here, Sun et al. [88] investigated the issue of high channel capturing period, due to longer preamble transmission, which may defer other nodes to transmit, since they have to wait for a longer time until the channel is freed, and ultimately, some of those nodes experienced higher delay than normal. Hence, considering such issues, the authors [88] introduced Receiver-initiated MAC (RI-MAC), that aims to reduce the channel capturing period in variable load conditions. Recently, a reinforcement learning-based MAC design has been suggested by Savaglio et al. [89], called Quality-learning MAC (QL-MAC). The main objective of QL-MAC is to provide a self-adjustable feature to a conventional MAC design. Consequently, the conventional MAC design is able to self-adapt against various dynamic changes in the network (e.g., topological changes).

In conventional networks, such as IEEE 802.11, better channel or bandwidth utilization is a prime concern. However, switching and making certain adaptations in the radio state (i.e., energy saver mode) is certainly an optional feature in IEEE 802.11 and generally happens in the WSN scenario, where nodes have been idle for most of the time. In the WSN environment, achieving maximum possible bandwidth utilization is not as important as in other networks. The design of a MAC protocol that is suitable for MANETs requires smart amendments because various performance parameters in the MANET are acute. These performance parameters are the chances of dynamic changes in link characteristics (i.e., bandwidth, delay, channel error, loss rate, and level of interference), mobility induced topology changes, bursty and highly-loaded traffic, channel error and contention induced losses. We will not only have to think at MAC level design, but we will have to contemplate through every level of the traditional layered structure and bring appropriate changes.

A cross-layer-based routing protocol (described extensively in Section 3.8) may trigger sleep mode by sending a command to the MAC layer. The sleep mode mechanism is easy to deploy and can be adapted into well-established routing protocols, such as AODV. For example, the Efficient Power Aware Ad hoc On-Demand Distance Vector (EPAAODV) protocol [90] is a modification of AODV, that uses the "power-save" idea to improve the energy efficiency of AODV to extend network lifespan. Other power-save approaches [91,92] are based on the minimum energy threshold (limit) to decide whether a node should remain in active mode or to be in sleep mode to save energy. Remya et al. [93] designed the Energy-efficient

Multipath Routing protocol using Adjustable Sleeping window (EMRAS) by employing two algorithms: (1) Power and Delay Aware Multipath Routing Protocol (PDMRP) and (2) Slow start Exponential and Liner Algorithm (STELA), using a cross-layer design. The STELA algorithm improves the energy efficiency of the network by adjusting the sleeping window if there are no network activities. If there is any network activity, PDMRP selects the path that is energy efficient and that is the shortest. The EMRAS protocol increases the overall residual energy and reduces the total energy consumption without degrading the QoS parameters.

In summary, a drawback of the "power-save" method is that it increases the end-to-end delay. As nodes in sleep mode cannot transmit and receive any packets, packet retransmission is required. Such retransmission of packets from the source node leads to increased energy consumption. The increased waiting period for the route request or reply for the new routing path provokes the whole situation if the intermediate node in the routing path is in sleep mode. Another drawback is that, in any energy-inefficient routing path, the intermediate nodes cannot be set in sleep mode, as the goal is to improve network capacity and totally reduce energy consumption [79]. Additionally, some low-duty cycle energy-aware MAC designs (S-MAC, T-MAC, X-MAC, R-MAC, DW-MAC, B-MAC, RI-MAC) are highly limited to some applications, where the data generation rate is not very bursty, and mostly these schemes have been evaluated over WSN environment where the nodes are mostly in a sleeping state. Another category of power-aware optimization solutions is routing protocols, based on adaptive load balancing, which consider power consumption.

3.2. Routing Protocols Based on Adaptive Load Balancing

For selecting the optimum path, an energy-efficient load distribution-based routing protocol well utilizes energy-rich nodes that are under-utilized in the network and distributes the load amongst them accordingly. Such protocols mainly concentrate on efficiently balancing the load amongst under-utilized higher-energy-rich nodes by competently selecting the path. Nevertheless, in such schemes, the path chosen may not necessarily be the shortest one. Nonetheless, the main aim of such schemes is not to estimate the minimum power consumption path, but such schemes effectively assist in preventing certain low energy nodes from being over-utilized and, hence help in improving the lifetime of the network.

Some of the energy-aware techniques [61,62,94–96] that we have discussed so far have a major disadvantage that they have presumed a stationary network structure where nodes are not moving at all. Although this hypothesis simplifies their analyses, the legitimacy of their suggested conclusions is practically limited. It is difficult to say which policies or which class policies will be effective in all kinds of scenarios of MANETs.

Many researchers implemented adaptive load balancing approaches to reduce the problems of minimum power control communication methods. For example, Woo et al. [97] introduced an energy-aware load balancing technique called Local Energy-Aware Routing (LEAR). The LEAR scheme extends the route-discovery basic structure of DSR. In LEAR, every node decides whether to take part in routing or not. Whenever a node receives a Route Request (RREQ) packet, instead of directly processing it, the node firstly checks whether it has a certain amount of power or not. If it has, then the node takes part in the route-discovery process, otherwise, it will not take part in route-discovery. Consequently, the chosen path will automatically contain energy-rich intermediate nodes. This will significantly reduce the chances of route disconnections in the network and will also result in a significant drop in power loss and, hence, it results in improved network lifetime. However, Kim et al. [98] extensively discussed that considering only the residual power metric of a node does not give assurance that a high energy-rich node along a path will successfully sustain its battery power during the lifetime of intense traffic conditions. That means that, if a node is highly proficient enough in terms of residual power metric, it could accept all the incoming RREQ packets and, hence, much traffic load will have passed through it. It means that the energy consumption drain rate of the nodes, which are essentially participating in forwarding, will likely be very high, which results in a severe drop in their battery power lifetime. Consequently, there is the danger of the premature death of such high energy-rich nodes. Typically, considering such an issue, Kim et al. [98] suggested a drain rate metric-based Minimum Drain Rate (MDR) scheme. In the MDR scheme, every node estimates the average energy dissipation drain rate per unit second. The MDR scheme regularly monitors such drain rate caused by the reception, overhearing, and transmission events. The MDR scheme explicitly calculates a cost function (i.e., the ratio of residual battery power and drain rate), which suggests the lifetime of a path. Similarly, in succeeding years, many energy-aware schemes [99–103] have been suggested, considering an extension of the DSR basic route-discovery structure. Since most of these energy-aware metrics have been applied with DSR, some of the researchers have decided to evaluate these metrics via a proactive routing scheme, called the Optimized Link State Routing (OLSR) [104] protocol. Consequently, many energy-aware schemes [105–108] have been suggested in the past, considering an extension of OLSR basic structure as well. De Rango et al. [59] extensively evaluated the performance of OLSR and DSR protocols in terms of power consumption. The authors extensively assessed these routing protocols in terms of parameters, such as mobility, protocols' schemes (i.e., link-failure announcement and reply via route-cache), overhearing effects, and idle power consumption. The authors determined that, in a dense network environment, the issue of overhearing severely affects the lifetime of the network, no matter the underlying network routing protocol. The authors also suggested that the performance of OLSR in terms of power consumption worsens as the network density and size increase. Tarique et al. [109] brought another energy-aware policy—Energy Saving DSR (ESDSR)—which also extends DSR's basic route-discovery structure. ESDSR incorporates the advantages of the minimum power control communication and adaptive load-balancing scheme together. Chang et al. [110] introduced the Color-theory-based Energy-Efficient Routing (CEER) scheme, which shows more scalability than ESDSR on increasing network size. Additionally, the CEER scheme is capable of preserving more power than ESDSR in a dense network environment because it effectively utilizes the concept of optimal CH selections and effective data aggregation. Numerous energy-efficient resource allocation policies [111–114] have been suggested to maximize efficiency in terms of energy usability for multiple fading wireless channels. Classically, due to the severe insufficiency of the spectrum, the network designers should consider spectrum efficiency as an important design feature in a highly dynamic MANET environment, typically for high rate multimedia communication systems. Unfortunately, spectrum efficiency and energy efficiency are two oppositely natured features, and they both mostly conflict with each other; hence, how to balance them is a hot research topic. Zhou et al. [115] comprehensively investigated the characteristics of the spectrum and energy efficiency required for video-streaming in MANETs, respectively. Subsequently, the authors came up with a novel technique, called Energy-Spectrum-Aware Scheduling (ESAS), which enhances video quality and decreases power consumption as well.

According to [20,23,116–119], there are two subcategories of load-balancing approaches:

- Concurrent path forwarding/routing/transmissions-based schemes: These schemes utilize multiple available paths at once, regarding the least energy consuming path. Examples of such schemes are LEAR, MDR, ELGR, Adaptive-sleep + Adaptive MAC-Retx [22], Disjointed Multi-Path routing_Extended OLSR (DMP_EOLSR) [120].
- Alternate path forwarding/routing/transmissions-based schemes: Such schemes utilize alternate path for transmissions. Examples of schemes that utilize either single path or alternate paths for transmissions are the prediction and smart-prediction energy-aware protocol [42], Power-aware Heterogeneous AODV (PHAODV) [45,121], Energy-level based routing protocol (ELBRP) [122], and Multi-path OLSR (MP-OLSR) [123]).

According to [13,124], there can be three subcategories of multipath routing policies:

- The node disjointed path policy, which does not share the identical links or intermediate nodes between each available network paths.
- The link non-disjointed path policy, in which the multiple available network paths can share identical links or intermediate nodes.
- The link disjointed path policy, which can have an identical relaying node, but it does not allow for a shared link between each path. Mueller et al. [124] suggested that disjointed based routing schemes can have significant advantages over non-disjointed-based routing policies. Nevertheless, it is not always possible to fully estimate disjoint paths in MANETs, especially in high mobility scenarios [13].

Chettibi and Benmohamed [125] developed a power-aware and multipath on-demand source routing scheme, called Multipath and Energy-Aware DSR (MEA-DSR), which effectively utilizes the residual battery power of nodes and path diversity. The main goal of MEA-DSR is to decrease the number of dead node-induced path disconnections in the network. Through performance evaluation, the authors demonstrated that the overall power consumption in the MEA-DSR scheme is significantly lesser than that of DSR, especially in higher mobility scenarios. Nevertheless, the routing overhead and PDR performance of MEA-DSR is not up to the mark in scenarios with lower mobility. This occurs since MEA-DSR dismisses the idea of DSR packet salvaging, hence, it certainly upsurges the packet loss probability compared to the original DSR. Meanwhile, MEA-DSR allows for the propagation of duplicate RREQs (by relaying nodes), which undoubtedly assist in increasing routing overhead. Afterwards, Guodong et al. [126] introduced Energy-efficiency and Load-balanced Geographic Routing (ELGR), which associates both load balancing and energy efficiency metrics to make forwarding conclusions. The ELGR scheme effectively assesses the link's quality for the packet reception level to increase the power efficiency of the network. Moreover, the ELGR protocol also suggests the method of identifying the network load (local) by adaptive learning policy to improve the load balancing in the network. Through experimental results, the authors exhibited that the ELGR scheme effectively improves the PDR performance than other geographical forwarding algorithms (i.e., DREAM [127], GPSR [128], GEAR [129]). However, high complexity in estimating the forwarding and reception rate parameters is the main drawback of this scheme. Moreover, the ELGR scheme blindly assumes that each node knows its location information, which is not fair to assume in such a constantly changing MANET environment. Balachandra et al. [130] introduced the Multi-constrained and Multi-path QoS-Aware Routing Protocol (MMQARP) which estimates multiple paths by considering path link delay, reliability, and energy constraint as QoS parameters. Indeed, MMQARP, with the help of these QoS-based parameters, estimates multiple node disjointed paths. Subsequently, the scheme heavily relies on the overhead of maintaining proper management to calculate the geographical information and average delay to estimate path reliability. Consequently, MMQARP suffers from the problem of high routing overhead in the network. Additionally, MMQARP is not able to offer good QoS demands to the user in the case of lower mobility scenarios.

In summary, the adaptive load-balancing schemes do not care whether the chosen path is smaller or larger. It depends on the availability of intermediate nodes that have a sufficient power level. Hence, such schemes will undoubtedly influence the overall end-to-end delay performance of the network. Moreover, the idea of dynamically utilizing multiple available paths for load-balancing does not always guarantee that the selected paths are optimized (paths) in terms of minimum energy consumption. That is why, instead of being completely dependent on such load-balancing policies, we also have to include other policies in the study so that we can design a better routing policy which is good in every way.

3.3. Location-Based Routing Protocols

A location-based routing protocol uses the geographic location of each node to select the best routing path, while the routing decision is based on the location of the destination node that is obtained through location services [131]. For the period of the data routing process, a Global Positioning System (GPS) acquires the location information used as the network address. Location-based routing assumes that each node is a GPS-enabled mobile device, but this is not always true. Location-based routing can achieve high scalability in large MANETs but encounters numerous challenges, such as inaccurate positioning, local optimum problems, optimum forwarder selection, and broadcasting overheads. Additionally, location-based routing is difficult when holes exist in the network topology, and nodes are roaming or are often disconnected to preserve energy. These issues can be addressed by using the terminode routing protocol [132]. Terminode routing combines location-based routing (i.e., terminode remote routing) and link state-routing (i.e., terminode local routing). Terminode remote routing is applied to a faraway destination node, while terminode local routing is applied to a local destination (i.e., destination is close).

The Greedy Perimeter Stateless Routing (GPSR) protocol [128] and the Location Aided Routing (LAR) protocol [133] are two common location-based routing protocols for MANETs. The problem of finding energy-efficient routes, based on geographical information, has been addressed in many power-aware routing protocols. These protocols are based only on the local information and the reduced routing overhead to find the best route. As each node in a MANET keeps only local information, a power-aware routing protocol of this category does not exploit global information, such as the generation rate of data.

An interesting energy-efficient location routing protocol is the Localized Energy-Aware Restricted Neighborhood (LEARN) [134]. To guarantee the high-power efficiency of a route, the node selects the neighbor node (within a restricted neighborhood) as the next-hop node, having the largest energy mileage (i.e., the distance traveled per unit of energy consumed). The LEARN algorithm performs as a greedy routing algorithm when such a neighbor node (inside the restricted neighborhood) cannot be found. The total energy consumed by the established path (from the source to the destination) constitutes a constant factor of the optimal energy consumption. LEARN has a similar performance in terms of throughput and latency, compared to a typical location-based routing protocol. LEARN performs better in random networks in terms of energy consumption because it only focuses on the energy consumption of the path and does not take into account other decisive factors for selecting the best neighbors. Such factors could increase the maximum throughput per unit of energy consumption by the network. For example, such a factor could be to select a neighbor node that maximizes the bandwidth of links. The main drawback of LEARN is that it selects a long routing path (having more hops), since it frequently uses links that are shorter than those used in greedy routing. This is probably due to the fact that, a long routing path affects the average end-to-end delay. Another scheme is the Location-aided Energy-Efficient Routing (LEER) algorithm [135]. Every node in LEER has a table that stores the node location information of the entire network during the route discovery phase. From this table, the source node can achieve its destination's location. In LEER, intermediate nodes transmit packets to a destination with fewer route discovery messages. This is obtained from the existence of a GPS and a suitable packet block that contains: (1) the message-ID; (2) a source location (X,Y); (3) a destination location (X,Y); (4) the length of the entire packet; (5) the DATA of the packet. If a node leaves the network or if a link failure occurs, the route maintenance phase is performed using a cache to set up new routes. In LEER, it was proven [135] that the sum of the energy transmitted over multiple-hops (routing) is less than the transmission energy consumed for a single hop (routing).

Finally, the Zone-based routing with a parallel Collision-Guided broadcasting protocol (ZCG) [136] employs a parallel and distributed broadcasting method to reduce redundant broadcasting and accelerate the path discovery process. This broadcasting technique guarantees low node energy expenditure and preserves a high reachability ratio. In ZCG, a one-hop clustering algorithm is used for splitting the network into zones guided by powerful Cluster-heads (zone leaders). Zone leaders have high battery power and are normally static (they have zero/low mobility). The broadcasting technique used in ZCG reduces redundant broadcasting by the use of the zone-to-live (ZTL) technique. The ZTL technique decides the number of zones a broadcast needs to propagate from end-to-end before it is discarded by member nodes. The main drawbacks of ZCG are the following:

- The cluster-heads (CHs) can probably perform selfish behavior. Therefore, there is a need to increase fairness among nodes to protect zone members from such selfish CHs.
- ZCG generates higher routing overheads compared with other protocols. The main reason is that inactive member nodes change their location/status frequently.
- The clustering procedure of ZCG and the zone selection mechanism may limit the scalability of ZCG in a highly dynamic MANET.

Vehicular Ad hoc Networks (VANETs) and Flying Ad hoc Networks (FANETs) are subclasses of MANETs. Recently, Srivastava et al. [137] presented various location routing protocols which are suitable for VANETs, while Bujari et al. [138] conducted an interesting performance analysis of position-based packet routing algorithms for FANETs.

Hereafter, we discuss multicast-based routing protocols which additionally consider the energy consumption issue. This category of power-aware optimization solutions is specifically designed for group-oriented applications.

3.4. Multicast-Based Routing Approaches

Group-oriented applications use multicast flows in which the delivery of real-time multimedia content must fulfill particular QoS requirements. Strict QoS constraints, along with energy conservation, must be satisfied by considering the QoS profile of the current application. For example, Figure 3 depicts the multi-constraint QoS profile of an application that emphasizes reliability, throughput, and energy efficiency.

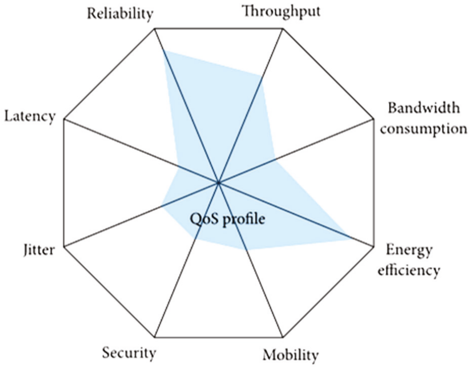

Figure 3. Quality of service (QoS) parameters in MANETs [139].

A group-oriented application, such as multicasting video over a MANET, requires mainly inter-destination multimedia synchronization, reliable delivery, and a multicast routing mechanism to route one-to-many multicast data transmissions under time-critical conditions. From another viewpoint, group communication requires the dynamic construction of resourceful and reliable multicast routes in an environment with high node mobility and dissimilar path properties.

Multicast routing mechanisms in MANETs [140] consider different performance criteria, such as power-efficient route establishment, PDR, network lifetime, quicker and faster proactive route recovery, reliability, QoS based on bandwidth, delays, jitters, and security. Such routing mechanisms can be categorized into different topological routing groups, such as mesh, tree, zone, and hybrid [140]. In multicasting, in every session there is only one sender and many receivers, while a multicast tree is used. In a multicast tree, a root node also suffers from greater energy depletion. Therefore, it can shut down earlier than other nodes as it is responsible for performing more tasks than other nodes. For the period of route discovery, multiple paths are discovered for each of the multicast destinations. Among them, an energy-efficient multicast routing protocol (combining power-awareness with the multicast capability) must select only one path, depending upon its lifetime. Priority can be given to the paths that will survive up to the completion of the present session of packet transfer from the particular source to the destination node. From another viewpoint, a power-efficient multicast routing protocol must also address the mobility of the nodes by supporting multicast membership dynamics (joining and leaving), since the multicast tree is no longer static [141].

The Lifetime-aware Multicast Tree (LMT) [142] routing algorithm discovers routes that minimize the residual energy variance of nodes. Thus, LMT maximizes the lifetime of the source-based multicast tree network. Still, the LMT algorithm assumes that the energy required for packet transmission is comparable to the source–destination distance. In this sense, LMT is theoretically unfair to the bottleneck node. The tLMT algorithm calculates the least expensive path from the set of unconnected multicast receivers to the partially constructed tree. To estimate the cost of a path between the source and each receiver, LMT examines two metrics in the multicast tree:

- The transmit power level, that helps in selecting a path having the minimum total power consumption;
- The remaining battery capacity which helps in balancing energy consumption over all nodes in the network.

Through simulation experiments, the authors [142] evaluated the performance of LMT and demonstrated its effectiveness over a variety of simulated scenarios. Regardless of the size of the multicast group, LMT did better than several other multicast routing schemes in terms of the residual battery energy, the network lifetime, PDR, and the energy consumed per delivered packet. However, LMT increases the number of flooding procedures. In particular, if the number of receivers in the multicast group increases, the number of flooding procedures increases too.

The Predictive Energy-efficient Multicast Algorithm (PEMA) [143] was designed for large-scale MANETs. PEMA uses network statistical parameters to address scalability and overhead issues. PEMA does not depend on information about the route or the network topology. The size of the multicast group determines how fast the PEMA algorithm is running, and thus PEMA is scalable for dense MANETs. The following three parameters are required to select the optimum routing path based on the predicted path energy values:

- The location of group members;
- The average node density in the network;
- The individual unicast routes from the source node to the group members.

PEMA can exactly predict the communication energy consumption by defining two bounds (upper and lower) on energy consumption. After that, the predicted energy values become weighted averages of these two bounds. Using these predicted energy values, PEMA decides how to efficiently send packets to the destination (group) members. PEMA improves energy conservation compared to other related algorithms. However, the energy model used in PEMA does not take into account the energy consumed by retransmissions, due to the MANET dynamic conditions (e.g., interference and packet collision). This information was neglected in the performance analysis of PEMA.

In MANETs, the quality of group communication depends on various QoS parameters, such as path loss, link life, mobility, channel fading, signal quality, the transmission and reception energy of nodes, and battery backup. In general, the problem of QoS multicast routing with multiple QoS constraints is NP-complete [144]. To resolve this problem, Yen et al. [145] proposed an energy-efficient genetic algorithm mechanism. Particularly, they deployed a source-tree-based routing algorithm and constructed the shortest-path multicast tree to minimize the delay time. For this reason, a small population size was used in the genetic algorithm. In the route computation, only a few nodes were involved. The genetic sequence and topology encoding, which calculate the residual battery energy of all nodes in the multicast tree, were improved significantly. As a result, the lifetime of mobile nodes was prolonged. Extensive simulation results showed that their method is a competent and robust algorithm used for multicast route selection.

An energy-efficient and delay-constrained genetic algorithm for MANETs was proposed in [146]. For the period of route selection, the genetic algorithm examines two criteria: (1) the bounded end-to-end delay; (2) the minimum energy cost of the multicast tree. The second criterion is examined to reduce the total energy consumption of the multicast tree. This source-based genetic algorithm performs crossover and mutation processes on probable trees. This facilitates the coding operation and rejects the coding/decoding process. A heuristic mutation method can reduce the entire energy consumption of a multicast tree and, as a result, extend the battery lifetime of nodes. The performance of the genetic algorithm was proven through simulation experiments. The authors [146] demonstrated its efficiency in terms of success ratio, convergence performance, and running time, compared to the least delay multicast tree algorithm. A drawback of the suggested algorithm is that it does not examine shared multicasting trees and it focuses completely on source-based routing trees. Varaprasad [147] suggested an energy-aware multicast algorithm that enhances the network lifetime using a tradeoff. This tradeoff is based on minimizing energy consumption and load. It is also achieved by discovering a multicast that is inclined to minimize the variation of residual battery energy across all nodes. Particularly, if a source node wants to send multicast packets, it selects a node with greater residual battery energy. If all middle nodes have the same residual battery energy, it selects a node with the larger relay capacity. The algorithm takes into account two metrics: (1) the capacity of the residual battery; (2) the relay capacity of the node to multicast packets from the source to the destination nodes. Further, the proposed algorithm forwards data packets through three tables: (1) the neighboring-node table; (2) the routing table; (3) the group table that includes information for all the destination nodes. The author claims that the algorithm can select more reliable paths and achieve the best results in terms of node lifetime, network lifetime, and throughput, compared to previous multicast algorithms. However, the main disadvantages of this algorithm are the following:

- The algorithm is inclined to produce extra control traffic (although the same happens in any power-aware multicast protocol).
- It ignores an important practical issue—it does not examine packet loss in the network.

The Residual-Energy-based Reliable Multicast Routing (RERMR) protocol [148] achieves a longer network lifetime, improved path reliability, and forwarding rate. In RERMR, an energy model observes the residual energy of nodes used for selecting paths with nodes with a high energy level to maximize the network lifetime. RERMR selects the most reliable path for forwarding data, and thus it improves data delivery. In RERMR, a network model is also used to estimate the reliability of a path. It can be said that RERMR achieves a balance between data forwarding and energy reserves. RERMR selects a higher-quality path with minimal packet loss and minimal energy consumption, while it reduces the number of route request packets and retransmissions. In a high-mobility environment, RERMR outperforms similar schemes in terms of network stability rate, packet reliability rate, end-to-end delay, and communication overhead. However, RERMR is based on assumptions that are inappropriate in practice. Such assumptions are prior knowledge of the nodes' directions of motion, the location of the center of a trustable loop, and the constant rate of data delivery, irrespective of the transmission power.

The demand for an optimal path amongst MANET nodes has attracted the use of Swarm Intelligence (SI)-based techniques, such as Particle Swarm Optimization (PSO) and Ant-Colony Optimization (ACO). SI-based techniques can solve many routing problems because routing in MANETs must be implemented by considering node mobility. Robinson et al. [149] introduced an interesting SI-based scheme for multipath routing. It is called particle swarm optimization-based bandwidth and link availability prediction algorithm for multipath routing. Their scheme is based on local rerouting and ensures forwarding continuity with compound link failures. The authors used particle swarm optimization based on available bandwidth and link quality. To provide the multipath routing in MANET, their scheme is based on the mobility prediction algorithm. In the prediction phase, the available bandwidth, link quality, and mobility parameters are used to select the node based on their fuzzy logic. The selected node broadcasts information among all the nodes and the details are verified before transmission. In the case of a link failure, the nodes are stored into a blacklisted link. Furthermore, the routes are diverted and sent back again to find a good link as a forwarder or intermediate node. The proposed scheme can achieve a significant improvement in PDR, path optimality, and end-to-end delay.

The Predictive Energy-Efficient and Reliable Multicast Routing (PEERMR) protocol [150] uses a PSO algorithm to construct a reliable, energy-efficient multicast tree. The fitness function of the PSO algorithm takes into account various parameters to extend the node lifetime and ensure the stability of the path among the source and the destination. These parameters are path delay, expected path energy, and path stability. In PSO, each node moves to random destinations in the search space and has a randomized speed. The best global and individual positions are set by the fitness value. The PSO algorithm entails three basic steps: (1) calculation of the fitness value of each node; (2) renewing of positions and individual and global fitness values; (3) renewing of the velocity and position of every particle. The authors [150] declare that PEERMR is more energy-efficient and reliable than the algorithm proposed in [151], but it is noteworthy that the root nodes in PEERMR are overloaded.

Sinwar et al. [152] introduced the Ant-Colony Optimization Protocol (ACOP), that provides optimized PDR, throughput with low power consumption, and reduced packet delay. Moreover, they performed a comparative study of ACOP with various existing routing protocols (DSDV, AODV, and AOMDV) using the Random Waypoint Mobility Model. The purpose of using this mobility model was to generate different scenarios for the same purpose. The analysis of these protocols was done by implementing irregularities in the scenario using Network Simulator (NS2). Various performance metrics, including packet delivery fraction, throughput, and end-to-end delay, were used for validating the comparative study. Experimental simulation results indicated that the performance of the ACOP protocol was better than the other routing protocols.

The Energy-Efficient Lifetime Aware Multicast (EELAM) route selection strategy [153] is a multicast route discovery scheme for MANETs that was developed using an adaptive genetic algorithm. EELAM functions based on tree topology and adapts an evolutionary computation strategy (a genetic algorithm). This genetic algorithm plays a vital role in terms of selecting optimal middle nodes with maximal residual energy and minimal energy usage. The proposed adaptive genetic algorithm formulated the fitness function that aims to improve the energy consumption ratio, the residual battery life, and the multicasting range. Simulation results showed that EELAM is the best route discovery approach in its category because the process and the methods adopted are contemporary. Furthermore, the adaptive algorithm used in EELAM is different from conventional genetic algorithms. Finally, the Weight-based Energy-efficient Multicasting (WEEM) scheme [154] selects the path with the highest lifetime (weight) as optimal. If more than one path is expected to remain alive till the multicast session is over or none of the available path options have a chance to live till the end of the multicast session, weight is assigned to the paths by the destination. Three parts contribute to the calculation of Weight: (1) the residual energy; (2) the multicast packet transmission capability of nodes in a path; (3) the number of multicast destinations residing in that path. If more than one path has the same weight, then priority is given to the one path suffering less delay. Extensive simulation results demonstrated that WEEM produces more packet delivery ratio and alive node ratio at much less control message cost than other competing multicast protocols.

In summary, existing power-aware multicast algorithms often produce additional control traffic. Moreover, they do not consider any packet loss, or the energy consumed by retransmissions because of the dynamic conditions (e.g., packet collision and interference) [20].

3.5. Proactive (Link-State-Based) Routing Protocols

In proactive routing, each node is exchanging information about the current network topology with other nodes to update its own routing table. Thus, proactive routing can immediately find the shortest path as the route discovery process has no delays. Based on the algorithm used, proactive routing can be categorized into groups: (1) link-state-based routing protocols, such as OLSR; (2) routing schemes, which are based on the distance–vector algorithm, such as DSDV.

In this subsection, we focus on the first group and analyze OLSR-based energy-efficient routing approaches, since the OLSR is the leading proactive (hop-by-hop) routing protocol for MANETs. In OLSR, each node distributes topology control (TC) messages all over the network. This information is used by individual nodes to compute routes to all destinations. To reduce TC message overheads (traffic), the OLSR routing algorithm selects a small set of nodes (called Multi-Point Relays (MPRs)) among one-hop and two-hop neighbor sets of host, while the MPR selection algorithm is based on topological information. MPRs are responsible for forwarding link-state information and improving flooding in the network. To further reduce the number of TC messages, Boushaba et al. [155] suggested two policies to improve the MPR selection algorithm. Both policies are employed to select MPR by using a simple modification in the OLSR protocol without extra signaling overheads. The improved OLSR variants outperform simple OLSR and cooperative OLSR in terms of routing cost and the number of TC messages.

Many OLSR-based algorithms have tried to optimize the selection of MPR sets for efficiently reducing the consumption of network topology control, the delivery rate of data packets, and the end-to-end delay of packet transmission between nodes. In their attempt to make OLSR more energy-aware, Kunz and Alhalimi [42] introduced an energy-efficient routing scheme that is based on accurate state information about the available energy levels of nodes. This routing scheme exploits the nodes' energy levels as QoS metrics for route selection. To increase the accuracy of the energy levels at all traffic rates, the authors proposed two new techniques: (1) Prediction; (2) Smart Prediction. In the first technique, the energy level of a node is regulated based on its previous consumption rate. The second technique is an improved version of the first technique, where a node's energy level is adjusted based on the average of all known consumption rates for other nodes if no consumption rate can be determined for the node. However, both techniques have similar overheads as those in the simple OLSR since they use the same MPR selection mechanism. Moreover, both techniques do not take into account load balancing or other QoS metrics which should be involved in the routing process. Consequently, these techniques are incomplete as they address only the energy level issue.

Guo et al. [43] proposed the OLSR-energy-aware (OLSR_EA) routing scheme, in which the route calculation algorithm selects paths based on a composite energy cost. This cost is considered the energy routing metric and computed by combining the residual energy and consumed transmission power of each node. OLSR_EA uses the auto-regressive integrated moving average time-series method to measure and predict the per-interval energy consumption. Similarly, Jabbar et al. [156] introduced a proactive forwarding for MANETs that is based on a multi-metric criterion. Another proactive routing scheme for MANETs that incorporates an energy conservation mechanism was proposed in [157]. This scheme exploits the new Energy Conserving Advanced Optimized Link State Routing (ECAO) model used for the prediction of the energy consumption level of the node. Such a prediction is used for the calculation of the energy cost. The performance of the ECAO model was compared with the existing OLSR and other advanced OLSR models. The ECAO model attains better performance in terms of the number of transmission control messages, PDR, average time, end-to-end delay, and link delay and energy consumption. Jain and Kashyap [158] introduced a new mechanism for selecting MPR among the nodes' neighbor sets to make OLSR more energy-efficient by taking into account the willingness of the node. The proposed energy-aware MPR selection mechanism was incorporated in Modified Dynamic OLSR (MD-OLSR) and compared with the conventional OLSR. Simulation results showed improved performance, such as higher throughput, larger Packet Delivery Ratio (PDR), and lesser end-to-end delay.

In [159], a novel location-based routing protocol has been proposed. It improves routing in MANETs in terms of both link stability and energy efficiency. The protocol is called GBR-DTR-CNR and uses the stable routing protocol Greedy-based Backup Routing (GBR) with a Dynamic Transmission Range (DTR) with Conservative Neighborhood Range (CNR) for neighbor selection. The GBR-DTR-CNR algorithm selects the links of the route based on two criteria: (1) an estimation of link expiration time; (2) a conservative neighborhood range. The GBR-DTR-CNR protocol enables high connection throughput but it enhances energy efficiency by exploiting an adjustable dynamic transmission range that considers node mobility. Consequently, GBR-DTR-CNR chooses the next node from those stable neighboring nodes that will not move out of the transmission range. It was proven that the connections formed in GBR-DTR-CNR are substantially more stable than other routing algorithms. Compared to similar routing schemes, GBR-DTR-CNR achieves higher throughput and PDR. It also improved the energy efficiency in terms of maximum energy consumed per node and average energy consumed per packet delivered, while requiring fewer routing control message exchanges. Nevertheless, over various node densities, GBR-DTR-CNR did not outperform the other protocols in terms of the average energy consumed per node. This is because in GBR-DTR-CNR, the nodes in the idle state do not forward packets, and they consume slightly more energy than idle nodes in other routing algorithms. Thiyagarajan and SenthilKumar [25] proposed the Memetic Optimized Adjacent Exponentially Distributed Routing (MO-AEDR) which considers route distance and power during route selection. In MO-AEDR, the route discovery selects a route that optimizes a weighted function of route distance and energy. In particular, MO-AEDR includes route energy consumption in its calculations and employs the Adjacent Exponentially Distributed Route Maintenance mechanism to include an energy awareness feature with mean data packet arrival rate and link breakage rate to the identified route discovery mechanism. The simulation results showed that MO-AEDR increases the PDR while reducing the end-to-end delay and routing overhead.

Some link-state-based routing protocols for MANETs are based on a Q-Routing algorithm that embeds a learning policy at every node to adapt itself to the changing network conditions, which leads to a synchronized routing. For example, the Mobile Q-Routing (MQ-Routing) protocol [160] has a modified Q-Routing algorithm that is quickly adaptable to the changes in the network topology. During the routing process, MQ-Routing considers resource usage and link stability by examining three metrics:

- The residual energy of the nodes. This metric is used for increasing the (minimum) lifetime of nodes and for balancing the traffic among them.
- The prediction of GPS-based link availability. This metric is used in order of Q-Routing to avoid the loss of a constant traffic part if it is required to manage a link failure due to node mobility.

- Node mobility. The MQ-Routing algorithm chooses more stable nodes with a high mobility feature. These nodes are not expected to rapidly change their neighbor sets.

By using these metrics, changes in the network topology and the levels of node energy are taken into account. These metrics enable MQ-Routing to be fully adaptable in such changes. Proper energy-efficient policies in MQ-Routing can also increase the minimum lifetime of a node and may lead to a fairer balance of energy. The main disadvantage of MQ-Routing is that it exploits only a single path at a time for data transmission and rapidly switches to the best path along with the Q-values in the routing table. Finally, Zhang et al. [161] proposed QG-OLSR, a kind of new quantum–genetic-based OLSR protocol for MANETs. QG-OLSR adopts the MPR technology in OLSR. QG-OLSR can effectively reduce the consumption of network topology control, improve the delivery rate of data packets, and reduce the end-to-end delay of packet transmission between nodes. This is because it embeds a new augmented Q-Learning algorithm (i.e., a model-free reinforcement learning algorithm that learns a routing policy) and combines the OLSR algorithm to optimize the selection of MPR sets. Simulation results showed that the QG-OLSR protocol is reliable and highly efficient.

In high mobility MANETs, proactive routing protocols exhibit the highest packet delivery ratio and the shortest end-to-end delay, while costing the most in protocol overhead. In such MANETs, we can measure the variation in links set by using the topology instability metric (TIM). TIM is defined by the number of links established and failed in a certain statistical period. In high mobility MANETs, a glitch in the TIM causes unnecessary protocol overhead. To address this problem, Jiayu et al. [162] proposed a scheme using the exponential weight-moving average (EWMA) of the topology instability metric (TIM) to dynamically adapt the topology update intervals in proactive routing protocols. Simulation results showed that EWMA of TIM exhibits better glitch suppression than the instantaneous value of TIM and decreases the unnecessary protocol overhead effectively in relatively stable scenarios.

3.6. Reactive (Source-Initiated-Based) Routing Protocols

Reactive routing does not depend on the periodic exchange of routing information or route calculation. When a route is required, the node must start a route discovery process. A reactive routing protocol finds a route from a source to a destination if the source node must send data packets. In particular, the source node checks its routing table to decide if it has a route to the destination. If there is no available route, the source node tries to find a path through a route discovery process performed more frequently as the node's mobility increases. As a result, reactive routing requires lower control overhead traffic compared to proactive routing. Typical reactive routing protocols for MANETs are AODV, DSR, and TORA.

Apart from energy conservation, the stability of the end-to-end path is a key issue for transmitting multimedia traffic over MANETs. The Weight-Based DSR (WBDSR) [163] is an improved DSR-based scheme that selects the optimum path by considering the weight of an intermediate node as a metric. The Node weight is used to select the most energy-rich and stable intermediate nodes to forward packets to the destination node. In MANETs, the stability of a node can be defined as the possibility of this node to be as long as possible within the same neighborhood [163]. As shown in Equation (1), the node weight is calculated as:

$$Node\ weight_i = Baterry\ level_i + Stability_i \tag{1}$$

The weight of a route is the minimum weight of all nodes forming the route. WBDSR selects the most efficient route (i.e., the route with the maximum route weight). However, if two or more routes have an equal route weight, WBDSR selects that route with the minimum number of hops. The performance of the WBDSR routing algorithm depends on the network size, as this parameter affects the node's stability. Thus, we conclude that WBDRS performs well only in small MANETs. Afterwards, Tiwari et al. [164] proposed an enhanced protocol of WBDSR called Bandwidth Aware Weight-Based DSR (BAWB-DSR). This new energy-efficient routing protocol not only considers the battery power and stability of the node, but also the bandwidth to determine the optimum path. Such a consideration of bandwidth is vital for satisfying the QoS requirements imposed by video applications.

Dhurandher et al. [165] proposed an energy-efficient ad hoc on-demand routing protocol (EEAODR) for MANETs, that balances energy load among nodes so that a minimum battery energy level is preserved among nodes, and thus the network lifetime increases. To prevent nodes from becoming exhausted, EEAODR locates a superior energy-saving path, while the routing path is calculated by examining the time, the energy level of each node, and the number of hops. Precisely, EEAODR has an optimization function that examines all those factors leading to the depletion of node energy. Such factors are packet type, packet size, and the distance between nodes. The optimization function decides the best route by considering energy conservation, while paths with nodes that exhibit low energy levels are excluded. Through simulation results, the authors showed that EEAODR is superior to AODV regarding performance. However, if the energy levels of all nodes are equal, the EEAODR algorithm does not perform well because the cost of links is based on the minimum battery power among nodes in the route. It is noteworthy that, if all routes have an equal energy-based cost, the shortest path will be selected as the best path. However, from the viewpoint of energy, the shortest path is not always the optimal path. EDSR [166] is an energy-efficient routing algorithm for MANETs that preserves the main concepts of DSR. It maximizes the network lifetime by minimizing the power consumption during route selection. Besides, EDSR can locate and address selfish intermediate nodes that might drop packets for other nodes to save their own batteries. In EDSR, most packets are allowed to be routed without an explicit source route header. This results in a reduction in the protocol overhead. Experiment results showed that EDSR increased the PDR and the average node lifetime, while it decreased the total energy consumed. Nevertheless, the modified route discovery process causes an increase in the time delay since the enhanced route discovery process requires extra time to process the path cost. Shivashankar et al. [167] proposed the Efficient Power-Aware Routing (EPAR) scheme, that identifies the capacity of a node not just by its residual battery power, but also by the expected energy consumed in consistently forwarding data packets over a detailed link. EPAR chooses the path that has the biggest packet capacity at the minimum residual packet transmission capacity. This goal is obtained by using a mini-max formulation. EPAR was compared with two other ad hoc routing protocols (MTPR, and DSR) in different network scales, taking into consideration the power consumption. It was found that EPAR reduces for more than 20% of the total energy consumption and decreases the mean delay, especially for high load networks, while achieving a high PDR.

The Energy-Level-Based Routing Protocol (ELBRP) [122] decreases the delay of data packet delivery, reduces energy consumption, and extends network lifetime. ELBRP is based on the energy level of nodes and uses different forwarding mechanisms. The energy level of a node is classified into four phases which map the four states: very dangerous; dangerous; sub-safe; safe. Additionally, nodes are classified into five states (transmitting, receiving, listening, sleep, and dead), where a node with a zero-energy level is dead. The ELBRP protocol has a modified request delay mechanism that is based on the delay mechanism of AODV. The protocol forces nodes to sleep in the "very dangerous" state and preserves "danger" and "safety" states without a delay function, as in the original forward strategies of AODV. ELBRP only adopts the delay function in the "sub-safe" state. In ELBRP, nodes with lower energy levels send request packets that are forwarded after a longer delay (sub-safe state) to the neighborhoods. As these request packets arrive after the request packets from nodes with higher energy, they are discarded. This happens because each node accepts only an earlier request packet and discards later duplicate requests. As a result, the nodes with high energy levels are only involved in routing packets to the destination. Through simulation results, the authors proved that ELBRP is a practical and energy-efficient routing scheme. Particularly, they proved that ELBRP balances the energy consumption, prolongs the network lifetime, and decreases the delay of data packet delivery. However, in the performance analysis of ELBRP, the authors focused only on energy-based metrics and ignored the impact of other parameters, such as network size and traffic load. Furthermore, QoS metrics, such as throughput, the delivery of packets, and overhead, were not examined. Er-rouidi et al. [168] introduced an energy-efficient AODV-based routing protocol (EE-AODV) that considers, in each period, the rate of energy consumption instead of being limited to the current residual energy of a node. The rate of energy consumption permits EE-AODV to obtain accurate information about the energy that is consumed when transmitting and receiving the packets. This is achieved without the complex calculation of these values. Based on the residual energy and the estimated consumption rate, EE-AODV calculates a more accurate remaining lifetime of nodes. The EE-AODV was compared with the basic AODV and EQ-AODV (Energy and QoS-supported AODV), and it was proven that it significantly reduces the energy consumption of the nodes.

Anand and Sasikala [169] proposed a routing protocol that improves the energy-efficiency in MANETs. Their protocol is an enhanced AODV, called Intelligent Routing AODV (IRAODV) that improves the routing strategy in packet transmission. IRAODV is based on the calculation of the distance of the packet transmission by the individual nodes with other nodes. For this calculation, it uses the RSSI (Received Signal Strength Indication) parameter. The authors simulated IRAODV and compared its performance with AODV. They found that IRAODV outperforms AODV in terms of PDR, throughput, end-to-end delay, and residual energy. Bamhdi [170] proposed another protocol, called Dynamic Power-AODV (DP-AODV). DP-AODV adapts the AODV protocol to dynamically adjust transmission power usage. To achieve this improvement, the DP-AODV protocol uses the dependence of a transmission range on density. Simulation results demonstrated that, as density increases, DP-AODV shows a decrease in delay, compared to AODV, and offers better performance for highly-populated networks exceeding 200 nodes. The simulation results showed that DP-AODV increases network throughput whilst reducing node interference in a dense region, as well as enhancing the overall network performance concerning the increased packet delivery fraction, reducing the control overheads and jitter, enhancing overall throughput, reducing interferences and finally, shortening the end-to-end delay in medium–high-density conditions.

In summary, energy-efficient reactive routing protocols have better scalability than the link-state-based (proactive) routing protocols. Nevertheless, in reactive routing schemes, the overall time delay is high since the node needs extra time to wait for the route discovery process after the node tries to deliver a packet. Another interesting category of power-aware optimization solutions follows. It includes routing protocols that are based on transmission power regulation methods. Such methods can improve the overall MANET performance by increasing throughput and simultaneously reducing power consumption.

3.7. Transmission Power Control-Based Routing Protocols

In general, each node can decide the transmission power level, rate adaptation method, and routing strategy that it will use. However, if the transmission power level is very high, the node would sense and interfere with several neighbors. This might cause channel saturation, contentions, and collisions. On the other hand, if the transmission power level is low, a node could detect very few neighbors (or none) which would lead to a failed transmission. A transmission power control routing protocol saves energy by selecting the best routing path from the source to the destination in order nodes to consume the minimum amount of energy [20]. To determine the cost of the routing path, a few energy-related metrics can be used. For example, the amount of energy stored in each node (battery) and/or the amount of energy required to perform wireless signal transmission for next-hop forwarding can be used for determining the cost of each potential routing path. Four criteria are often used for estimating the cost of routing paths: (1) transmission power; (2) remaining energy capacity; (3) estimated node lifetime; (4) combined energy metrics. In practice, a power-aware routing protocol uses more than one energy-related metric to get the best routing path. Such energy-related metrics are: (1) the path crossed using minimal wireless signal transmission power;

(2) the intermediate node having sufficient residual battery power; (3) avoiding network partitioning caused by overused nodes; (4) selecting the routing path with the least power consumption per packet [23].

In the late 1990s, many authors [94–96] proposed topology control policies considering active energy consumption states. Those studies aimed to find the optimum path that has a minimized consumption of transmission power between a pair of senders and receivers. Later, based on this idea, various researchers introduced smart energy-efficient routing policies. Chang and Tassiulas [62] framed the routing issue to optimize the network's lifetime and subsequently suggested the Flow Augmentation and Redirection (FAR) scheme. The FAR scheme actively stabilizes the rate of power consumption amongst the node in fractions of their power reserves. Nevertheless, the FAR scheme needs to have prior information about the rate of data generation at the source. Along with this, the performance of the FAR scheme was measured only on the static networks. Afterwards, Li et al. [63] introduced an energy-aware smart routing called the On-line Max–Min (OMM) scheme. The OMM scheme, in contrast to FAR, effectively improves the network lifetime without having prior information about the rate of data generation at the source. However, OMM preferably requires information about the current residual energy of all other nodes in the network. Therefore, the OMM scheme may not be scalable enough in a dense network environment. Along with this, the FAR and OMM schemes assumed that there is a fixed or constant pattern in rates of message arrival between the different sender and receiver pairs, and that assumption makes these schemes highly infeasible. Then, Kar et al. [171] and Liang and Guo [172] suggested another energy-aware smart routing scheme, which explicitly improves the OMM scheme. The scheme's main objective is to maximally route the total amount of data without getting any advanced information on the upcoming rate of message arrivals and data generation, respectively. Nevertheless, these schemes do not perform well in the case of the larger networks. Doshi et al. [65] have shown the specialties of their work by addressing some of the following issues: (1) how can we gather exact power information? (2) how much routing overhead is allied with the energy-aware scheme? (3) how are we able to sustain minimum power paths in the presence of high mobility? Considering these issues, Doshi et al. [66] introduced the Minimum Power Routing (MPR) scheme. For this, they extended the original implementation of the DSR protocol and made proper amendments in the IEEE 802.11 (MAC) standard as well. Badal and Kushwah [173] proposed the Modified DSR that applies an energetic-aware mechanism to DSR protocol and by using energy consumption for transmission as part of routing cost calculation. Additionally, the Modified DSR uses energy consumption metrics for energy consumption balancing purposes as it also incorporates the energy-aware routing protocol with a load distribution solution.

To find the optimal paths between the communicating nodes in MANET, Prasath and Sreemathy [174] modified the traditional DSR algorithm by using the Firefly algorithm. In particular, the Firefly algorithm, as used in their framework, improves the DSR routing performance with well-organized packet transfer from the source to the destination node. The optimal route is found based on link quality, node mobility, and end-to-end delay. The authors conducted simulation experiments (with 25 nodes) and compared the performance of the traditional DSR, link quality-based DSR for selecting a route, and the proposed Firefly algorithm for optimal route finding. For this comparison, they used QoS parameters, such as throughput, end-to-end delay, number of retransmitted packets, and the number of hops to the destination. Moreover, they found that their method, with the Firefly algorithm, outperforms the other DSR schemes. From another perspective, Zhang et al. [175] proposed a genetic algorithm (GA)-bacterial foraging optimization algorithm to perform the selection of the optimal routing in DSR. After searching out multiple routes to the destination node, the paths are initialized. Then, the GA algorithm is started. This algorithm quickly finds the positions of the maximum probability optimal paths, which are the initial positions of bacteria for the bacteria foraging optimization (BFO) algorithm. Through using the BFO algorithm, it is easy to search out the extreme value and the optimal path to compensate for the poor accuracy of the GA algorithm. The proposed optimized strategy improves the routing selection algorithm without changing the complexity of DSR and proves the convergence of the algorithm to the global optimal solution.

The Ad hoc On-demand Multipath Distance Vector (AOMDV) [176] is an enhanced routing protocol based on AODV that provides multipath extensions. In AOMDV, the end-to-end delay is reduced by the utilization of parallel paths. AOMDV guarantees loop freedom and the disjointedness of alternate paths. The performance comparison of AOMDV with AODV showed that AOMDV, compared to AODV, can effectively cope with mobility-induced route failures. It can reduce the packet loss by up to 40% and can achieve an extraordinary improvement in the end-to-end delay. By reducing the frequency of route discovery processes, the AOMDV protocol also decreases the routing overhead by about 30%. Javan et al. [177] modified the AODV protocol, that results in a selection of zone-disjoint paths, to the extent feasible, and thus their protocol (ZD-AOMDV) achieves less end-to-end delay. The efficiency of the Zone-Disjoint (ZD) paths-AOMDV protocol was evaluated on various scenarios and there was a remarkable improvement in the PDR, and also in the reduction in end-to-end delay, compared to AOMDV.

Nayak et al. [178] suggested the Energy-Aware Routing (EAR) protocol, that is designed based on the transmission range that needs to be used when delivering network packets to their destinations. EAR was used in the AODV routing protocol as a case study for the required routing discovery when it is performed. Lalitha and Rajesh [179] proposed the AODV range routing (AODV-RR) protocol; an improved version of AODV that includes the “range routing” mechanism. According to this mechanism, AODV-RR selects particular nodes to be responsible for receiving and processing any routing request based on the Received Signal Strength (RSS). Then, it increases the one-hop distance of each hop and it reduces the path lengths in terms of the number of hops. In summary, AODV-RR is a routing protocol that maximizes the transmission range and minimizes the transmission power and the overall energy consumption of the network by minimizing the communication overhead. The authors evaluated AODV-RR for different network sizes and they found that it performs better than AODV in terms of PDR, routing load, throughput, end-to-end delay, and energy consumption. However, the “range routing” mechanism is not currently implemented for multipath routing.

The Ad hoc On-demand Multipath Routing with Lifetime Maximization (AOMR-LM) [79] is an energy-efficient multipath routing protocol that preserves the residual energy of nodes and balances the consumed energy to increase the network lifetime. The residual energy of nodes is used for calculating the node energy level. This energy level is used by the multipath selection mechanism to categorize the paths. AOMR-LM has been compared with two other protocols: AOMDV and ZD-AOMDV. The performance of AOMR-LM was evaluated in terms of energy consumption, network lifetime, and end-to-end delay. Finally, in [180], the Fitness Function technique was applied to optimize the energy consumption in a new routing protocol, called “Ad Hoc On Demand Multipath Distance Vector with the Fitness Function” (FF-AOMDV). In FF-AOMDV, the fitness function is used to find the optimal path from the source to the destination to decrease the energy consumption in multipath routing.

De Rango et al. [181] suggested the Link- stAbility and Energy-aware Routing protocol (LAER), that combines energy metrics with other metrics (i.e., link stability) for use in the routing decision. LAER not only focuses on routing protocol, but also on forwarding policy to make a reliable and energy-efficient MANET solution. The ECAO protocol [157] calculates the energy cost as extra metric performance in OLSR, as well delay, throughput, and the number of hops to calculate the cost of each identified routing path.

Katiravan et al. [182] suggested the energy-efficient and link quality-aware routing protocol (ELRPP). This protocol selects a route using three metrics—residual energy, SNR, and link quality—and has a variable transmission power control. Particularly, in the route discovery mechanism, there is a transmission power control deployed to set the optimal transmit power of nodes by classifying the nodes into Clusters using their transmission radius. As a result, ELRPP conserves residual energy, minimizes the power consumption, and improves network lifetime. Additionally, ELRPP exploits a steady link monitoring mechanism with error notification, which initiates a route discovery process for a poor link. Therefore, it minimizes the overhead incurred due to the usage of periodic control packets and improves the network throughput while it maintains network connectivity. For each link, the authors proposed a Cost Function (CF) based on Link Quality (LQ), and Available Energy (AE) as follows in Equation (2):

$$\mathrm{CF} = \alpha \cdot \mathrm{LQ} + \beta \cdot \mathrm{AE} \tag{2}$$

where α and β are the weights given to each metric with $\alpha + \beta = 1$.

Depending on the application requirements, different weights can be assigned to the metrics. LQ examines the actual channel conditions by taking into account the mobility and fading effects. The value of LQ is defined with the value of the SNR. In particular, each node continuously estimates the SNR of its neighbors. If the SNR is equal to or above a vital threshold required for successful packet transmission, the LQ is set to "1". Otherwise, the LQ is set to "0" as the SNR falls below the vital threshold. Bhople and Waghmare [183] proposed the Efficient Power-Aware Routing (EPAR) that measures the amount of remaining battery energy and estimates the cost of energy required when a route is selected. Route selection is based on the number of minimum hops along with the highest throughput value. Nevertheless, in EPAR the amount of energy used for the route process and the amount of remaining energy at each relay node are taken into consideration. Havinal et al. [184] proposed the Minimal Energy Consumption with Optimized Routing (MECOR) protocol that focuses on the use of energy consumption as the main performance metric for routing decisions.

From another perspective, Ourouss et al. [185] proposed an energy-aware routing protocol (called Double Metric), that obtains increased effectiveness by combining QoS and energy-efficiency in determining the best routing path to be selected. This approach ensures a balance between the robustness of routing and the energy efficiency of routing. The advantage of this energy-aware routing protocol method is that it is very efficient in obtaining the routing path with a minimal cost value. However, the main drawback of this protocol is that, if not combined with another energy-efficient approach, it will result in the overuse of limited energy resources from the battery of the intermediate nodes, thus resulting in network failure. Yang et al. [186] examined the packet delivery ratio and energy consumption under a multicast scenario by taking into account the transmission power control for each node. In their multicast scenario, a packet from the source node can be delivered to up to f different relay nodes. Each of the d destination nodes may receive the packet from these relay nodes (or the source node) before the packet lifetime τ expires. It can be said that, in this scenario, we have a redundancy factor f, multicast scale d, packet lifetime τ, and a power control parameter w for packet routing. The power control parameter w is fixed and equal for all nodes. Initially, the authors assumed a general two-hop relay RT (f, d, τ, w) algorithm with redundancy factor f, multicast scale d, packet lifetime τ and power control parameter w for packet routing. Next, they developed a Markov chain framework to depict the packet propagation process under this two-hop relay algorithm. Using this framework, they derived two analytical expressions for PDR and energy consumption. Finally, they validated their theoretical analysis and investigated how the abovementioned network parameters affect the PDR and energy consumption performance. Finally, Das and Tripathi [187] proposed the Multi Criteria Decision Making (MCDM) method combined with Intuitionistic Fuzzy Soft Set (IFSS) method. The authors placed special emphasis on the efficiency of utilizing energy capacity as part of route cost calculation by considering the rapid changes that occur in the identified routes. The use of the MCDM method, combined with the IFSS method, can calculate the cost of changing network routes efficiently and accurately. Table 2 summarizes the previous schemes and methods described.

Table 2. Important works on transmission power control routing protocols for MANETs.

Year	Ref.	Contribution
2019	[186]	A Markov chain framework that depicts the packet propagation process under a general two-hop relay algorithm. Two analytical expressions were derived for estimating PDR and energy consumption.
2018	[187]	Multi-Criteria Decision-Making method combined with Intuitionistic Fuzzy Soft Set (IFSS) method.
2017	[180]	The Fitness Function technique was applied to optimize the energy consumption in a new routing protocol (FF-AOMDV). In FF-AOMDV, the fitness function is employed to discover the optimal path from the source to the destination to reduce the energy consumption in multipath routing.
2016	[185]	The "Double Metric" energy-aware routing protocol obtains increased effectiveness by combining QoS and power-efficiency in determining the best routing path to be elected.
2016	[184]	The MECOR routing protocol addresses the use of energy consumption as the most important performance metric for routing decision.
2016	[183]	The EPAR routing algorithm measures the amount of remaining battery energy and estimates the cost of energy required when a route is selected.
2016	[157]	The ECAO protocol calculates the energy cost as extra metric performance in OLSR as well as throughput, delay, and the number of hops to measure the cost of each known routing path.
2015	[182]	The ELRPP routing scheme selects a route based on residual energy, SNR, and link quality. ELRPP incorporates a variable transmission power control mechanism.
2014	[79]	The AOMR-LM multipath routing protocol preserves the residual energy of nodes and balances the consumed energy to increase the network lifetime. The residual energy of nodes is used for calculating the node energy level.
2014	[179]	The AODV_RR protocol (an improved version of AODV) includes the "range routing" mechanism. AODV_RR selects certain nodes to be responsible for receiving and processing any routing request based on the RSS. It maximizes the transmission range and minimizes the transmission power and the overall energy consumption of the network by minimizing the communication overhead.
2015	[173]	The Modified DSR applies an energetic-aware mechanism to DSR protocol and uses energy consumption metrics for energy consumption balancing purposes.
2014	[188]	An energy-efficient routing algorithm finds routes, minimizing the total energy required for end-to-end packet delivery.
2013	[146]	An energy-efficient genetic algorithm-aided mechanism depends on bounded end-to-end delay and minimum energy cost of the multicast tree to solve QoS-based multicast routing problems.
2012	[189]	A cooperative routing algorithm considers electronic power consumption when constructing the minimum-power route leading from source to destination.
2012	[181]	The Link-stability and Energy-aware Routing protocol (LAER) combines energy metrics with other metrics (link status) for use in the routing decision.

Subsequently, we discuss cross-layer optimization-based routing approaches, which are based on effective cross-layer designs (CLDs) and provide better network management in terms of QoS, and energy consumption.

3.8. Cross-Layer Optimization for Energy Conservation in MANETs

3.8.1. Cross-Layer Optimization Defined

The Open Systems Interconnection-Reference Model (OSI-RM) provides a networking framework to implement the protocols within seven layers [190]. However, in the context of wireless networks, the OSI model has two main limitations: the principles of abstraction and encapsulation at each layer. The principle of abstraction dictates that the implementation details and interior parameters of the protocols within a layer are hidden to other layers. The inter-layer communication (that is restricted to procedure calls and responses) is performed only between adjacent layers. The principle of encapsulation maintains modularity in the network development and improves testing and error checking, but it prevents sharing critical information among the layers in the protocol stack. Because of the shared nature of the wireless channel, the different layers of MANET depend on each other. The conventional OSI layered design is, therefore, ineffective, resulting in redundancy within layered wireless protocols. If we design communication protocols intended for QoS provisioning on resource-controlled mobile devices, it is recommended [49] to consider the cross-layer coupling of functionalities. All cross-layer (CL) optimization processes have a common format that involves taking a set of parameter values from one (or a subset) of protocol layers and returning optimized parameter values to the same or other protocol layers. Khan et al. [191] defined a three-stage process of cross-layer optimization, as shown in Figure 4.

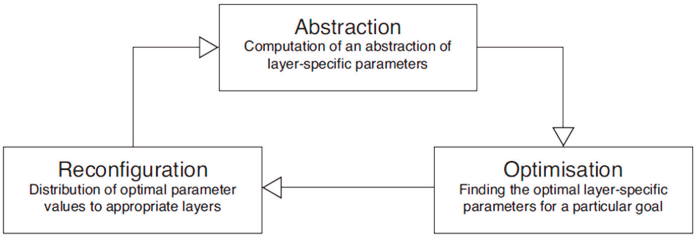

Figure 4. The stages of cross-layer interaction [191].

The first stage (Abstraction) is vital for reducing the processing and communication overheads. It decides if a small number of parameters are to be distributed, and underlying technologies covering. Then, Optimisation and Reconfiguration enable protocol adaptation to the existing network conditions and QoS requirements to maximize network performance. This is obtained by the tuning of the abstracted (or other related) parameters that are then returned to the network stack. These three steps can be repeated along with changing QoS requirements and resource capabilities.

3.8.2. Cross-Layer Designs for MANETs

Researchers have proposed numerous cross-layer routing protocols for ad hoc networks [192]. A Cross-Layer Design (CLD) [193] permits the communication architecture to operate as a system rather than a stack with different co-existing protocols. Particularly, CLD allows for interactions between different non-adjacent layers to defeat the OSI model's limitations (discussed previously) and provide better network management in terms of QoS, energy consumption, and other performance parameters. Thus, in a CLD approach for MANETs, the protocols and algorithms of the MAC, NET, Transport, and APP layers can function cooperatively to achieve: (1) high energy efficiency; (2) lower end-to-end delay; (3) minimization of energy consumption. A cross-layer approach can extract the cross-layer information from multiple layers, which can be additionally utilized to improve the overall performance and QoS in MANET. The sharing of cross-layer information can also satisfy the demand for high-quality multimedia communication and QoS provision in MANETs. In cross-layer approaches, video codecs can prioritize packets, split the source media into multiple streams, and generate redundant information that can be utilized by protocols and algorithms of different OSI-RM layers. In MANETs, each layer of the protocol stack is fully involved in providing QoS guarantees. New schemes are required at each layer of the protocol stack. For instance, MAC protocols are required for providing service differentiation and reducing end-to-end delay. Advanced coding techniques are also required, that will decrease encoder complexity and achieve maximum compression. In MANETs, where all layers depend on each other, QoS guarantees are achievable via the Cross-Layer Interaction (CLI) of different layers. For example, the MAC layer can be informed of the QoS requirements of the APP layer to obtain better scheduling for the execution of a multimedia application, and the Channel State Information (CSI) can be provided to the NET layer so that the routing protocol can keep away from paths containing channels in a bad state, as shown in Figure 5.

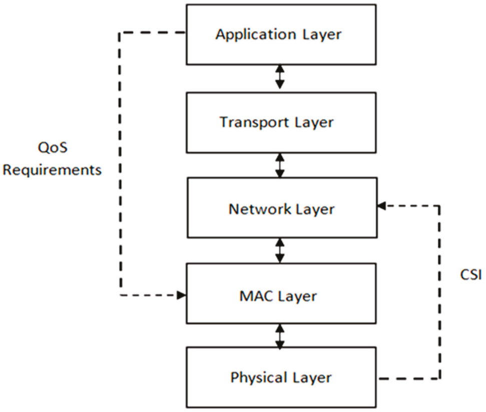

Figure 5. Two examples of cross-layer (CL) interactions in the protocol stack for MANETs (Adapted from [58]).

The applications in MANETs have different QoS requirements that determine the aim of the cross-layer design needed. Such cross-layer designs might be intended for reducing energy consumption and the end-to-end delay to improve the network's throughput, for striking an elastic tradeoff between any two of them, and for multiple-constraint optimization. Cross-layer design solutions use other layers to provide joint routing and scheduling, as well as power efficiency [194]. In MANETs, the routing process in the NET layer can interact with the access control module in the MAC layer. Additionally, there is the coupling between schedules in the MAC layer and power control in the PHY layer. Protocol designers can use cross-layer designs to adjust the system to the highly variable conditions of MANETs and confront system performance problems in an ideal way. For instance, a CLD can perform both local and global adaptations to network congestion. The MAC layer reacts locally to congestion by exponential back-off. If congestion is high, this response is deficient and it necessitates dual option compensation: (1) either the forwarding scheme can reroute traffic to avoid the bottleneck; (2) if alternate routes do not exist, the optimization can use transport protocol mechanisms to freeze traffic transmissions [30].

Hereafter, we describe some important works based on CLD that address transmission power in MANETs.

Ramachandran and Shanmugavel [195] proposed a CLD approach for power conservation based on transmission power control. Their approach includes three CLD proposals, which share the Received Signal

Strength (RSS) information among PHY, MAC, and routing layers: (1) in the first proposal, the minimum sufficient transmit power is computed to obtain energy conservation, interference reduction, and spatial reuse; (2) in the second proposal, the path loss incurred is computed to identify and reject the unidirectional links which greatly affect the performance of the routing protocol (AODV) in heterogeneously powered networks; (3) the third design proposal uses the RSS information to select reliable links to form stable routes by monitoring the signal quality to evaluate whether the neighbors are approaching or leaving.

It is well-known that a heterogeneous MANET has normal nodes (i.e., B-nodes) and powerful nodes (i.e., P-nodes). B-nodes are equipped with batteries, while P-nodes, have relatively unlimited power supplies (e.g., power scavenging units, such as solar cells or dynamos), when they are installed in mobile vehicles, etc. By utilizing the inherent device heterogeneity, Liu et al. [196] proposed a cross-layer designed Device-Energy-Load Aware Relaying framework (DELAR) that achieves energy conservation from multiple facets, including transmission scheduling, power-aware routing, and power control. The researchers implemented a power-aware routing protocol that integrates nodal residual energy information, device heterogeneity, and nodal load status to conserve energy. They developed a hybrid transmission scheduling scheme, that is a combination of reservation-based and contention-based MAC schemes, to coordinate the transmissions. Furthermore, they introduced the novel notion of "mini-routing" into the Data Link layer and proposed an Asymmetric MAC (A-MAC) scheme to support the MAC-layer acknowledgments over unidirectional links originated by asymmetric transmission power levels among normal nodes and powerful nodes. Additionally, they presented a multi-packet transmission scheme to enhance the end-to-end delay performance.

Tavli and Heinzelman [197] proposed an energy-efficient real-time data multicasting architecture for MANETs. This architecture is based on a CLD and is called Multicasting through Time Reservation using Adaptive Control for Energy efficiency (MC-TRACE). MC-TRACE is designed particularly for group communications (i.e., multicast and broadcast), and provides superior energy efficiency while producing competitive QoS performance and bandwidth efficiency.

Zoulikha and Amal [198] proposed another CLD among PHY, MAC, and Network layers. Their CLD uses the RSS information as a CLI parameter to provide reliable route discovery, stable links with strong connectivity, and energy conservation in transmitting data in a shadowing environment. Through simulation results, the authors have demonstrated that their cross-layer approach may reduce the packet latency and the routing overheads and may enhance the end-to-end performance of UDP flows when compared with customary solutions (single-path AODV routing protocol, and IEEE 802.11 DCF at the MAC layer). Ahmed et al. [193] suggested a cross-layer optimization framework that combines the PHY layer for controlling the transmission power, and the MAC layer for retrieving information about the RSS of a node. The modification of transmission power facilitates the node to adjust the transmission range dynamically at the PHY layer. With a dynamic transmission power control mechanism, each node calculates minimum RSS, average RSS, and maximum RSS. Using this information, each node knows its neighbor positions and guides itself to dynamically manage its power levels. As a result, the optimal transmission power and reliable communication range are obtained. Equations (3)–(5) calculate the average, minimum, and maximum receiver signal strength (RSS), correspondingly:

$$A_{RSS} = \frac{\sum_{i=1}^{m} RSS_i}{n} \tag{3}$$

$$A_{Min_{RSS}} = \frac{\sum_{i=1}^{Min_{node}} RSS_i}{Min_{node}}, \text{ for } RSS_i < A_{RSS} \tag{4}$$

$$A_{Max_{RSS}} = \frac{\sum_{i=1}^{Max_{node}} RSS_i}{Max_{node}}, \text{ for } RSS_i > A_{RSS} \tag{5}$$

where m is the sum of single-hop neighbor nodes of node X_i with RSS_i representing the sum of the RSS value of neighbor nodes. Each node determines the communication region by using these values. The RSS value is inversely proportional to the transmission distance. This means that a low value of RSS can cover a larger communication region and vice versa.

Iqbal et al. [49] presented a cross-layer multipath routing protocol for MANETs that is efficient and fault-tolerant in a diversity of application environments. The protocol is adaptive as it exploits those routes that are capable of providing more data rates with a lower packet loss ratio (PLR). The authors assume that MANETs are established for three types of applications: (1) simple; (2) multimedia; (3) applications with security requirements. A multimedia application needs such routes that have more bandwidth and minimum end-to-end delay. Taking into account the type of the application, the routing protocol chooses proper multipaths. For example, for a multimedia application, the proposed protocol selects two (or more than two) routes which are bandwidth-rich and have minimum delay from source to destination. Some important features of their protocol are as follows: (1) the APP layer defines the type of application; (2) the security module is working at the network layer; (3) bandwidth and end-to-end delay parameters are taken from the MAC layer. Their protocols were compared with other routing protocols (DSR, AODV, OLSR, CEDAR, PLQBR, QAODV, SAODV, and CSROR) using PDR, average delay, and routing overheads metrics with and without malicious nodes, and it was found to be efficient and fault-tolerant in most scenarios. Carvalho et al. [199] implemented a cross-layer routing protocol for a hybrid MANET that uses a fuzzy-based mechanism for all layers by employing two input parameters: energy and mobility. This mechanism offers a better quality of network resources and enhanced network lifetime. It consists of a decision metric in each layer, based on QoS and Quality of Experience (QoE) to enhance network lifetime and energy efficiency. Wang et al. [200] proposed and evaluated a cross-layer routing protocol, considering power control and rate adaptation by using a delay-based non-selfish cost function with a multi-agent Q-learning coordination mechanism. Simulation results showed that this protocol improves the average end-to-end latency and throughput with acceptable power consumption level. In the simulation experiments, various parameters were examined, such as node density, node mobility, traffic load, and the number of flows.

Mehta and Lobiyal [201] considered the problem of adjusting the transmission power of the nodes to an optimal power level. They incorporated low power consumption strategies into the routing protocol through an upward information flow cross-layer model between the MAC layer, and the Network layer. They proposed a new energy-efficient CLD to AODV, called Cross-Layer Energy Efficient AODV (CLEE-AODV). Using this CLD approach, they implemented the required changes in the route discovery process in the AODV. Through simulation results, they showed that the CLEE-AODV routing protocol has better performance enhancements than AODV, in terms of total transmission power, energy consumption per node, energy efficiency, and throughput. Singh and Verma [202] proposed an energy-efficient cross-layer routing protocol for heterogeneous cluster-based WSNs. The protocol is named ATEER to justify that it is Adaptive Energy-Efficient and based on the Threshold concept. The ATTER protocol assigns a node as CH, using the concept of weighted probability that is calculated based on the average energy of the whole network divided by the residual energy of every single node. The simulation results showed that ATEER has improved stability and prolonged the network lifespan when it was compared to other algorithms. Maitra and Roy [203] have suggested a cross-layer based protocol design explicitly for mix WSNs, called XMSN. This scheme effectively utilizes the concept of low power listening with a back-off congestion window scheme in order to accumulate neighbor information. Meanwhile, XMSN tries to accumulate the information of a suitable node, which will act as a parent for it. For this, XMSN utilizes the factors such as node and link quality, respectively. In fact, the authors have implemented and evaluated XMSN over Castalia simulator, and have concluded that the performance of XMSN is better than the previous approaches in terms of goodput, power consumption, and delay.

Chander and Kumar [204] suggested the Cross-layer Multicast Routing (CLMR) approach, that enhances the QoS based on a tree-based multicast routing protocol. To obtain QoS, the optimization of the tree management cost and tree operations was done. CLMR takes advantage of the functionality of the application layer, PHY layer, and network layer for QoS communication. The performance of CLMR is analyzed using the Multicast Ad Hoc On-Demand Distance Vector (MAODV) routing protocol under various parameters (i.e. throughput, delay, PDR, link cost, and energy consumption).

As was mentioned previously, it is vital to provide a mechanism that will effectively control the transmission power of a node. In this direction, Maygua-Marcillo and Urquiza-Aguiar [205] proposed a CLD mechanism that controls the transmission power of a node based on the detection of its neighbors. Such detection is performed by using AODV. The proposed mechanism is based on a cross-layering criterion to allow for the coordination, interaction, and exchange of information among the PHY layer and the network layer. Finally, Sekar and Latha [206] suggested a cross-layer-based, lightweight, reliable, and secure multicast routing protocol for MANETs. The protocol has three stages:

- In the first stage, a reliable multicast route discovery is completed. A multicast tree is set up and is hierarchically divided into clusters using the depth of the tree. Then, the CHs are chosen, based on link stability, residual energy, and residual bandwidth. Gateway nodes are selected depending on their residual energy and PDR.
- In the second stage, the trust value of each node is estimated and updated depending on each activity. Throughout multicast transmission, the trust values of CH and its gateway are monitored. CH and gateway are considered as misbehaving when their trust value is less than a minimum threshold. For protecting the data transmitted from the sender, a one-way hash function-based Message Authentication Code is used.
- In the third stage, bulk data loss recovery is performed at the receiver by applying the Automatic Repeat reQuest (ARQ) and Forward Error Correction (FEC) methods.

Table 3 presents previous works on CLD in MANETs.

Table 3. Important contributions of cross-layer designs in MANETs.

Year	Ref.	Contribution
2008	[195]	A CLD approach for power conservation based on transmission power control. This approach includes three CLD proposals aiming to solve special problems.
2011	[196]	The DELAR framework achieves energy conservation from multiple facets, including power-aware routing, transmission scheduling, and power control. DELAR focuses on heterogeneous MANETs.
2011	[197]	A cross-layer energy-efficient real-time data multicasting architecture (MC-TRACE) for MANETs. MC-TRACE addresses group communications and provides superior energy efficiency while producing competitive QoS performance and bandwidth efficiency.
2012	[207]	A cross-layer scheme jointly considers flow control, multipath routing, and random access control. The scheme is based on network utility maximization.
2013	[208]	A CLD for random-access-based fixed wireless multi-hop networks. This CLD is based on a physical interference model.
2014	[209]	A cross-layer distributed approach for maximizing the network throughput by jointly selecting stable routes and assigning channels based on mobility prediction.

Table 3. *Cont.*

Year	Ref.	Contribution
2014	[198]	A CLD among PHY, MAC, and network layers. The CLD uses the RSS information as a CLI parameter to provide reliable route discovery, stable links with strong connectivity, and energy conservation in transmitting data in a shadowing environment.
2015	[193]	A CL optimization framework combines the PHY layer for controlling the transmission power, and the MAC layer for retrieving information about the RSS of a node. The change in transmission power enables the node to adjust the transmission range dynamically at the PHY layer. Optimal transmission power and reliable communication range are obtained.
2016	[49]	A cross-layer multipath routing protocol is efficient and fault-tolerant in a variety of application environments. The protocol is adaptive as it exploits those routes which are capable of providing more data rates with less PLR.
2016	[199]	A cross-layer routing protocol for a hybrid MANET uses a fuzzy-based mechanism for all layers by employing two input parameters: energy and mobility. The fuzzy mechanism offers a better quality of network resources and enhanced network lifetime.
2016	[200]	A cross-layer routing protocol considers power control and rate adaptation by using a delay-based non-selfish cost function with a multi-agent Q-learning coordination mechanism.
2017	[201]	An energy-efficient cross-layer design to AODV (CLEE-AODV) adjusts the transmission power of the nodes to an optimal power level.
2017	[202]	An energy-efficient cross-layer routing protocol (ATEER) for heterogeneous cluster-based WSNs. ATTER assigns a node as CH using the concept of weighted probability that is calculated based on the average energy of the whole network divided by the residual energy of every single node.
2018	[204]	The CLMR approach enhances the QoS using a tree-based multicast routing protocol. This approach optimizes the tree operations and tree management cost to obtain QoS. CLMR exploits the functionality of the PHY, application, and routing layers for QoS-oriented communication.
2019	[205]	A mechanism controls the transmission power of a node based on the detection of its neighbors. The mechanism is based on a cross-layering criterion to allow for the coordination, interaction, and exchange of information between the PHY layer and the Network layer.
2020	[206]	A cross-layer based lightweight reliable and secure multicast routing protocol for cluster-based MANETs.

3.8.3. Cross-Layer Schedulers for Power Control

In the previous sections, we discussed how an important aspect is the energy efficiency of power-aware routing in MANETs [27,210–212]. Scheduling policies can contribute to this aspect. In particular, suitable periodic scheduling can reduce energy consumption and, as a result, conserve the battery power of MANET nodes to a great extent [213].

The cross-layer design framework in [214] considers the next neighbor node transmissions and eliminates multiuser interference. A node can only relay (send) data packets if the Signal-to-Interference-and-Noise Ratio (SINR) is an acceptable SINR level (i.e., single-hop transmission requirements). So, this framework increases single-hop throughput and reduces power consumption. Thus, it preserves battery power as much as possible. The framework includes two main algorithms: (1) the scheduling algorithm that synchronizes the transmissions of independent users (nodes) to eradicate strong levels of interference, such as self-interference; (2) the distributed power control algorithm that decides the admissible power vector (if one exists), that can be used by the scheduled users (nodes) to assure their single-hop transmission requirements. Moreover, the power control algorithm can cooperate with two types of wireless ad hoc schedulers: TDMA and TDMA/code-division-multiple access schedulers. For example, to minimize power consumption and decrease packet delivery delay in nodes, the TDMA MAC protocol can allocate time slots to nodes efficiently. The joint distributed interference-based TDMA link scheduling and power control algorithm in [215] is suitable for MANETs and is based on the SINR parameter. The algorithm supports multicast traffic and eradicates those links that generate a large amount of interference. In this way, it permits the remaining links to achieve an acceptable SINR level. In wireless networks, SINR provides theoretical upper bounds on channel capacity. The joint link scheduling and power control TDMA in [216] maximizes network throughput. The joint link scheduling algorithm is based on a Mixed Integer Linear Programming (MILP) formulation that describes the problem in wireless ad hoc networks. Then, the authors [216] suggest two options:

(1) By solving the MILP formulation, the joint link scheduling algorithm finds optimal solutions and allocates the bandwidth reasonably among all links;
(2) A polynomial-time heuristic algorithm is applied to unravel the matter. Using this heuristic algorithm at the value of a minor reduction in network throughput, the joint link scheduling algorithm allocates the bandwidth among all links. In this case, the polynomial-time heuristic algorithm is called Serial Linear Programming Rounding (SLPR) heuristic. It must be noted that it is very difficult to evaluate the performance of SLPR when optimal solutions are not known.

In a TDMA scheduling scheme, we know that time is divided into frames and each frame includes time slots. The number of time slots in each frame defines the frame length. To minimize the total frame length in TDMA scheduling, Behzad and Rubin [217] designed a mathematical programming formulation for MANETs that is based on an optimal joint TDMA scheduling and power control algorithm under the physical interference model. This physical interference model is based on a power-based interference graph that depicts the interference relationship of every two links along with the SINR of the receiver. Based on this graph, the authors tried to find a maximal link-independent set using a heuristic algorithm called the Minimum Degree Greedy Algorithm (MDGA). For a TDMA-based MANET, Li and Ephremides [218] proposed an algorithm of joint power control, scheduling, and routing. The use of this centralized and joint algorithm enhances network performance in terms of delay, throughput, and power consumption. However, in this algorithm, there is a trade-off among energy consumption and delay performance or network throughput. In the area of wireless sensor networks, Mao et al. [219] developed a joint link scheduling and power control algorithm for many-to-one communications. This algorithm minimizes TDMA frame length and energy consumption by applying a hybrid genetic and particle swarm optimization algorithm that improves the searching ability. The algorithm does better than the traditional node Max Degree First coloring algorithm. However, it is not appropriate for a MANET environment with high node mobility. An adaptive and distributed TDMA scheduling scheme (AD-TDMA) for MANETs was proposed in [220]. The AD-TDMA scheme causes energy saving by presenting a high-quality awake-sleep scheduling state for MANET nodes. AD-TDMA has a good performance against changes in MANET topology. The AD-TDMA performance implies a large improvement in energy saving and a decrease in packet delivery delay. Last but not least, Padmavathy and Jayashree [221] implemented an enhanced delay-sensitive data packet scheduling algorithm that can increase throughput, energy efficiency, and network lifetime. This scheduling algorithm can reduce delay, latency, and drop rate. Moreover, it schedules the data packets adopting high-weighted priority scheduling. After that, data packets are forwarded based on the channel medium, whether it is in a busy or idle state to avoid drop-rate and delay.

To summarize the main concepts discussed in Section 3, we present Table 4, which shows a comparison of the categories of power-aware optimization solutions for MANETs.

Table 4. A comparison of the categories of power-aware optimization solutions for MANETs.

Category of Power-Aware Solutions	Protocols/Schemes/Designs	Problem to Address/Objectives	Advantages	Disadvantages	Applicable Scenarios
Approaches based on adaptations of the radio state operational mode	PAMAS [74], Sleep and Awake Scheduler [76], GAF [77], SPAN [78], S-MAC [80,81], T-MAC [82], R-MAC [83], DW-MAC [84], WiseMAC [85], B-MAC [86], X-MAC [87], RI-MAC [88], QL-MAC [89]	**Problem to address:** These approaches deal with the issue of unnecessary energy consumption during overhearing and idle listening during communication. **Objectives:** To minimize needless energy consumption during in-active periods.	The idea of radio state adaptation is suitable in large dense MANETs. In such MANET environments, the issue of overhearing and idle listening gradually increases. Therefore, the energy consumption of nodes increases too. These approaches prolong network lifetime by reducing unnecessary energy consumption during inactive periods.	These approaches increase the overall end-to-end delay in the network. Nodes in sleep mode cannot transmit and receive any packets. Thus, packet retransmissions are required, which lead to increased energy consumption. These approaches require complex coordination and synchronization amongst nodes which are difficult issues to be implemented in MANETs.	The approaches/schemes [74–77] are specifically designed for static and dynamic ad hoc networks. The MAC designs [80–89] are highly limited to some applications where the data generation rate is not very bursty and these MAC designs have mostly been evaluated over the WSN environment where the nodes are mostly in a sleeping state.
The adaptive load balancing/distribution-based approach	Sharma and Kumar [19], Adaptive-sleep + Adaptive MAC-Retx [22], Toh [64], LEAR [97], MDR [98], DSR extension-based load-balancing schemes [99–103], OLSR extension based load-balancing schemes [105–108], DMP_EOLSR [120] PHAODV [45,121], ELBRP [122], MP-OLSR [123], MEA-DSR [125], ELGR [126]	**Problem to address:** Routing based on adaptive load balancing aims to solve the problem of minimum energy consumption by adopting various load balancing methods. **Objectives:** The main aim of these routing protocols is not to estimate the minimum energy consumption path, but these routing protocols effectively assist in preventing certain low energy nodes from being over-utilized and, hence, they help in prolonging the network lifetime.	The idea of dynamic load-balancing and distribution is highly suitable in dense MANETs and network environments with heavy traffic load. These routing protocols can effectively assist in maintaining the proper balance of the power consumption amongst all the competent nodes either by choosing the route with the relaying nodes, which have sufficient energy-level, or by dynamically distributing the traffic over multiple available network paths.	These routing protocols do not care whether the chosen path is smaller or larger; it depends on the availability of intermediate nodes that have sufficient power level. Hence, such routing protocols influence the overall end-to-end delay performance of the network. The idea of dynamically utilizing multiple available paths for load-balancing does not always guarantee that the selected paths are optimized (paths) in terms of minimum energy consumption.	These routing protocols can be applied in the form of two scenarios: (I) Concurrent path forwarding/routing/transmissions-based schemes (e.g., LEAR, MDR, DMP_EOLSR, and ELGR); (II) Alternate path forwarding/routing/ transmissions-based schemes (e.g., PHAODV, ELBRP, MP-OLSR, MEA-DSR).
The location-based routing method	GPSR [128], Terminode Routing Protocol [132], LAR [133], LEARN [134], LEER [135], ZCG [136]	**Problem to address:** Many existing routing protocols heavily rely on the current state regarding links on a path between a pair of source and destination or all links in the network. Subsequently, this may lead to poor network scalability when these existing protocols are directly applied over a dense network environment and when nodes are moving rapidly (high mobility) to save battery. **Objectives:** These routing protocols aim to rely on the geographic location (and perhaps mobility) of each node for finding the best routing path. These protocols aim to improve network scalability by decreasing the routing overhead and providing improved performance in terms of energy consumption.	These routing protocols efficiently assist in improving the network scalability by decreasing the network overhead significantly, (especially in high mobility scenarios). By utilizing the location information, these protocols ensure that the least amount of control packets have to be transmitted over the network.	These routing protocols encounter numerous challenges, such as inaccurate positioning, local optimum problem, optimum forwarder selection, and broadcasting overheads. Location-based routing is difficult if holes exist in the MANET topology, and when nodes are roaming or often disconnected to preserve energy.	These routing protocols are specifically designed for high mobility scenarios and dense network environment. When the nodes' mobilities are too high, these routing protocols can outperform other conventional policies/schemes.

Table 4. *Cont.*

Category of Power-Aware Solutions	Protocols/Schemes/Designs	Problem to Address/Objectives	Advantages	Disadvantages	Applicable Scenarios
The multicast-based routing method	LMT [142], PEMA [143], Varaprasad [147], RERMR [148], EELAM [153], WEEM [154]	**Problem to address:** Conventional routing cannot efficiently utilize the available bandwidth while a source node is relaying multiple copies of its packets to a group of multiple destinations. **Objectives:** Multicast routing aims to route data from one source to multiple destinations of a specific group while utilizing the available network bandwidth in the presence of high mobility-induced topology changes.	Multicast-based routing protocols can consider different performance criteria, such as power-efficient route establishment, PDR, network lifetime, quicker and faster proactive route recovery, reliability, QoS based on bandwidth, delays, jitters, and security.	In a multicast tree, a root node suffers from greater energy depletion. Thus, it can shut down before other nodes as a root node is responsible for performing more tasks than other nodes. As the multicast tree is no longer static, multicast routing must support multicast membership dynamics. Existing power-aware multicast algorithms often produce extra control traffic in the network.	Multicast-based routing protocols are specifically designed for multicasting scenarios (i.e., group-oriented applications). In multicast scenarios, there is only one sender and multiple receivers per session, where a sender transmits multiple copies of packets to a specific group of multiple destinations. Multicast routing assumes the use of a multicast tree.
The proactive (link-state-based) routing method	Kunz and Alhalimi [42], OLSR_EA [43], Boushaba et al. [155], Jabbar et al. [156], MQ-Routing [160], QG-OLSR [161]	**Problem to address:** Traditional routing protocols operate on less accurate computations of network conditions. Hence, these protocols react slower to sudden significant network changes. These protocols also highly suffered from the issue of route oscillations and long-term loops. **Objectives:** The main idea of proactive routing is that each competent node shares its local topological view to its immediate neighbors. Then, this information is propagated, utilizing a flooding scheme throughout the network. Consequently, each node gets updated with a full topological view of the network. Additionally, proactive routing aims to maximize performance in terms of throughput while minimizing packet loss, energy usage, and network overhead.	In proactive link-state-based routing, each node tends to exchange information about the current network topology with other nodes to update its own routing table. Thus, proactive routing can immediately find the shortest path as the route discovery process has no delays. By utilizing the concepts of triggered apprises and flooding, link-state-based schemes are able to converge more speedily since, in case of flooding, the changing network information is flooded almost instantaneously and estimated concurrently.	The amount of memory storage required for accumulating neighbored information, topological databases, and the routing table is very high. Additionally, frequent topological changes in the network (during high mobility scenario) lead to the issue of the uncontrolled dissemination of triggered update messages. Hence, routing overhead is very high in such scenarios. Additionally, such routing protocols are not suitable for dense networks at all.	These protocols can be applicable in two ways: (1) link-state-based routing protocols, such as OLSR; (2) schemes which are based on the distance–vector algorithm, such as DSDV. These protocols can be effective in low density and static network (i.e., where mobility is almost negligible) environments since, in such a network environment, the frequent topological changes are almost negligible. Hence, the overall bandwidth prerequisite is not that high for control packet transmission. Consequently, the data transmission phase are not hampered too much in terms of bandwidth availability. These protocols can be efficient in long or continual data connections (sessions) in the network since, in such a scenario, there is a definite sense of the overhead for sustaining the information of paths being comprehended as the maintained paths are mostly utilized.

Table 4. *Cont.*

Category of Power-Aware Solutions	Protocols/Schemes/Designs	Problem to Address/Objectives	Advantages	Disadvantages	Applicable Scenarios
The reactive (source-initiated-based) routing method	WBDSR [163], BAWB-DSR [164], EEAODR [165], EDSR [166], EPAR [167], EE-AODV [168]	**Problem to Address:** Reactive routing confronts the problem of high control overhead associated with the previous proactive routing method. **Objectives:** Reactive routing protocols perform path discovery on an on-demand basis. Reactive routing aims to handle the regular node mobility issue more cleverly than proactive routing. Additionally, reactive routing tries to maximize performance in terms of throughput, while minimizing packet loss, energy usage, and network overhead.	Reactive routing does not depend on the periodic exchange of routing information or route calculation. A reactive routing protocol finds a route from a source to a destination when the source node must send data packets. The path discovery takes place if the node does not have the information of the most current route. Reactive routing eradicates the overhead of periodic and triggered update flooding for sustaining route information. It reduces the issue of higher network overhead and improves network scalability compared to proactive routing.	In reactive routing protocols, the overall time delay is large, since the node needs extra time to wait for the route discovery process after the node tries to deliver a packet.	The proactive routing method is perceived as the pure extension of existing routing protocols from the common wired domain. While the reactive (source-initiated-based) routing method is purely designed for MANETs. The reactive routing method is best adapted to a network environment where mobility is too high and any constructed routing path between a pair of senders and receivers will certainly be momentary.
The transmission power control-based routing method	FAR [62], OMM [63], Doshi et al. [65,66], AOMR-LM [79], Kar et al. [171], Liang and Guo [172], Badal and Kushwah [173], EAR [178], AODV_RR [179], FF-AOMDV [180], LAER [181], ELRPP [182], EPAR [183], MECOR [184], Double Metric [185], MCDM [187]	**Problem to Address:** This type of routing confronts the following problem: If the transmission power level is very high, the node would sense and interfere with several neighbors. This causes channel saturation, contentions, and collisions. On the other hand, if the transmission power level is low, a node could detect very few neighbors (or none) which would lead to a failed transmission. **Objectives:** To reduce unnecessary energy consumption by selecting the best routing path between a pair of sources and destinations in order for the nodes to consume the minimum amount of energy.	A transmission power regulation method can improve the overall network performance by increasing throughput performance and simultaneously reducing energy consumption. This method has also suggested a pronounced viewpoint to reduce unnecessary energy consumption.	This type of routing must satisfy the challenging feature of complex transmission power adaptations. Since, in such routing protocols, a high possibility of network segregation could be there, which ultimately leads to the issue of high latency and packet losses when the transmission power is adapted to some lower value.	This type of routing can address the dynamic environment of MANETs. However, it can only improve network performance under discrete conditions (i.e., fixed packet sizes and mobility speed). In the past, some transmission power regulation schemes were also able to reduce the possibility of avoidable power consumption, but they failed in improving throughput performance. Later, many authors insisted on the combined usage of the MAC and network layers for such protocols. Subsequent power-aware methods have been given by accumulating power information along with node positioning and topological state information.

Table 4. *Cont.*

Category of Power-Aware Solutions	Protocols/Schemes/Designs	Problem to Address/Objectives	Advantages	Disadvantages	Applicable Scenarios
The cross-layer optimization-based routing method	Iqbal et al. [49], Ramachandran and Shanmugavel [195], DELAR [196], MC-TRACE [197], Zoulikha and Amal [198], Ahmed et al. [193], Carvalho et al. [199], Wang et al. [200], CLEE-AODV [201], ATEER [202], CLMR [204], Maygua-Marcillo and Urquiza-Aguiar [205], Sekar and Latha [206]	**Problem to address:** The conventional OSI layered design is ineffective as it results in redundancy within layered wireless protocols. Due to the OSI–RM model policy of restricting interactions between non-adjacent layers, it is quite challenging to provide better network management in MANETs in terms of QoS, energy consumption, and other performance constraints. **Objectives:** These routing protocols (based on cross-layer designs-CLD) provide dynamic interactions among non-adjacent and adjacent layers. These routing protocols are intended for reducing the energy consumption and the end-to-end delay, for improving the network's throughput, for striking an elastic tradeoff between any two of them, and for multiple-constraint optimization.	This type of routing allows interactions between different non-adjacent layers and provides better network management in terms of QoS, energy consumption, and other performance parameters. In this type of routing, the protocols and algorithms of the MAC, NET, Transport, and APP layers can function cooperatively to achieve: (1) high energy efficiency; (2) lower end-to-end delay; (3) minimization of energy consumption. A CLD approach can extract the cross-layer information from multiple layers. This information can be additionally utilized to improve the total performance and QoS in MANETs. The sharing of cross-layer information satisfies the demand for high-quality multimedia communication and QoS provision in MANETs.	The implementation of these routing protocols requires an extensive change in terms of conventional layered architecture. Thus, regarding the involvement of every layer to perform certain estimations, calculating channel conditions at once becomes quite challenging when the designers implement them. To implement such routing protocols, especially for real-time applications, many amendments are required both at the hardware and software levels. Therefore, the practicability of such protocols and their performance evaluation conclusions are highly limited.	This type of routing can effectively handle the dynamic properties of MANETs. The traditional layered model is not able to do so because of its stern and rigid architecture. Hence, for the sake of handling these unusual properties of MANETs well, reactive/proactive forwarding methods can be jointly applied with the proposed cross-layer design (CLD).

4. Some Lessons Learnt

Recently, the wireless services over MANETs added dynamic competencies, such as QoS and multimedia. The design of energy-aware forwarding schemes is one of the imperative research topics in wireless communication. Until the late 1990s, various power-aware schemes considered energy management at the PHY layer only. Later on, numerous power-aware designs considered other issues of the higher-level protocol stack (wireless). Initially, many power-aware forwarding approaches took into account the power information for two tasks: (1) selection of routes with minimum power consumption; (2) balanced usage of multiple available nodes (i.e., load-sharing and balancing, respectively). Despite the presence of routes with high-power, the resulting performance of the network lifetime by these policies (i.e., mostly based on the single-path communication paradigm) was not very high. This is because some of the suggested policies suffer from the problem of inefficient load sharing, distribution, and balancing amongst available nodes. Moreover, many of the energy-aware forwarding methods in MANETs were considered effective against unnecessary power consumption. Nevertheless, such a reduction in power consumption comes at the cost of increasing the end-to-end delay and reducing the throughput performance.

Next, many approaches focused on topology control methods using transmission power regulations in MANETs as a transmission power regulation method to improve the overall network performance. Along with this, such a method has also suggested a pronounced viewpoint to reduce unnecessary power consumption. Some of these policies proved sufficient in improving throughput performance and simultaneously reduced energy consumption. However, these policies were able to do so only under some discrete conditions (i.e., fixed packet sizes and mobility speed). Some transmission power regulation schemes were also able to reduce the possibility of avoidable power consumption, but they considerably failed in improving throughput performance. Later, many authors insisted on the combined usage of the MAC and network layers for such schemes. Subsequent power-aware methods have been given by accumulating power information along with node positioning and topological state information. In the dynamic environment of MANETs the probabilities of mobility induced network topology changes and dissimilar wireless channel characteristics are reasonably high. In this environment, it is very difficult to assess the precise information of efficient energy-aware paths in the network. Even after assessing such a path, there is no guarantee of how long that estimated path will survive. Therefore, further research is needed to assess such highly varying wireless channel characteristics simultaneously with power-correlated parameters in finding the most suitable paths.

Meanwhile, other researchers proposed schemes based on the low-duty cycle associated with contention-based MAC design, especially for WSNs. Such a design has a great perspective to improve the overall network throughput performance and simultaneously reduces unnecessary power consumption as well. Nevertheless, most of these proposed schemes were completely tested, keeping a particular environment in mind, where the maximum possible bandwidth utilization was not important at all. Additionally, it is quite evident that such policies should be tested on a regular heterogeneous environment where throughput and delay performance are equally important, along with energy performance. Afterwards, not only at the MAC level, several works contemplated every level of the traditional layered structure and brought appropriate changes to the optimal energy-aware path selection scenario. Recently, many authors proposed many cross-layering-based energy-aware routing schemes which simultaneously take into account various parameters of the network and MAC layers. The incorporation of many optimization schemes simultaneously with the cross-layering concept for assessing energy-aware optimal paths, is an exposed concern for the forthcoming research. Nonetheless, the practical implementation of the cross-layer designed policies is highly infeasible, since most of them require extensive changes to existing network devices and already implemented conventional layered architectures, which are quite impractical. This is why most energy-aware schemes fail in practical scenarios. The cross-layering concept is an open research topic in itself as it is not only being used to solve the power-related issue but also other issues (i.e., congestion) as well. Moreover, whatever energy-aware forwarding policies were suggested until now focused on the concept of the single-path communication paradigm. Unfortunately, even though the prevalent route diversity has been accessible on the Internet, past schemes have entirely concentrated on the single-path communication paradigm just for the sake of its less composite feature and lower overhead (network). Nonetheless, this less complex natured paradigm is neither able to handle the rapidly growing traffic nor deliver appropriate stability and reliability in terms of energy consumption as well.

Subsequently, researchers brought about the concept of the multi-path communication paradigm that introduces new power-aware policies by utilizing the concept of load-balancing. Such multi-path power-aware approaches significantly assist in managing the network's lifetime by actively exploiting the available paths' resources (i.e., buffer availability and channel capacity). Awkwardly, if we consider the multi-path communication paradigm only, then this paradigm has further serious issues as well. Indeed, the biggest question is whether we should use multiple paths concurrently for transmissions or whether have to use other paths only after fully using one path. If we use all the paths together and schedule our load concurrently (equally) to all the available network paths, then we make full competency of multiple available paths. Now, a new issue comes from here, whether all those routes are completely disjointed or not. If yes, this policy will offer benefits in terms of throughput and reduced power consumption performance. Otherwise, there can also be a situation in which there can be some common nodes in all those paths, and transmitting huge loads on all those available network paths simultaneously could lead to the premature death (i.e., battery exhaustion) of all those common nodes. Hence, it ultimately leads to the problem of network segregation. Meanwhile, other issues ultimately degrade overall network performance, such as inter-path interferences and the un-ordered delivery of data chunks to the receiver (i.e., buffer-blocking problem). In a broader sense, we can say that the ability of a multi-path scheme is entirely dependent on the physical distribution of paths. Indeed, if the physical distribution of all the estimated paths is in such a way that all of them are not within interfering range of each other, the multi-path forwarding scheme will perform better. Otherwise, their performance can be degraded further, since more inter-path interference leads to higher link-layer contention-induced losses, which further results in a high number of retransmissions, which ultimately leads to the problem of high energy consumption in the network. If we use one path at a time, it means that we are not using the full competency of multiple available paths, which is more or less the same as that of a single path communication scenario.

Hereafter, we present Table 5, which summarizes and compares important power-efficient proposals and some conventional routing protocols.

Table 5. A qualitative comparison of the important power-efficient proposals and some conventional routing protocols.

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
DSDV [68] (1994)	Network Layer	Not Specified	Newest, Next available, or Shortest Path	-	-	-	-	-	-	Looping problem of the Bellman–Ford Algorithm in the Routing Table.	DSDV maintains up-to-date topological information (status) of the network.	Routing overhead is high, especially when the node mobility is very high. Not suitable for dense networks at all. DSDV severely floods the destination generated sequence number, which ultimately causes high network and communication overhead.	High
WRP [69] (1996)	Network Layer	Not Specified	Shortest Path	-	-	-	-	-	-	Transient Looping problem of the Bellman–Ford Algorithm in the Routing Table and slow convergence problem.	WRP assists in eradicating transitory looping circumstances. Thus, it offers quicker path convergence than other schemes when a link failure occurs.	Memory requirement is very high, especially when the network density is large.	Low
CGSR [222] (1997)	Network Layer	Not Specified	Newest, Next available, or Shortest Path	-	-	-	-	-	-	Dynamic changes in wireless channel characteristics.	Numerous heuristic approaches, such as gateway code scheduling, resource reservation of path, and priority-based token scheduling, can be employed to improve the performance of the CGSR scheme.	The LCHC algorithm of CGSR may lead to the problem of the rippling effect in the network.	High
PAMAS [61,74] (1998)	MAC and Network Layer	Not Specified	PPP and supreme node cost or Shortest Cost Forwarding	Y	Y	Y	-	Y	Y	Shorter life of node and network problems associated with conventional routing approaches.	The radio state adaptation idea of PAMAS significantly assists in reducing unnecessary power consumption in the case of a large dense network environment.	Nodes involved in excessive transmission will lose their power faster than other lighter (or non-loaded) nodes in the network. Subsequently, it leads to the problem of the unbalanced power-level of nodes in the network. PAMAS assumes that there is no mobility scenario in the network.	Low

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
[223] (1999)	Not Specified	Not Specified	It is based on the fixed groups of sender and receiver pairs and the rate of traffic producing flows (i.e., one to one)	Y	Y	-	-	-	-	Nodes involved in extreme transmission will lose their power quicker than other lighter or less loaded nodes in the network. Afterwards, it leads to the problem of low network lifetime.	The scheme forwards the transmission in such a way that the power consumption is well-poised amongst all nodes in the network.	The scheme has been evaluated over a static network scenario (i.e., almost no mobility in nodes). Hence, the applicability of the evaluated results is highly limited. Additionally, the energy required for data reception had not been considered at all.	Low
FAR [62] (2000)	Transmission EnergyControl	Not Specified	FAR is based on the fixed groups of sender and receiver pairs and the rate of traffic producing flows (i.e., one to many)	Y	Y	-	-	-	-	Nodes that are involved in extreme transmission will lose their power quicker than other lighter or less loaded nodes in the network. Afterwards, it leads to the problem of low network lifetime.	The scheme forwards the transmission in such a way that the power consumption is well-poised amongst all nodes in the network.	The scheme has been evaluated over a static network scenario (i.e., almost no mobility in nodes). Hence, the applicability of the evaluated results is highly limited. Moreover, the energy required for data reception had not been considered at all. FAR needs to have prior information about the rate of data generation at the source.	Low
OMM [63] (2001)	Transmission EnergyControl	Not Specified	Min–Max Remaining Energy Level	Y	Y	-	-	-	-	OMM focuses on the problems based on minimizing energy depletion that arise during communication. OMM also emphasizes the problem of acquiring prior information about the rate of data generation at the source.	The OMM scheme effectively improves the network lifetime without having prior information about the rate of data generation at the source.	OMM preferably requires information about the current residual energy of all other nodes in the network. Therefore, the OMM scheme may not be scalable enough in a dense network environment.	High
[65,66] (2002)	Network Layer (Transmission Energy Control)	Constant Bit Rate (CBR) Sources	Newest, Next available, or Minimum Hop-count Path	-	Y	Y	-	-	-	The scheme addresses some issues, which are: (1) how to gather exact power information; (2) how much routing overhead is allied with the energy-aware scheme; (3) how we can sustain minimum power paths in the presence of high mobility.	The scheme effectively assists in minimizing overall power consumption during transmission by avoiding the low power nodes.	In high mobility scenarios, the scheme's performance was significantly affected as compared to minimum hop-count forwarding performance.	High

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
S-MAC [80,81] (2002, 2004)	MAC Layer (Synchronous MAC design)	Not Specified	Not Specified	-	-	Y	Y	-	-	S-MAC deals with a basic problem of unnecessary power consumption, due to overhearing and idle listening (IL).	S-MAC significantly reduces the problem of idle listening overhead by actively utilizing a periodic awakening and sleeping scheme.	S-MAC experiences certain degradation in both latency and fairness (per-hop) performance.	Low
T-MAC [82] (2003) RMAC [83] (2007) DW-MAC [84] (2008)	MAC Layer (Contention-based Synchronous low-duty cycle based scheme)	Not Specified	Not Specified	-	-	Y	Y	-	-	The schemes address the problem of a fixed duty cycle of S-MAC's scheme in order to reduce idle listening consumption.	These schemes have suggested an improvement in S-MAC by making adaptations in the active and sleep slot of the frame. They radically abridge the active slot of the frame when the channel is idle. These schemes significantly assist in reducing idle listening power consumption.	T-MAC experiences certain degradation in both latency and fairness (per-hop) performance. RMAC and DW-MAC schemes typically require an additive synchronization which further introduces complexity and overhead in the system.	High
LMT [142] (2004)	Network Layer (Multicast-based approach)	CBR Sources	Transmit energy level and Residual battery power.	Y	Y	-	-	-	-	LMT addresses the problem of low network lifetime.	LMT discovers routes that minimize the residual energy variance of nodes. Thus, LMT maximizes the lifetime of the source-based multicast tree network.	LMT scheme assumes that the energy needed for packet transmission is analogous to the source–destination distance. In this sense, LMT is theoretically unfair to the bottleneck node.	High

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
Blazevic et al. [132] (2005)	Location-based Routing	CBR Sources	Geo-graphical map and Friend-assisted-based path metrics.	-	-	-	-	Y	-	The scheme addresses the issues of location-based routing, such as local optimum problem, inaccurate positioning, optimum forwarder selection, and broadcasting overheads.	The scheme assists in maintaining the scalability advantages of location-aware forwarding.	The Geo-graphical map-based path discovery may require an additive network overhead of dispensing exact topographical information. Nevertheless, building and maintaining a full geographical map, especially in a high mobility environment, incurs high CO.	High
Liang and Guo [172] (2006)	Multicasting-based approach	Not Specified	Minimum Energy (multi-cast tree)-based optimal path.	Y	-	-	-	-	-	The scheme deals with throughput (multicast) maximization problem.	The scheme maximally routes the total amount of data without getting any advanced information on the upcoming rate of message arrivals and data generation.	The scheme is not able to perform well in case of the larger networks.	Low
EA-OLSR [35] (2006)	Network layer/MAC layer	CBR Sources	Minimum Energy-based optimal path.	-	Y	Y	-	-	-	The scheme deals with the issue of the selection of the optimal power-aware MPR set in OLSR.	EA-OLSR suggests improved performance in terms of network lifetime and lesser energy consumption, since the scheme considers energy consumption at both network and MAC layer level.	The scheme has been evaluated over low mobility scenarios. Hence, the applicability of the evaluated results is highly limited. EA-OLSR should be evaluated considering RE metric as well.	It depends on the identified MPR set size. If the chosen MPR set size is big, NO will be high. Otherwise, NO will be low.

Table 5. *Cont.*

Protocol (Year)	**Solution Type**	**Traffic Pattern**	**Path Metric**	**Factors Considered**						**Problem to Address**	**Advantages**	**Disadvantages**	**CO/NO**
				NE				**NC**	**ND**				
				RE	**TE**	**NO**	**IL**						
WiseMAC [85] (2004) B-MAC [86] (2004) X-MAC [87] (2006)	MAC Layer (Contention-based Asynchronous low-duty cycle-based scheme)	Not Specified	Not Specified	-	-	Y	Y	-	-	These schemes deal with a basic problem of unnecessary power consumption due to overhearing and idle listening.	These schemes effectively assist in eradicating the problem of the complex synchronization overhead required in the synchronous low-duty cycle-based systems and also suggest improved performance in terms of lower power consumption.	Sun et al. [88] have extensively discussed that asynchronous low-duty cycle schemes only achieve good performance in lighter traffic conditions. There is a serious decline in packet delivery, energy efficiency, and latency performance in such a policy as soon as traffic intensity increases.	Low
[224] (2007)	PHY, MAC, and network Layer (Adaptive Transmission Power Control)	CBR Sources	Not Specified	-	Y	-	-	-	-	The scheme effectively considers the restrictions and trade-offs of utilizing a fixed-range transmission method.	The suggested variable-range transmission-range scheme utilizes lower transmission energy and increases network capacity.	The scheme adopts that the intermediate or relaying nodes are available at the edge of the overlapping section [224]. Still, it does not imitate the chances of finding such relaying nodes within this section already. Consequently, the suggested path-duration estimation model does not advocate actual real-time values.	Low
EE-OLSR [107] (2008)	Link-state-based solution	CBR Sources	MDR-based optimal path	Y	-	Y	Y	-	-	EE-OLSR addresses the problem of low network lifetime.	The scheme assists in increasing network lifetime without compromising throughput, delay, and overhead performance.	EE-OLSR should be evaluated considering the RE metric as well.	Low

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
EEAODR [165] (2009)	Source-initiated-based solution	Not Specified	Hop count and link cost	Y	-	-	-	-	-	This scheme deals with issues such as high power consumption and lesser network consistency.	The scheme assists in increasing network lifetime by effectively balancing load amongst other high-rich energy nodes.	This scheme does not perform well when the energy levels of all nodes are equal. EEAODR takes much time in estimating an optimal path, since the receiver node has to wait for some time after getting its first RREQ packet.	High
ELGR [126] (2010)	Energy-aware load distribution (balancing) solution	CBR Sources	Newest, Next-hop (minimum cost)	Y	Y	-	-	-	-	ELGR deals with the decrease packet reception rate issue of greedy forwarding in unpredictable MANET environments.	ELGR scheme effectively improves the PDR performance compared to other geographical forwarding algorithms (i.e., DREAM, GPSR, GEAR).	The high complexity in estimating the forwarding and reception rate parameters is the main drawback of this scheme. Moreover, ELGR blindly assumes that each node knows its location information, which is not fair to assume in such a constantly changing MANET environment.	High
OLSR_EA [43] (2011)	Link-state-based solution	CBR Sources	Newest, Next-hop (composite power cost)	Y	Y	-	-	-	Y	OLSR_EA addresses the problem of low network lifetime.	OLSR_EA effectively uses the auto-regressive integrated moving average time-series method to measure and predict the per interval energy consumption.	OLSR_EA scheme is not scalable enough in a high dense network environment, since collision and interferences significantly hamper its QoS performance.	High
Sharma et al. [17] (2012)	Network Layer	Not Specified	Quality-value-based path cost	Y	-	-	-	-	-	This scheme deals with the issue of high power consumption during the transmission, reception, idle, and sleep states.	The scheme significantly assists in managing unnecessary power consumption in the network.	The scheme is specially designed for a special WSN environment. The scheme has been evaluated over low mobility scenarios. Hence, the applicability of the evaluated results is highly limited.	High

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
Lu and Zhu [146] (2013)	Energy-aware Multicasting solution	Not Specified	Quality-value-based path cost	-	Y	-	-	-	Y	The scheme assists in resolving the QoS multi-cast forwarding issue.	The scheme shows its effectiveness and efficiency in terms of convergence performance, success ratio, and running time, compared to the least delay multicast tree algorithm.	It does not consider shared multi-casting trees and it focuses completely on source-based forwarding trees.	Low
MMQARP [130] (2014)	Energy-aware load distribution (balancing) solution	CBR Sources	QoS parameters, such as path reliability, link delay, and energy constraint-based path estimation.	Y	-	-	-	-	Y	MMQARP addresses the problem that conventional forwarding strategies pose to energy-aware and reliable paths.	MMQARP estimates multiple paths by considering path reliability, link delay, and energy constraint as QoS parameters. MMQARP, with the help of these QoS-based parameters, estimate multiple node disjointed paths and accordingly balance the load effectively.	MMQARP suffers from the problem of high routing overhead in the network. Additionally, MMQARP is not able to offer good QoS demands to the user in the case of lower mobility scenarios.	High
ELBRP [122] (2015)	Network Layer	CBR Sources	RREQ delaying based path estimation	Y	-	Y	-	-	Y	ELBRP addresses the problem of conventional forwarding strategies to not offer energy-aware and reliable paths.	ELBRP’s RREQ delaying mechanism significantly assists by guaranteeing that only those nodes will participate in route discovery, which will have a significant amount of power.	ELBRP’s abrupt energy-level-based classification scheme leads to the problem of unbalanced energy-levels in the network. Subsequently, this greatly increases the probability of network partitioning.	Low
ECAO [157] (2016)	Link-state-based solution	Not Specified	Newest, Next-hop (power cost)	-	-	-	-	-	-	ECAO addresses the problem of conventional forwarding strategies to not offer energy-aware paths.	ECAO assists in improving the network’s lifetime.	ECAO has the problem of unbalanced energy levels in the network. Subsequently, this greatly increases the probability of network partitioning.	High

Table 5. *Cont.*

Protocol (Year)	Solution Type	Traffic Pattern	Path Metric	Factors Considered						Problem to Address	Advantages	Disadvantages	CO/NO
				NE				NC	ND				
				RE	TE	NO	IL						
Sharma and Kumar [19] (2017) Sharma et al. [22] (2018)	Energy-aware load distribution solution (Network/MAC/Physical layer solution)	CBR Sources	RREQ delaying-based path estimation	Y	-	Y	Y	Y	Y	These schemes address the problem of conventional forwarding strategies in that they do not offer energy-aware and reliable paths. Additionally, these schemes address the problem of ELBRP's abrupt energy-level-based classification scheme.	The RREQ delaying mechanism significantly assists these schemes by guaranteeing that only those nodes with a significant amount of power will participate in route discovery. Moreover, the schemes' adaptive fuzzy-based energy level classification scheme further assists in managing proper energy-level balancing in the network.	These schemes typically require additive synchronization, during the high danger phase state of a node, which further introduces complexity and overhead in the system.	High
Jabbar et al. [21] (2017)	Energy and Mobility aware multi-path load balancing Link-state solution	CBR Sources	RE and mobility conscious stable links	Y	-	-	-	-	Y	This scheme deals with the issue of not taking mobility into consideration while designing the power-aware schemes.	The scheme works significantly fine in comparison to traditional OLSR protocols by choosing more stabilized forwarding links.	The scheme can be modified and requires extensive evaluation in a dense and heterogeneous network environment. Hence, the applicability of the evaluated results is highly limited. Extensive evaluation regarding normalized routing and MAC load is required for this scheme.	Low
EELAM [153] (2019)	Multicast route discovery-based solution	CBR Sources	Not Specified	Y	-	-	-	-	-	This scheme deals with the issue of choosing sub-optimal relaying nodes in terms of RE and energy usage.	This scheme plays a vital role in terms of selecting optimal intermediate nodes with maximal residual energy and minimal energy usage. EELAM is the best route discovery approach in its category because the process and the methods adopted are contemporary.	EELAM has been evaluated over a low mobility scenario. Hence, the applicability of the evaluated results is highly limited. The energy required for data transmission, reception, overhearing, and sleep, which also consume a significant amount of power, had not been considered at all.	Low

NE: Node Energy; RE: Remaining Energy; TE: Transmission Energy; NO: Node Overhearing; IL: Idle Listening; NC: Network Congestion; ND: Network Delay; CO/NO: Communication Overhead/Network Overhead.

5. Challenges and Future Research Directions

Although a large amount of work has been completed on energy-efficient optimization techniques in MANETs, there are still some challenges that need to be addresses.

5.1. Challenges

Hereafter, we present the main research challenges, as shown in Table 6, in energy-efficient optimization for MANETs.

Table 6. Challenges in the development of energy-efficient optimization solutions for MANETs and their solutions.

Challenge in the Development of Energy-Aware Optimization Solutions/Goal	Solution	Reasons
A wireless transmission among a couple of terminals is considered as interference in other terminals. Close terminals relay the overhearing information without gains. **Goal:** To improve the performance of MANETs in the MAC layer.	Design of Cooperative MAC protocols for MANETs	• Cooperative transmission can utilize close terminals to relay the overhearing information and obtain a variety of gains. • A CMAC protocol exploits the medium access layer interactions and signaling overhead due to cooperation.
Conventional prediction methods are based only on the past locations of the node and they are ineffective for setting up a routing path with longevity. **Goal:** To set up a routing path with much longevity. This goal requires the prediction of the location of nodes based on the temporal and spatial characteristics (about its node's neighborhood).	Multipath routing based on hybrid modeling	• New hybrid methods are based on the temporal and spatial characteristics concerning its node's neighborhood. • Such a routing protocol is based on predicted node positions. Heuristic methods can use soft computing approaches, such as ML algorithms, to predict the future location of nodes.
In a multicast on-demand routing protocol, a method to select optimal multiple routes to a set of destinations is required. **Goal:** To improve the performance of multicast routing protocols.	Fuzzy-logic support in multicast routing	• A fuzzy set of rules can be used for selecting optimal multiple routes to a set of destinations. Such rules can be based on available network bandwidth, route stability, and node-to-node delay. • Fuzzy-logic support can be adopted in a cross-layer design.

(1) Design of Cooperative MAC protocols for MANETs: Using cooperative transmission, the performance of an ad hoc network can be improved [225]. Cooperative Communication (CC) [226] is a capable method that utilizes close terminals to relay the overhearing information to obtain a variety of gains. Traditionally, a wireless transmission among a couple of terminals is considered as interference in other (third) terminals. In CC, third terminals can receive and process this wireless transmission for performance gains. The broadcast nature of the wireless channel is also exploited cooperatively. However, to cope with the complex medium access interactions made by relaying and influencing the advantages of such cooperation, we must design capable Cooperative MAC (CMAC) protocols. The CMAC protocols must consider the medium access layer interactions and signaling overhead due to cooperation. Otherwise, the performance gain through the PHY layer cooperation may not improve end-to-end performance. Wang and Li [225] suggested a cross-layer distributed energy-adaptive location-based CMAC protocol (DEL-CMAC) for MANETs. DEL-CMAC improves the performance of MANETs in terms of network

lifetime and energy efficiency. Akande and Salleh [227] proposed another CMAC protocol for MANETs called network Lifetime Extension-Aware CMAC (LEA-CMAC). The LEA-CMAC protocol enhances network performance through cooperative transmission to complete a multi-objective target orientation. To accomplish a multi-objective target-oriented CMAC protocol, the authors formulated the optimization problem to extend the network lifetime. They considered symmetric and asymmetric transmit power rules. In particular, they suggested a distributed relay selection process to choose the finest retransmitting node among the qualified relays. This selection process takes into account the transmit power of the node, the sufficient residual energy after cooperation, and a high cooperative gain. The LEA-CMAC protocol can obtain a multi-objective target orientation by exploiting an asymmetric transmit power rule to improve the network performance. Recently, Su et al. [228] have suggested a reinforcement learning-based (e.g., Q-Learning) relay selection scheme without considering any prior information and network models. The suggested scheme has been extensively evaluated over parameters, such as system capacity, power consumption, and outage probability. Their widespread evaluated results show that the performance of the suggested scheme is better than other approaches in terms of the abovementioned parameters. As was mentioned previously, unplanned energy conservation methods decrease the node's lifetime and deface the consistency of packet flows. This results in a tradeoff between network throughput and node energy, resulting in post-network failure. The post-network failure results in limited Time to Live (TTL) values of the nodes and retarded network throughput with higher control overhead. To bridge the gap between network throughput and energy conservation under limited control overhead, Yamini et al. [229] proposed a Transition State supporting cooperative MAC broadcast (TSMP) protocol for both conserving node energy and to utilize available nodes efficiently before their energy drain. The TSMP protocol reduces the total energy consumption to a maximum extent of 14–21% higher than the Dynamic Power Consumption MAC protocol (DPCMP) and 24–33% higher than the Static Power Consumption MAC protocol (SPCMP). Comparatively, the routing overhead falls almost 45–52% higher than SPCMP and 27–31% higher than DPCMP.

(2) Multipath routing based on hybrid modeling: Multipath routing schemes can be based on predicted nodes positions. New hybrid methods are required for estimating the node location. Indeed, to set up a routing path with much longevity, it is supportive to have a routing protocol that is based on predicted node positions. Most conventional prediction methods are based only on the past locations of the node. New hybrid methods are required that will be based on the temporal and spatial characteristics concerning the node's neighborhood. Heuristic methods can use soft computing approaches to predict the locations of nodes. Precisely, machine learning (ML) algorithms can be trained by using features extracted from mobility patterns. The future locations of the node can be obtained by using this ML predictor. For instance, Ghouti et al. [230] proposed a mobility prediction based on an extreme learning machine. Every node knows its position, direction of movement, and velocity. Future node positions, velocity, and movement can be predicted. Based on the predicted future distances, the routing protocol is adjusted to choose the next hop. The effectiveness of the method depends on the training volume. At each node, the mobility is predicted using past information and it involves a lot of cost in exchanging this information to neighbor nodes. Recently, Farheen and Jain [231] suggested a multipath routing protocol that uses estimated probability locations with path diversion at required places along the path for improving routing performance without bigger packet overhead.

(3) Fuzzy-logic support in multicast routing protocols: Multicast on-demand routing protocols use tables for selecting optimal multiple routes to a set of destination nodes. A fuzzy set of rules can be used for this purpose. The integration of the cross-layer design idea with fuzzy-logic support can enhance the performance of multicast routing protocols. In this direction, Sivakumar et al. [232] proposed the Cross-layer optimized Multicast Route finding Protocol (C-MRP), integrated with a light fuzzy-logic set of rules for selecting optimal multiple routes to a set of destination nodes based on available network

bandwidth, route stability, and node-to-node delay. Experimental results demonstrated that C-MRP outperforms other multicast routing protocols in all characteristics.

5.2. Future Directions

- Modeling Optimizations: In MANETs, flooding strategies such as Multi-Point Relays (MPRs) flooding can enhance the efficiency of routing protocols for MANETs in terms of energy and time consumption through the use of an energy-aware mechanism. Indeed, an energy-aware mechanism is required to control the flooding process in MANETs when route discovery is performed. Such an energy-aware mechanism (called Energy Aware Flooding) was proposed in [233]. It is noteworthy that this mechanism also improves the security of routing schemes to avoid Denial-of-Service (DOS) flooding attacks in MANETs. Creating and testing new mathematical models for flooding techniques, those mainly working under well-established power-efficient routing schemes will be very challenging and promising [234]. This direction will help researchers to propose new energy-aware flooding mechanisms in MANETs.
- Hybrid optimization algorithms for topology management in cluster-based MANETs. In cluster-based MANETs, new optimization algorithms are required for making effective clustering and adjusting power and energy parameters using topology management. The management of the network topology demands the construction of a graph that is equivalent to the real network. After that, the optimization algorithm will perform the clustering of this graph to make an optimal CH. To adjust power, the optimization algorithm can be based on an objective function that considers some factors that involve power, connectivity, mobility, link lifetime, and distance. An example of such an optimization algorithm is the Chronological-Earth Worm optimization Algorithm (C-EWA) [11] that does effective clustering and adjusts power and energy parameters using topology management. In MANETs, the regular re-clustering of nodes is required, but this process generates a network overhead (overload). To reduce this overload, Sharifi and Babamir [235] presented a clustering method that optimizes energy consumption in routing. The authors proposed a method called Imperialist Competitive Algorithm (ICA) that is based on evolutionary algorithms. ICA via numerical coding can find proper CHs. By estimating the mobility direction of nodes, it prevents the additional re-clustering of nodes. As a result, it reduces the overload generated from the re-clustering process. In ICA, a fitness function is used that accepts various parameters (e.g., battery power, network range, node degree, node velocity, and coverage rate of nodes) as inputs to increase the efficiency of routing. The authors validated the accuracy and reliability of their method using statistical tests and three sample case studies, including different numbers of nodes and ranges.
- Energy-efficient routing based on Learning Automata (LA): The LA theory can be used for improving the performance of energy-efficient routing protocols for MANETs. A learning automaton is a machine learning algorithm that selects its current action based on past experiences from the environment. Recently, based on the LA theory, Hao et al. [236] suggested a stable and energy-efficient routing algorithm for MANETs. First, they constructed a novel node stability measurement model and defined a successful energy ratio function. On that starting point, they gave the node a weighted value, used as the iteration parameter for LA. After that, the authors developed an LA theory-based feedback mechanism for the MANET environment to optimize the selection of available routes and to verify the convergence of their algorithm. The experiments showed that the suggested LA-based routing algorithm obtained the best performance in route survival time, energy balance, energy consumption, and satisfactory performance in end-to-end delay and PDR.
- Energy-Efficient Routing Mechanisms for Cloud-Assisted MANETs: In 5G networks, the Device-to-Device (D2D) communication has increased the rate of data transmission among mobile nodes.

A Cloud-Assisted MANET enhances the features of a MANET by joining it with cloud data centers and D2D communication. In a CA-MANET, cloud and MANET are formed in an overlay, while the MANET accesses the data centers of cloud servers via the super-peer nodes. Peer nodes are the mobile devices that are connected directly or indirectly within the MANET. Due to various causes (e.g., link failure, mobility, routing overhead, and even low battery power), the connection among the mobile nodes and peer nodes often renew. During this time, CA-MANET consumes a large amount of energy in seeking and connecting the mobile nodes. Therefore, in CA-MANETs, we must propose new energy-efficient routing mechanisms that will perform fast local route discovery between mobile nodes and peer nodes to minimize energy consumption. Such a scheme was proposed recently in [14].

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Abbreviations

AD-TDMA: Adaptive and Distributed TDMA; AMC: Adaptive Modulation and Coding; AODV: Ad Hoc On-Demand Distance Vector; AODV_RR: AODV Range Routing; AOMDV: Ad Hoc On Demand Multipath Distance Vector; AOMR-LM: Ad Hoc On Demand Multipath Routing with Life Maximization; CEER: Color-theory based Energy-Efficient Routing; CH: Cluster-Head; CL: Cross-layer; CLD: Cross-Layer Design; CLI: Cross-Layer Interaction; CLSP: Cross-Layer Scheduling Protocol; CR: Cognitive Radio; CSI: Channel State Information; DARPA: Defense Advanced Research Projects Agency; DSDV: Destination-Sequenced Distance Vector; DMP_EOLSR: Disjointed Multi-Path Routing Extended OLSR; DSR: Dynamic Source Routing; EAR: Energy Aware Routing; EELAM: Energy Efficient Lifetime Aware Multicast route selection strategy; ELBRP: Energy-Level Based Routing Protocol; ELGR: Energy-efficiency and Load-balanced Geographic Routing; EPAR: Efficient Power Aware Routing; ESAS: Energy-Spectrum-Aware Scheduling; ESDSR: Energy Saving DSR; FANET: Flying Ad hoc Network; FAR: Flow Augmentation and Redirection; FF-AOMDV: Ad Hoc On Demand Multipath Distance Vector with the Fitness Function; GPS: Global Positioning System; GPSR: Greedy Perimeter Stateless Routing; HCN: Host-Centric Networking; LAER: Link-stability and Energy-aware Routing protocol; LAR: Location Aided Routing; LEAR: Local Energy-aware Routing; LEARN: Localized Energy-Aware Restricted Neighborhood; LEER: Location-aided Energy-Efficient Routing; LMT: Lifetime-aware Multicast Tree; MAC: Medium Access Control; MANET: Mobile Ad hoc Network; MDR: Minimum Drain Rate; MTPR: Minimum Transmission Power Routing; MEA-DSR: Multipath and Energy-Aware on-Demand Source Routing; MECOR: Minimal Energy Consumption with Optimized Routing; MILP: Mixed Integer Linear Programming; MIMO: Multiple-Input Multiple-Output; MPF-MH: Modified Proportional Fairness model with Multi-Hop; MP-OLSR: Multi-Path OLSR; OFDM: Orthogonal Frequency Division Multiplexing; OLSR: Optimized Link State Routing; OMM: On-line Max–Min scheme; PAMAS: Power Aware Multi-Access protocol with Signaling; PEERMR: Predictive Energy-Efficient and Reliable Multicast Routing; PEMA: Predictive Energy-efficient Multicast Algorithm; PHAODV: Power-aware Heterogeneous AODV; PLR: Packet Loss Ratio; PSO: Particle Swarm Optimization; QoS: Quality of Service; QoE: Quality of Experience; RERMR: Residual-Energy-based Reliable Multicast Routing; RI-MAC: Receiver-Initiated MAC; RSS: Received Signal Strength; SINR: Signal-to-Interference-and-Noise Ratio; SLPR: Serial Linear Programming Rounding; S-MAC: Sensor-MAC; TORA: Temporally-Ordered Routing Algorithm; TDMA: Time Division Multiple Access; T-MAC: Timeout-MAC; VANET: Vehicular Ad hoc Network; WEEM: Weight-based Energy-Efficient Multicasting; WMSN: Wireless Multimedia Sensor Network; WSN: Wireless Sensor Network; ZCG: Zone-based routing with a parallel Collision-Guided broadcasting protocol.

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Review

Survey on Routing Protocols for Vehicular Ad Hoc Networks Based on Multimetrics

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Abstract: In the last few years, many routing protocols have been proposed for vehicular ad hoc networks (VANETs) because of their specific characteristics. Protocols that use several metrics have been shown to be the most adequate to VANETs due to their effectiveness in dealing with dynamic environment changes due to vehicle mobility. Metrics such as distance, density, link stability, speed, and position were selected by the authors for the best proposal. Several surveys of routing proposals have been generated to categorize contributions and their application scenarios, but none of them focused on multimetric approaches. In this paper, we present a review of the routing protocols based on more than one metric to select the best route in a VANET. The main objective of this research was to present the contemporary most frequently used metrics in the different proposals and their application scenarios. This review helps in the selection protocols or the creation of metrics when a new protocol is designed.This survey of multimetric VANET routing protocols employed systematic literature-review (SLR) methodology in four well-knownown databases that allowed to analyze current state-of-the-art proposals. In addition, this paper provides a description of these multimetric routing protocols. Our findings indicate that distance and speed are the most popular and versatile metrics. Finally, we define some possible directions for future research related to the use of this class of protocols.

Keywords: routing protocols; intelligent transportation systems; VANETs; vehicle routing

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1. Introduction

The constant mobility of people, the increasing number of vehicles on roads, and the need for infrastructure-less communication technology for intelligent transportation systems (ITS) make vehicular ad hoc networks (VANETs) an important research topic in vehicular and wireless technologies.

Over the past few years, improvements in ITS have been focused on mitigating traffic congestion to reduce toxic emissions and fuel consumption, the enhancement of traffic safety, and offering mobile infotainment to passengers by improving on-road communication and making vehicles aware of their surroundings [1]. To achieve the main communication requirements of both safety and non-safety applications in a VANET scenario, there is a need to enhance vehicular communication and smart communications.

A VANET is a subclass of a mobile ad hoc network (MANET), in which vehicles communicate with each other and with nearby fixed roadside equipment. VANET communications include several models, such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). Figure 1 shows a typical

VANET scenario where V2I communications can be used to access location services or obtain traffic statistics. V2V could be employed to alert about emergencies or reach out of coverage nodes through multihop communication.

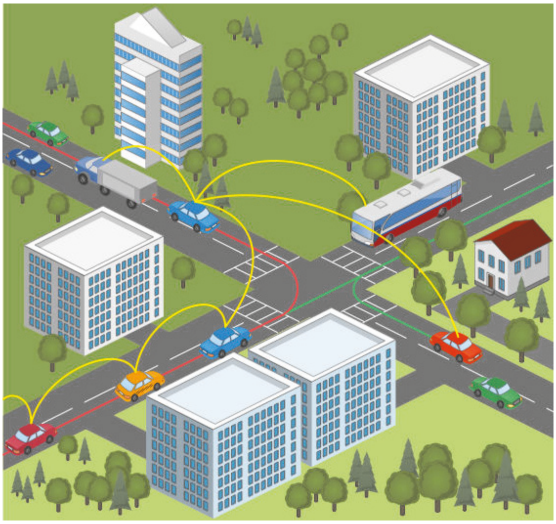


Figure 1. Example of a vehicular ad hoc network (VANET) scenario: accident-information dissemination using vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) to send data to emergencies services.

Due to rapid growth in vehicular communications, there are many studies covering all of its aspects, including channel modeling [2], appropriate scalable design of medium-access-layer (MAC) procedures [3], security and privacy policies [4], reliability and latency improvements [5], integration of VANET-LTE [6], and mainly routing protocols aiming to offer good performance and adaptability to changes in network topology.

Routing protocols are extremely important in ad hoc networks because they are responsible for initiating and maintaining routes to facilitate multi-hop communication and extend the service area of the network. Moreover, VANET routing protocols are designed for different scenarios considering the main characteristics and constraints in vehicular networks, such as mobility of nodes, interference, and bandwidth limitations. As we said, VANET has dynamic topology and, at run time, the network may support any kind of application. So, continuous research is in progress to improve routing decisions while considering the restrictions and challenging issues of VANETs [7].

VANET routing protocols can be classified according to their power-aware and predictive mobility capabilities. This classification looks to distinguish protocols with the efficient utilization of limited resources and quality-of-service (QoS) improvement. In this context, cluster-based routing protocols provide centralized control and they can be very useful to avoid saturation in very crowded networks [8]. Other protocols designed for low-latency applications based on topology or position information are presented in [9]. Finally, for reliable QoS routing, there are different approaches to obtain an optimal protocol according to different parameters [10] such as end-to-end delay [11], security, low collision, and interference [12].

Despite the different application-oriented classifications, standard criteria have been used more often to survey and classify them. Depending on if vehicles use infrastructure (e.g., RSUs) or not to forward packets to the final destination, VANET routing protocols can be categorized as V2I and V2V [8,13]. The former can be seen as a special case of V2V routing protocols, so almost no survey distinguishes between them. A typical classification of routing protocols is presented in [14] and it is based on transmission strategies in which a protocol can be unicast, multicast, broadcast, or geocast. This well-accepted classification of routing protocols was used in the survey of [7,8]. Moreover, unicast protocols were further split based on routing information in topology or position-based in [15,16], and cluster-based in [13].

According to a recent survey [17], unicast routing protocols are organized in the categories of topology, geographic, hybrid, clustering, opportunistic, and data fusion. Altayeb et al. [9] presented a routing-protocol survey with both, based on transmission strategies and routing-information classification. It is clear that the second assortment is a subclassification of unicast protocols.

Geographical routing protocols for VANETs are an important subset of unicast protocols into protocol classification based on routing information because they make their forwarding decision by using local information; therefore, this kind of protocol can react fast to frequent topology changes. As a consequence, many surveys specifically target geographical (also known as position-based) protocols in the literature. In [18], the authors explained the importance of a geographic protocol in VANETs and provided an updated survey. More specific reviews of geographical-routing proposals have been published over the years. In [19] only greedy approaches for geographical routing were presented, while [20] reviewed geographical routing for Vehicular Delay-Tolerant Networks (VDTNs) and group proposals according to the geographical knowledge needed for their operation. The traffic-aware classification of geographical-routing protocols proposed in [21] identified protocols that use surrounding information to improve communication performance.

Surveys of VANET routing protocols along years show that the forwarding criteria, especially in geographical protocols, have evolved from using only one metric to more novel proposals that employ several metrics, like vehicle speed and direction. In this paper, we concentrated on unicast routing protocols designed for VANETs using different metrics in hop-by-hop selection to improve vehicular communications. We present the principal metrics, their importance in vehicular scenarios, and which of them are selected by the proposals explained below.

The rest of this paper is organized as follows: Section 2 presents the main characteristics of VANETs that are relevant in the context of the paper. After that, Section 3 presents the systematic literature-review process used in this survey. Section 4 presents the most common metrics used by researchers in their routing protocols and their multimetric proposals. Next, Section 5 discusses our findings, and Section 6 presents conclusions.

2. VANET Characteristics

In VANETs, vehicles equipped with data wireless devices act as mobile hosts and routers for other nodes. Even though VANETs share characteristics with classical mobile ad hoc networks, such as a short transmission range, self-organization and self-management, and low bandwidth, vehicular ad hoc networks have special characteristics that distinguish them from other types of mobile ad hoc networks as follows [7,22]:

- Ability to provide continuous power: the node (vehicle) itself can, via a long-life battery, provide continuous power for computing and communication devices compared to the capabilities of typical MANET nodes.
- High computational capability: operating vehicles can use significantly higher computing, communication, and sensing capabilities compared to other mobile nodes (such as smartphones).
- Predictable mobility: vehicles have more predictable movements than typical MANET nodes. Vehicles only move over roads. Roadway information is available from positioning systems and map-based technologies. The future position of a vehicle could be estimated as a function of speed and road trajectory. The hour of the day or the specific day of the week is also a determinant parameter to predict vehicle mobility.
- Large scale: vehicular networks could cover an entire road network including many participants. Its coverage area can range from a neighborhood to an entire city. In highways, a VANET can easily reach tens of kilometers.

- High mobility: the topology created by vehicles in a VANET is extremely dynamic and includes different configurations. For instance, topology information of a vehicle that leaves an avenue to go to a residential area can dramatically change. In this regard, the density of nodes plays a very important role. If the density of vehicles is very high, as in, during rush hour, topology changes can be minimal. On the other hand, very low vehicle density, such as during week nights, leads to more changes in topology due to high mobility.
- Partitioned network: vehicular networks are frequently partitioned because of the nature of traffic. In residential and rural areas, there are intervehicle gaps because these are sparsely populated scenarios. This forms several isolated clusters of nodes.
- Various communication environments: very related to the mobility and partition ratio of VANETs are the communications environments in which they are typically operated. These scenarios can be, most of the time, highways or urban areas; the former are relatively simple and straightforward, while cities include more signal perturbations because of different types of obstacles, such as buildings, houses, and trees.
- Interaction with on-board sensors: Currently, vehicles are equipped with a good number of on-board sensors that provide information on the vehicle that can be used to make routing decisions (speed, direction) or to monitor surroundings (temperature, wind, humidity, etc.).

All these characteristics should be taken into account when designing a routing protocol or application dedicated to a vehicular network.

3. Systematic Literature Review

We developed a systematic literature-review (SLR) as suggested in [23] to guarantee replicability [24] of this survey in the future. We intend to summarize the information concerning how routing protocols based on multimetrics for VANETs make the best routing decisions. An SLR is a means of identifying, evaluating, and interpreting the available research pertinent to a particular research question, area, subject, or phenomenon of interest; it is composed of six phases: research questions, search process, inclusion and exclusion criteria, quality assessment, data collection, and data analysis.

3.1. Research Questions

According to [23], research questions we had to consider were population, intervention, comparison, and outcomes.

In our case, this survey is useful for VANET researchers who need a robust routing protocol to obtain better results in the development of new emergency- and data-interchange-focused services. More specifically, we targeted the improvement of hop-to-hop decisions in vehicular communications of multimetric routing protocols compared to prior proposals (that usually use one metric for routing decisions). The outcome of our review was to validate how the use of several metrics in a routing protocol improves the decision-making process in vehicular communication.

Based on the mentioned strategy, our Research Questions (RQ) are the following. With them, we aimed to know how important metric selection is in routing protocols for VANETs, and how multimetric use improves path selection.

1. Which are the most used metrics in routing protocols for VANETs?
2. Which combination of metrics is the most used for improved routing decisions?
3. Which are the routing protocols with the most comparatives?
4. Which network simulator is most used currently?

3.2. Search Strategy

It is necessary to determine and follow a search strategy to answer our research questions. The research sources we used were the following repositories with restricted access: IEEE, ACM, Scopus, and Science Direct. The construction of the research questions was used as a base to extract some keywords that were then used to search for primary studies. First, we had the following keywords: VANET, routing, multimetric, metrics, and protocol. Nevertheless, to obtain more specific and concrete results, we decided to link the words and use a search string to increase the number of potential pertinent studies: routing protocol VANET, metrics routing protocol VANET, and multimetric routing protocol VANET. The search covered the time period from 2005 to early 2019, but we then decided to reduce the period to 2009 to obtain better and newer results; these results are presented in Table 1. To improve the search, Boolean expressions were used, the results of which are presented in Table 2.

Table 1. Research results using search string.

Digital Libraries	IEEE	Scopus	ACM	ScienceDirect
routing protocol vanet	1316	1598	34,411	1153
metrics routing vanet	223	273	18,407	4
metrics routing protocol vanet	204	231	28,592	761
multi-metric routing protocol	47	65	52,035	75
multimetric routing protocol vanet	7	1	18,206	4

Table 2. Rresearch results using Boolean expressions.

Digital Libraries	IEEE	Scopus	ACM	ScienceDirect
"routing" and "protocol" and "VANET"	3874	7147	92	1153
"multimetric" and "routing" and "protocol" and "VANET"	19	51	7612	4
"metrics" and "routing" and "protocol" and "VANET"	1790	1365	28,592	761
"multimetrics" and "routing" and "protocol"	42	328	17,960	75
"multimetric" and "routing" and "protocol" and "VANET"	1	50	18,206	4

3.3. Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were based on the research questions. These should be taken into account to guarantee that results can be reliably interpreted and to correctly categorize studies.

We selected the following inclusion criteria to find the relevant publications that answered our research questions:

(i) Publication date 1 January 2009–1 January 2019;
(ii) new routing protocol proposal for VANET is presented; and
(iii) the routing decision was based on more than one metric.

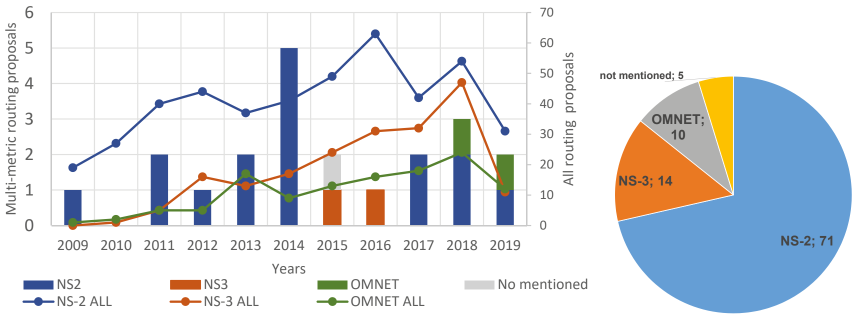
For the exclusion criteria, we used:

(i) Only already known compared protocols and
(ii) duplicated documents from the same study.

3.4. Study Quality Assessment

The first search, without any exclusion-criteria, shown in Tables 1 and 2, returned a high number of documents, several of which were duplicated. After the use of the exclusion/inclusion criteria, many documents were dismissed. All separate authors of this work individually checked the activity of searching for publications to ensure the quality of the place of publication. Quality evaluation was then separately performed to verify the obtained information. After the selection of around 100 documents, only 21 papers fulfilled the requirements of this study (e.g., publication period, new protocol proposal, more than one metrics used in the selection of forwarder nodes) and were selected in this review.

We note that the proposals were presented between 2009 and 2019 and that, between 2013 and 2018, a higher number of proposals were published (see Figure 2a. This figure also shows the simulators used by these proposals.).



(**a**) (**b**)

Figure 2. Multimetric routing protocols proposed for VANETs along time. (**a**) Bars account for multimetric routing proposals grouped by network simulator. All routing proposals for VANETs over the years are plotted in lines for different network simulators. (**b**) Distribution of network simulator that used multimetric routing proposals.

We can also observe in Figure 2b that proposals were often evaluated using NS-2, specifically, 71% of the analyzed proposals. NS-2 is a highly accepted network simulator in the research community. In comparison with other well-known network simulation tools, NS-2 has several advantages: (1) the code is open-source, research-community-accepted, and facilitates openness to modify the existing mechanism; (2) extensibility and stability; and (3) it can support large simulation scenarios where the number of nodes can be up to 20,000, making the simulation results more realistic [25]. NS-2 was one of the first simulators with these features. It is important to note that the two other simulators also share these characteristics, although they appeared after NS-2.

A summary of the whole SLR process is presented in Figure 3, from the identification of the articles in the four databases until the final selection going through the different selection filters.

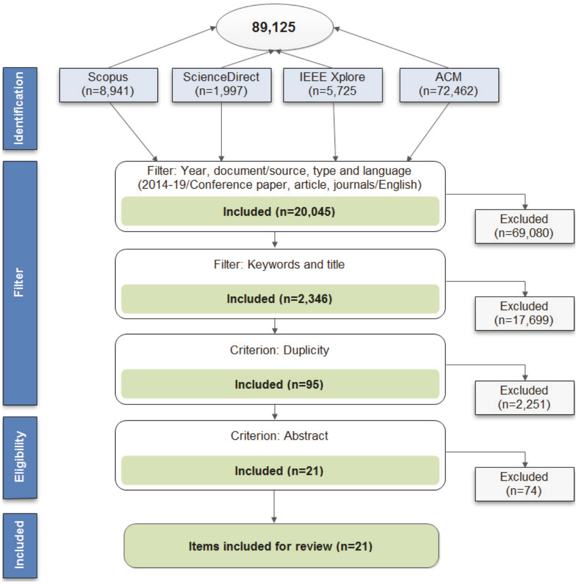


Figure 3. Systematic literature-review (SLR) selection process.

The protocols selected as relevant for this study are presented and analyzed in the following sections.

4. Routing-Protocol Proposals Based on Metrics

In this section, we summarize the selected protocols in this SLR. First, we present the metrics most commonly used in these proposals and explain their utility.

4.1. Metric-Based Routing

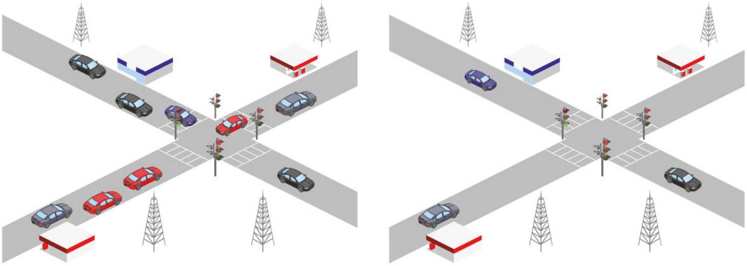
This section presents some designing factors and strategies adopted in routing protocols that consider more than one metric into the selection of the best route. This summary aims to help new researchers in the area to analyze existing routing protocols for VANETs.

Currently, there are several metrics to improve routing protocols for vehicular communications. We first explain the metrics that have global importance. This means that the values of this kind of metric provide an idea of closeness or path quality to destination.

- Minimum hop count: counting the number of hops between a source and a destination to a particular path [26].
- Distance: used to select the node that is closer to the destination as the next hop to be the best candidate node [7]. Basically, it is the distance between each candidate node and the destination node [13].
- Route cost metric (RCM): this metric was proposed in [27]. It is based on packet-delivery ratios, and also includes information on the level of link stability. Is possible to define the RCM of a link from a source to the destination vehicle by the Bellman equation.
- Packet reception rate (PRR): gives information about the efficiency of the dissemination scheme and the reliability of the data forwarding [9]. PRR is a metric highly related to the number of data losses in the network.

So-called local metrics provide information about the candidates to next forwarding nodes. They are usually employed to increase the probability of finding the next suitable hop or to recover from path-creation problems (e.g., broken links).

- Density: In order to find a reliable routing path, traffic density is a c very frequently used metric. Considering the high density in hop-by-hop selection, disconnection could be avoided. Using beacon messages, each node can analyze its own neighboring density based on the number of neighbors and include it to select a more stable route [1]. This is also called the degree of a vehicle, the number of vehicles within the transmission range [28] (see Figure 4).



(**a**) Dense scenario. (**b**) Sparse scenario.

Figure 4. Density example.

- Speed: the speed of each node helps to calculate other metrics, such as movement direction, link quality, or link lifetime. It helps to predict link breakage [18].

- Link/route lifetime: it is defined as the shortest period during which two nodes can interchange data packets in a link or route [1,22] (see Figure 5).

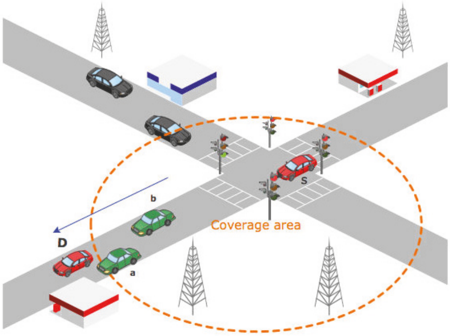


Figure 5. In this scenario node, s should select neighbor a as next hop, but even if that is not the closest to destination D, b ensures a better link lifetime than a.

A stable routing path is provided by a longer link lifetime, which results in a reduction of packet losses. Consider (x_s, y_s) and (x_i, y_i) as coordinates of source nodes s and neighbor i, with their corresponding speed given by v_s and v_i, where $v_s < v_i$. Let R be the receive range. So, the link lifetime between s and i is calculated using Equation (1).

$$L_{s,i} = R - \frac{\sqrt{(x_i - x_s)^2 + (y_i - y_s)^2}}{v_s - v_i}. \tag{1}$$

- Movement direction: the movement of vehicles is an important consideration in routing selection. If the source does not take into account the moving direction of the next possible hop, it could make the wrong forwarding decision by sending packets t vehicles that are moving against the direction of the destination [1] (see Figure 6). This is especially important if vehicles implement carry and forwarding. This means that, during the time that the vehicle carries the packet, it just moves packets away from the destination.

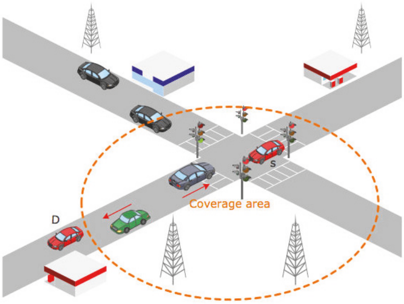


Figure 6. Node s should select the green vehicle that is moving toward destination D, thus being the node with the correct movement direction in this example.

- Link quality: select the link with the fewest neighboring transmitting vehicles, buildings, and obstructions that affect link quality between vehicles [18].

4.2. Multimetric-Routing Proposals

Some routing-protocol proposals that use more than one of the previously explained metrics are presented below, applying to a specially developed systematic literature review.

Before we begin with routing-protocol proposals based on several metrics, it is important to mention three main routing protocols for ad hoc networks in general, ad hoc on-demand distance vector (AODV) [26], greedy perimeter stateless routing (GPSR) [28], and GeoNetworking protocol [29].

On the one hand, AODV and GPSR are the base in ad hoc network routing in MANET and VANET, which is our study field. They are the most commonly compared protocols with new proposals. On the other hand, GeoNetworking is the standardization effort from ETSI for VANET routing. In this sense, GeoNetworking must be used as a baseline for future proposals.

4.2.1. AODV

AODV is a routing protocol designed for mobile ad hoc networks. It is a reactive protocol, and routes are created only when a node wants to send a packet. It uses traditional routing tables, one entry per destination, and sequence numbers to determine up-to-date routing information. AODV store the routes (source–destination) while the source requires us to send information while the connectivity between nodes is active.

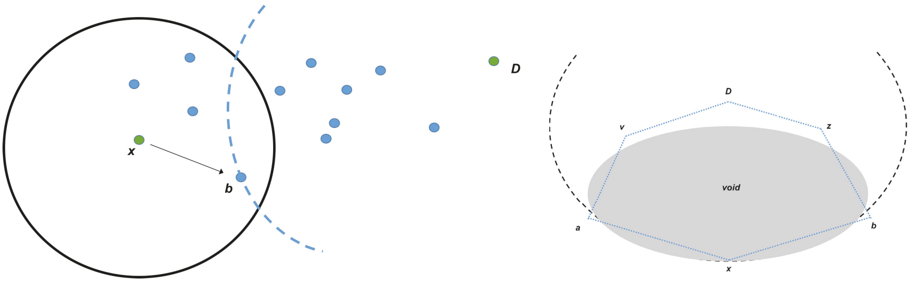
The principal stage of this protocol is route discovery, which works by the source node broadcasting route request messages (RREQ) to the other nodes to find the destination node. Route reply messages (RREP) are sent back to the RREQ source in unicast communication. The full path is formed storing information in intermediate nodes along the route in local routing tables. It also uses error messages (RERR) to notify when a communication break occurs. In this case, a new route-discovery process should begin.“Hello” messages are permanently used for detecting and monitoring connectivity with neighbors [26].

4.2.2. GPSR

GPSR [28] is an efficient routing protocol for wireless and mobile networks that exploits the geographical routing idea.

GPSR is based on two methods to forward data: greedy forwarding and perimeter forwarding. The first algorithm sends packets to the neighbor node closest to the destination, and this is used by default (see Figure 7a); the second method is selected in cases when greedy forwarding cannot be used (there is no closer node than the current one; see Figure 7b). In perimeter mode, GPSR exploits the idea of the right-hand rule to forward packets around voids where no closest neighbor is found.

In this protocol, the decision is based on the hop-by-hop rule, and it does not need end-to-end full-path establishment [11,30,31].



(**a**) (**b**)

Figure 7. Greedy perimeter stateless routing (GPSR) operation. (**a**) greedy-forwarding example. b is the x's closest neighbor to D. (**b**) In perimeter mode, node x is void with respect to destination D.

4.2.3. GeoNetworking Protocol

The GeoNetworking (GN) protocol [29] is the routing-protocol standard from the European Telecommunications Standards Institute (ETSI); therefore, it is an important geographic-routing standard. GN is a network-layer protocol that provides packet routing in ad hoc networks. It is a VANET geographic-routing protocol where packets are routed by the VANET based on the geographical position of the nodes and the position of the packet destination, assuming the use of GPS to know their location. Packets are forwarded by different intermediate nodes from origin to destination, establishing multihop communication. In the GN protocol, there are two types of main packet delivery: geo-unicast and geobroadcast. The nodes use a location table (LT) that maintains the position of its neighbors and is used to make forwarding decisions; it also has packet buffers for location-service, store-carry-and-forward, and forwarding algorithms [32]. Several evaluations have been presented in [32], where the authors evaluated the performance of six variants of GeoBroadcast forwarding algorithms in ETSI GeoNetworking; in [33], the authors analyzed the performance of the GN protocol by simulation when provided Internet access from VANETs; in [34], the authors compared the behavior of ITS-G5/802.11p-based protocols for ad hoc networks and the available cellular infrastructure, called Cellular-based Vehicular Communication Systems (Cellular-VCS).

Now, we present the routing protocols designed for VANETs that use more than one routing metric.

4.2.4. Analytical Hierarchical Process (AHP)-Based Multimetric Geographical-Routing Protocol (AMGRP)

AMGRP [35] is an efficient routing protocol that considers multiple metrics, such as link lifetime, mobility, density, and node status under an AHP to obtain good protocol performance.

The forwarding decision in this proposal is very dependent on the use of mobility metrics such as distance, speed, and moving direction. This protocol assumes that each node knows its position and the position of the destination. This is important to prevent making wrong forwarding decisions by sending packets to vehicles that are moving against the destination direction. Suppose source vehicle s is at (x_0, y_0), the destination node is at (x_d, y_d), and neighbor vehicle i is at (x_i, y_i); then, the moving angle between source and neighbor i toward destination d can be obtained as shown in Equation (2):

$$A_{s,i}^{(d)} = arccos\frac{(x_d - x_0)(x_i - x_0) + (y_d - y_0)(y_i - y_0)}{\sqrt{(x_d - x_0)^2 + y_d - y_0{}^2}\sqrt{(x_i - x_0)^2 + y_i - y_0{}^2}}. \tag{2}$$

The second metric (link lifetime) is calculated as in Equation (3), where R is the radio range, (x_s, y_s) and (x_i, y_i) are the source and neighbor location, respectively, and v are the velocities.

$$L_{s,i} = \frac{\sqrt{(x_i - x_s)^2 + (y_i - y_s)^2}}{v_s - v_i}. \tag{3}$$

If the queue length is small, the node could be congested because more data packets need to be processed. Before selecting the next hop, node status is obtained by calculating the buffer capacity $(Q_i(t))$ and can be calculated as follows:

$$Q_i^{(t)} = \frac{Q_{max} - Q_i^{(t)}}{Q_{max}}, \tag{4}$$

where Q_{max} gives the maximum buffer size. $Q_i^{(t)}$ is defined as the number of packets in the buffer queue at time t [35]. Density is also computed to minimize the local maximum; using the hello packet, each node calculates node density to select paths with a high number of vehicles and avoid intermittent connectivity.

Between each metric, there is a relative ranking, with the mobility metric as the most important criterion, node density as the second most important, node status as the third, and finally link lifetime as the least important criterion, as we can see in the values of Table 3. It is important to observe that the mobility metric has higher priority and an important role in the decision of the next-hop selection, in contrast with link lifetime that is least important among the four metrics included in decision criteria. Finally, a total score is assigned to each neighbor from the neighbor list considering the relative weights for the deciding factors to establish an optimal multihop routing path selecting an efficient forwarding node; a difference between path selection in AMGRP and GPRS is shown in Figure 8.

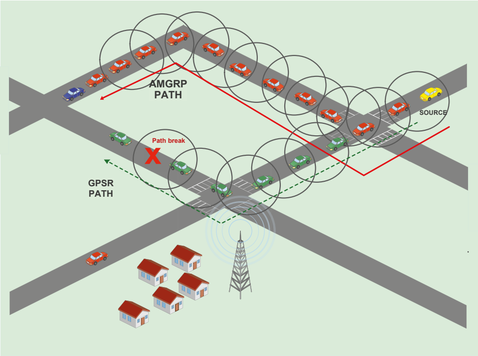


Figure 8. Path considered by source in analytical hierarchical process (AHP)-based multimetric geographical-routing protocol (AMGRP) and in GPSR to reach destination [35].

Table 3. Relative ranking of criteria.

Metric	Value
Mobility metric	0.413846
Node density	0.256923
Node status	0.216923
Link lifetime	0.112308

4.2.5. AODV with Predicting Node Trend (AODV-PNT)

AODV-PNT is a novel routing protocol proposed in [36], suitable for vehicular networks, which considers VANET topology features. It is an enhanced version of AODV. This proposal includes two main changes: the routing metric improvements and the estimation of the total weight of the route (TWR). This TWR includes analysis of movement direction, acceleration, vehicle speed, and link quality. Due to frequent topology changes, future TWR was included where it was attempted to calculate a relatively stable relay vehicle over a lapse of time in the future.

The authors calculated the TWR from a source node to the next hop, as shown in Equation (5).

$$TWR = f_s \times |S_n - S_d| + f_a \times |A_n - A_d| + f_d \times |\theta_n - \theta_d| + f_q \times Q, \tag{5}$$

where,

- θ_n, S_n, A_n: Direction, next-hop node's speed and acceleration.
- θ_d, S_d, A_d: Direction, destination node's speed and acceleration.
- f_s: Speed weight factor.
- f_a: Acceleration weight factor.
- f_d: Direction weight factor.
- f_q: Link-quality weight factor.
- Q: Link quality between source and next-hop vehicle.

Note that the TWR is defined by differences of link quality, speed, direction, and acceleration. The next-hop node is best with the least TWR and similar acceleration, speed, and direction compared to the destination vehicle and sound link quality between source node and next-hop node, as shown in [36].

4.2.6. AODV with Multi-RREP (AODV-MR)

A new scalable routing scheme, AODV-MR, was proposed in [27]. This proposal focused on link reliability and stability using an anycast approach. To find an optimal and suboptimal path, it uses a combination of route cost metric (RCM) and minimum hop count, and includes the carry and forwarding mechanisms to deal with broken routes.

RCM calculation of a source–destination link is defined by the Bellman Equation (6):

$$RCM = C_{sj} + C_j, \tag{6}$$

where C_{sj} is a cost of a hyperlink (s, j); s is the vehicle source, and j is a set of hyperlinks. The remaining any-path cost from j to destination node is C_j.

4.2.7. Named Data VANET Protocol (NVP)

NVP was presented in [37], a novel routing protocol for VANET based on the named data network (NDN). The authors enhanced the routing path by using a new distance metric in the protocol, preventing the shortcomings of the hop-count-based metric. It also uses an incremental and adaptive broadcast strategy according to vehicle density.

The authors propose a novel transmission-cost-estimation method as follows (Equation (7)):

$$Cost = \begin{cases} (\frac{seqnum_t - seqnum_{t-w}}{count(t-w,t)}) & ,count(t-w,t) \neq 0 \\ \infty & ,count(t-w,t) = 0 \end{cases} \tag{7}$$

Seemingly, the higher the value of the transmission cost is, the worse the link quality is. Due to that, this metric can more accurately calculate link quality between communication nodes compared to the minimum hop-count metric [37]. Taking into account the scenario in Figure 9, we can notice vehicles between the source (s) and destination (D); A, B, and C are the forwarding nodes. However, even when A has the lowest number of hops, that route is not considered due to the block of the building causing packet losses. So path B–C–D was established because it offers better link quality.

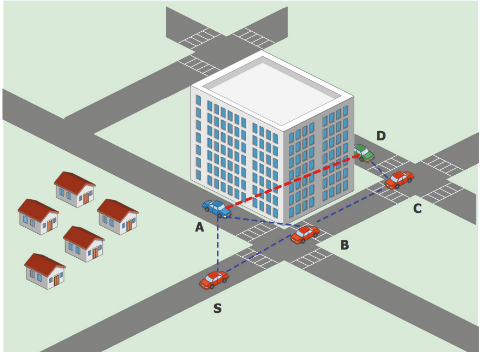


Figure 9. Hop-count-based metric without line of sight (LOS) [37].

Another improvement is the dynamic adjustment of backoff time according to vehicle density due to scenarios in a VANET. The authors separated the scenarios into three categories based on vehicle density: sparse ($0 < N <= 4$), normal ($4 < N <= 7$), and dense ($N > 7$). The new back-off time could be calculated with the following equation:

$$wait\_time = factor * max(0, d - (dstDist - j)). \tag{8}$$

In Equation (8), factor represents a waiting factor; $dstDist$ represents transmission cost between source and destination. Finally, the authors found the optimal waiting factors of 2.4, 3.6, and 5 in sparse, normal, and dense conditions, respectively.

To evaluate the proposal, virtual urban scenario V-city was designed to generate real-world traffic and set up a coordinative testbed integrating SUMO with NS-3. Simulation results indicated that the proposed protocol was more appropriate for VANET scenarios than AODV.

4.2.8. Multimetric Unicast Data-Dissemination Scheme (MUDDS)

Two important problems were identified in VANETs due to the frequent changes of topology, broadcasting storm (due to high density) and network disconnection (due to velocity). MUDDS was proposed in [38], a new protocol that uses link availability (LA), based on distance, which guarantees fewer hops; and packet reception rate (PRR), which guarantees reliability.

PRR is calculated as shown in Equation (9), where N_s is the quantity of successfully received packets, N_t is the total number of sent packets, and N_l is the number of losses. These lost packets are many due to collisions that can take place in the network. When the network is close to its saturation, the number of collisions increases.

$$PRR = \frac{N_s}{N_t} = \frac{N_t - N_l}{N_t}. \tag{9}$$

The LA was evaluated as shown in Equation (10), where $distance_i$ is the space between actual node and selected forwarder, t_i is the duration of link availability, T total time, and R the maximum achievable transmission range. This metric considers $link\, availability\, rate(l,t) = \frac{t_i}{T}$ as an indicator of link state and link length (distance between sender and possible forwarder). This metric goal is to minimize network-disconnection problems.

$$\begin{aligned} LA_i \quad &= distance_i \times availability\, rate_i = \tfrac{distance_i \times t_i}{T} \\ &0 \leq distance_i \leq R \\ &0 \leq t_i \leq R \end{aligned} \tag{10}$$

4.2.9. Multimetric Opportunistic Routing (MMOR)

In [39], MMOR was presented, which included multimetrics in the selection of the best opportunistic next forward. To choose the forwarding candidate, it takes into account the distance to the destination, the load of the node, moving direction, velocity, and density. These parameters are key metrics in this proposal when the candidate for the next hop is selected.

After calculating each metric value, the opportunistic forward decision can be computed with these values, combined by Equation (11).

$$Opp(N_i) = \Sigma_{i=1}^{5} U_i \tag{11}$$

The $Opp(N_i)$ decides each node's priority. The node with the highest value among the candidates is selected as the best opportunistic forwarding node.

4.2.10. Multimedia Multimetric Map-Aware Routing Protocol (3MRP)

One of the most important applications in VANETs is the efficient management of accidents. When an accident occurs, a vehicle could transmit a short video about the situation through the VANET and alert the emergencies services or other vehicles in the area. In this context in [10], the proposal was an effective routing protocol to operate video-reporting messages in vehicular ad hoc networks; the proposal provides video-reporting messages over VANETs in smart cities, and is called the multimedia multimetric map-aware routing protocol (3MRP). The proposal included five metrics to improve the selection of the best routing path, distance, density, trajectory, available bandwidth estimation, and MAC losses.

When a sender vehicle receives hello messages (HM) from its neighbors in transmission range, the node updates its neighbors' list with all those vehicles in line of sight (LOS), only considering the neighbors that sent their HM with enough power. Then, the source evaluates and assigns a total multimetric score to each neighbor as a possible candidate for the next forwarding node. As a first step, the authors considered the same weights (w_1, w_2, w_3, w_4, w_5) to each metric ($u_{dst,N_{gh}}$, $u_{trj,N_{gh}}$, $u_{dns,N_{gh}}$, $u_{abe,N_{gh}}$, $u_{los,N_{gh}}$), respectively, in the multimetric score $\overline{u}_{N_{gh}}$ of each neighbor N_{gh}. Finally, a multimetric score was obtained for each candidate node using Equation (12). The final quantification varied between 0 and 5. The neighbor with the highest multimetric value is selected as the best next forwarding node.

As mentioned before, the authors first considered the same rank of importance to all the used metrics, i.e., $w_i = 1/5, 1 \leq i \leq 5$; as the next improvement, the authors proposed to dynamically actualize the scores of the candidate neighbor vehicles using an algorithm to calculate the self-configured weights of the metrics.

$$\begin{aligned} \overline{u}_{N_{gh}} \quad &= \textstyle\sum_{i=1}^{5} u_{i,N_{gh}} \cdot w_i = u_{dst,N_{gh}} \cdot w_1 + \\ &u_{trj,N_{gh}} \cdot w_2 + u_{dns,N_{gh}} \cdot w_3 + \\ &u_{abe,N_{gh}} \cdot w_4 + u_{los,N_{gh}} \cdot w_5 \end{aligned} \quad . \tag{12}$$

4.2.11. Fuzzy-Control-Based AODV Routing (FCAR)

The basic idea of FCAR [40] is to use the percentage of same-directional vehicles and route lifetime as a routing metric to evaluate a path using the method of fuzzy logic and fuzzy control to make routing decisions under multiple selection criteria. The proposal ensures that the route has better stability and is not easily broken.

The basic idea is made up of a series of "$if - then$" as conditional declarations. The precursor of the conditional statement is the input, and the consequent is the output. The rule base is very important for the fuzzy-control system; in [40], the authors obtained it through simulation by a mass of tests and adjustments.

Table 4 shows the corresponding six values of the two inputs, there are $3^2 = 9$ rules (R1...R9). From the fuzzy membership functions, only four out of the nine were in simultaneous operation.

4.2.12. Multimetric Next-Hop Vehicle Selection for Geocasting in Vehicular Ad-Hoc Networks

Multimetric next hop vehicle selection for geocasting in VANETs was presented in [41]. The authors proposed to choose an optimal next-hop vehicle (ONHV) based on various metrics divided into link-based and node-based metrics. The link-based metrics were link delay, link jitter, and link lifetime; the node-based metrics were velocity and degree. The metrics were individually evaluated, and objective function OF_i was then calculated for every i^{th} (node) in the routing table. The OF was calculated as shown in Equation (13).

$$OF_i = Max(w_1 * link_{lifetime} + w_2 * link_{delay} + w_3 * link_{jitter}) \tag{13}$$

where w_1, w_2 and w_3 are weighing factors for corresponding link metrics that act as tuneable parameters for application and $\sum_{i=1}^{3} w_i$=1, the node with highest OF as ONHV.

Table 4. Rule base for fuzzy-control-based ad hoc on-demand distance vector (AODV) routing (FCAR) protocol [40].

	Route Lifetime (Input)	**Percentage of Same-Directional Vehicles (Input)**	**Route Select Probability (Output)**
R1	Short	Low	Weakest
R2	Medium	Low	Weakest
R3	Long	Low	Weak
R4	Short	Medium	Weakest
R5	Medium	Medium	Weak
R6	Long	Medium	Normal
R7	Short	High	Normal
R8	Medium	High	Strong
R9	Long	High	Strongest

4.2.13. Reactive Routing Protocol for VANETs (RRPV)

RRPV [12] was proposed based on the idea of combined metrics as direct-connection reliability, hop count, and cochannel noise. With this selection, it tries to choose an appropriate path which minimizes interference.

When top-count HP, average best cochannel noise $BEST_{CCN}$, and average reliability-probability $DCRP_{path}$, then the RRPV metric has to be adequately defined as a multiobjective function, as shown in Equation (14).

$$m_{RRPV}(p) = \beta_1 \cdot m_{HC}(p) + \beta_2 \cdot m_{CCN}(p) + \beta_3 \cdot m_{DCRP}(p) \tag{14}$$

where p is a considered route, and m_{HC}, m_{CCN}, and m_{DCRP} are three normalized related terms that can be expressed as follows:

$$\begin{aligned} m_{RRPV}(p) = \quad & \beta_1 \frac{BEST_{CCN}(p)}{CCN_{MAX}} + \beta_2 \frac{HC(p)}{HC_{MAX}} + \\ & \beta_3 \left(1 - \frac{DCRP(p)}{DCRP_{MAX}}\right) \end{aligned} \quad , \tag{15}$$

where terms in the metric have been normalized in order to be comparable. At this moment, when node v_i has to select among different routes to a destination, the choice of the best path is made by minimizing the following value:

$$m_{RRPV}(p^*) = \min_p [m_{RRPV}(p)]. \tag{16}$$

The proposal establishes a time of 60 ms as parameter to update the period of calculation of the metric to select the next hop due to high speed and topology changes. This value is optimal in order to guarantee a correct path refresh.

4.2.14. VANET Routing Based on Real-Time Road-Vehicle Density

The basic idea in a routing protocol is to select the shortest route; in VANET, this could be a road with low vehicle density. To improve this, authors in [30] proposed a vehicular routing protocol that considers real-time road-vehicle-density information. Therefore, not only was position information used by vehicles, but also road-vehicle density was calculated. In this way, each vehicle could establish a reliable route to forward the information, as the reader can see in Figure 10.

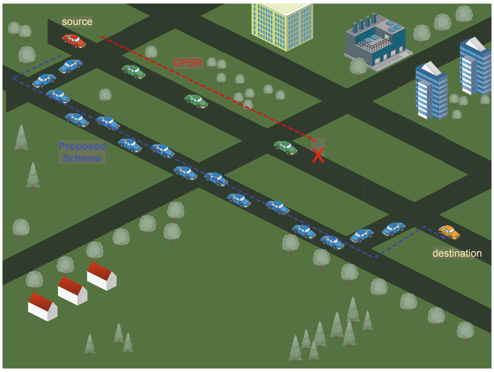


Figure 10. Example with various road-vehicle densities [30].

In the proposed routing scheme, each node keeps the Road Information (RI) to store the path–vehicle density computed from the information in beacons. RI of a vehicle is generated when the vehicle enters the road and is updated upon receiving a beacon from a vehicle moving in the reverse direction. Each node estimates its own total quantity of reverse cars (TRC), and the value of the reverse car in its RI to calculate road-vehicle density and send signalling messages containing the calculated TRC value to its one-hop neighbors. It is possible to calculate the TRC value as shown in Equation (17):

$$TRC = M_c \times \frac{R_d}{C_d} \tag{17}$$

where M_c is the value of the Reverse Cars field (vehicles moving in the reverse direction), moving distance after entering the road is C_d, and R_d the length of the road. The value of the reverse-car field is increased by one when a vehicle receives a beacon. Then, the value of density of cars (DC) is modified as follows:

$$DC_n = R_{TRC} + STRC \tag{18}$$

$$DC = \alpha \cdot DC_n + (1 - \alpha) \cdot DC_{n-1}, \tag{19}$$

where R_{TRC} is the TRC value of the vehicle, and $STRC$ the TRC value in the beacon. DC_{n-1} is the previously calculated DC, and α the weight value.

These values are used in the RREP and RREQ schemes, and it finally selects the route with the highest MinDensity.

4.2.15. Pheromone-Based Vehicle to Vehicle (PBV2V) Routing

PBV2V Routing [25] is a bionic V2V routing scheme that introduces the concept of pheromones. All vehicles frequently exchange their position using beacons to vehicles in the same transmission range, as well as their pheromone densities.

In PBV2V, each vehicle receives and updates one broadcast message from each neighbor in every period, denoted by T_{update}, and the set of i neighbors is represented by N_i. For every potential destination d, vehicle i finds the set of neighbors that have the highest pheromone densities, i.e., Equation (20), and the highest pheromone value is $P_{id}^{MAX} = arg \max\limits_{j \in N_i} \tau_{jd}$.

$$N_{id}^{MAX} = \left\{ j' | \tau_{j'd} = \max_{j \in N_i} \tau_{jd} \right\} \tag{20}$$

If N_{id}^{MAX} is not empty and $P_{id}^{MAX} > \tau_{id}$, some neighbors must have higher pheromone density (i.e., closer to target d than i). Therefore, i sets its pheromone τ_{id} as $P_{id}^{MAX} - 1$. Otherwise, to simulate evaporation, the pheromone density of d is reduced by 1. So, the selection of the transmission path from source to destination is based on pheromone density. This proposal reduces network overhead and search time.

4.2.16. Adaptive Geographical Routing Based on Quality of Transmission for Urban Vehicular Networks (AGQOT)

In [42], AGQOT was proposed. The authors proposed a metric named quality of transmission (QOT) to measure the performance of each road segment, which combines the connectivity with Packet Delivery Ratio (PDR). They also proposed an improved greedy-forwarding strategy to guarantee fast and reliable packet transmission.

The novel metric, the proposed QOT represents connectivity and PDR together on the path segment, and it was evaluated as shown in Equation (21).

$$\begin{array}{c} p_{qot} = a \cdot p_{connectivity} + b \cdot p_{pdr}, \\ a >= 0; b >= 0; a + b = 1; \end{array}, \tag{21}$$

where p_{qot} represents QOT, $p_{connectivity}$ indicates connectivity, and p_{pdr} stands for the corresponding PDR when the path composed of vehicles is connected.

For convenience, the weight of each road segment was defined as the negative logarithm of the corresponding QOT, by which these weights across several road segments can be added, i.e., $C_i = -log p_{quot}$.

Finally, when a packet arrives at one intersection, several adjacent intersections appear as candidates. The one with larger QOT in the set obtains the higher priorities.

4.2.17. Speed Based on Demand Vector (SODV) Link Routing Protocol

In [43] SODV was presented, an AODV-based routing protocol. SODV improves the routing process and makes the selection of neighboring vehicles incresingly relevant by taking into account vehicle velocity in the packet-transmission process.

The authors selected the geometric average velocity to calculate the vehicle's average velocity because it is more reliable and better reflects reality than arithmetic average velocity. Geometric average velocity is calculated as shown in Equation (22), and the number of nodes is variable from i to n.

$$\text{Geometric average velocity} = \sqrt[n]{\prod_{i=1}^{n}} \tag{22}$$

Simulation analysis showed that SODV improved the AODV routing protocol, especially with regard to transmission delay.

4.2.18. Greedy Curvemetric Routing Protocol (GCRP)

GCRP [31] is a new routing protocol designed to select the next hop by using curvemetric distance instead of Euclidean distance. The authors took that each vehicular node acknowledges its position, direction, and velocity using a Global Position System (GPS) receiver, a preloaded digital map of the city that is mainly needed to calculate curvemetric distance. This protocol faces an important challenge in an urban environment due to radio obstacles such as trees and buildings that decrease signal quality and reduce the successful packet reception.

The following expression is used to calculate the curvemetric distance between two nodes:

$$curvemetric_{dist}(n_i, n_j) = ShortestPath_{length}(n_i, n_j), \tag{23}$$

where $ShortestPath$ can be found by using the Dijkstra algorithm. Considering the situation in which the next-hop selection scope is a local optimum, if the forwarding node does not have any vehicle neighbors closer to the destination than itself, the carry-and-forward method is used, in which the forwarding node holds the packet until a new closer vehicle enters its transmission range. Finally, the proposal was evaluated via simulations in urban environments and compared it with GPSR protocol.

4.2.19. Reliable Intervehicular Routing (RIVER) Protocol

RIVER [11] is a position-based and greedy V2V routing protocol for vehicular ad hoc networks. This proposal choose the forwarding path by using traffic monitoring in real-time. RIVER is a geographic protocol that identifies the neighbor location using signaling messages. It also uses traffic monitoring to avoid routes with a sparse density which do not guarantee information transmission. So, traffic monitoring by RIVER can calculate reliable paths to forward data through the network. This proposal is not a shortest-path routing algorithm in a general sense; its edges are weighted with their reliability rating.

In the RIVER model, each node assigns a weight to every edge in its street graph. These weights are used to determine reliable routes based on first-hand observation (including information that each node sends or receives as messages to and from another node) and knowledge (including passive monitoring of known edge lists stored in beacons, probes, and routing packets). A small weight (the minimum weight is zero) indicates greater reliability; a large weight indicates an unreliable edge, and the maximum weight indicates an edge that is known to not be traversable.

When using reliability as a metric path, distance is still taken into consideration. Dijkstra's least-weighted-path algorithm finds the least-weighted path based on the sum of the path weights. If two paths P_x and P_y have equal weights on each edge, but P_x has more edges (is a longer path) than P_y, then P_y is chosen because its total weight is less. The shortest path between these two is chosen.

An example of this is demonstrated in Figure 11. In this figure, all edge weights (shown as w) except for $V_s \rightarrow V_d$ are of equal weight. Shortest path $V_s \rightarrow V_d$ represents an unreliable path where packets would be dropped if transmission were attempted along this path. The other two paths from V_s to V_d have equal edge weights along each edge, but the paths are different lengths. For path ($V_s \rightarrow V_1 \rightarrow V_3 \rightarrow V_d$), the total weight is 3. Each edge of the other remaining path ($V_s \rightarrow V_1 \rightarrow V_2 \rightarrow V_3 \rightarrow V_4 \rightarrow V_d$) is equally reliable, but the total weight is 5, so RIVER chooses the shorter path.

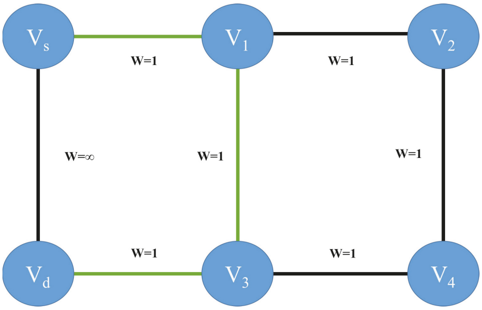


Figure 11. Example of three potential paths in reliable intervehicular routing (RIVER).

4.2.20. Greedy Perimeter Stateless Routing (GPRS)-Modified (GPSR-M)

The general idea of the GPSR forwarding process is to select the neighbor closest to the destination as the next hop. Due to the mobility of VANETs, that idea may not always be optimal. For this reason, in [44] GPSR-M was proposed that included a mechanism based not only on position, but also on speed, direction, and link quality. In the enhancement, two processes were also included, future-position prediction for establishing if nodes are moving in the same road and direction; and next-hop weight calculation.

The improved mechanism also incorporates a future-position prediction process (getFuturePos), a next-hop weight-calculation process (CalculateW) and a novel process that determines if nodes are moving in the same road and direction (inSameRD). Equation (24) shows how the future position is calculated.

$$\begin{array}{l} FutPos_x = Pos_x + Vel_x * dt(speed) \\ FutPos_y = Pos_y + Vel_y * dt(speed) \end{array}, \tag{24}$$

where $dt()$ is a mapping function that returns the time from 1.0 up to 4.0 s based on the speed parameter. The returned period decreases if the speed increases.

To review if two vehicles follow the same road and have the same direction, a process calculates the vehicle-velocity vector angle, their dot product, and their line distance. With this information, the algorithm computes if they are moving on the same road. GPSR-M calls a *Forward* procedure when packet transmission is needed. The best next-hop decision is made through the *BestNeighbor* procedure that unchains the *CalculateW* procedure. The resumed process is presented in Figure 12.

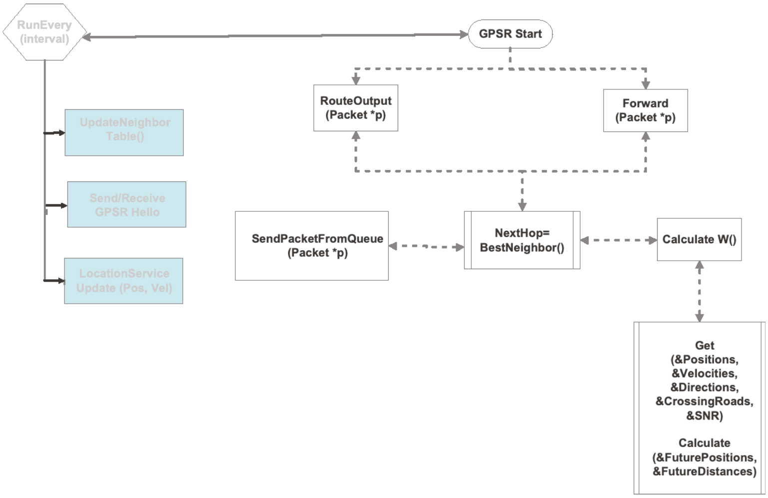


Figure 12. Mechanism procedure of greedy perimeter stateless routing (GPRS)-modified (GPSR-M) [44].

4.2.21. Anchor-Based Connectivity-Aware Routing (ACAR)

Position-based routing protocol ACAR for vehicular ad hoc networks was proposed in [45]. This protocol uses the greedy-forwarding approach and store–carry–forwarding to reduce loss of information. ACAR proposes to make routing more efficient in a fully connected scenario based on position and direction; in a network sparse scenario, selection is based on connectivity (density).

The proposal considers two scenarios: if the network is (1) dense or (2) sparse. In the first case, each vehicle knows the position and direction of itself and its neighbors (assuming the use of GPS). The data packet is then transferred from source to destination using this closest path. In the second case, if there is no neighboring vehicle in the range of the node that ensures connectivity, the store–carry–forward mechanism is started. This method introduces a delay, but it is more admissible than dropping the packet; the workflow is described in Figure 13.

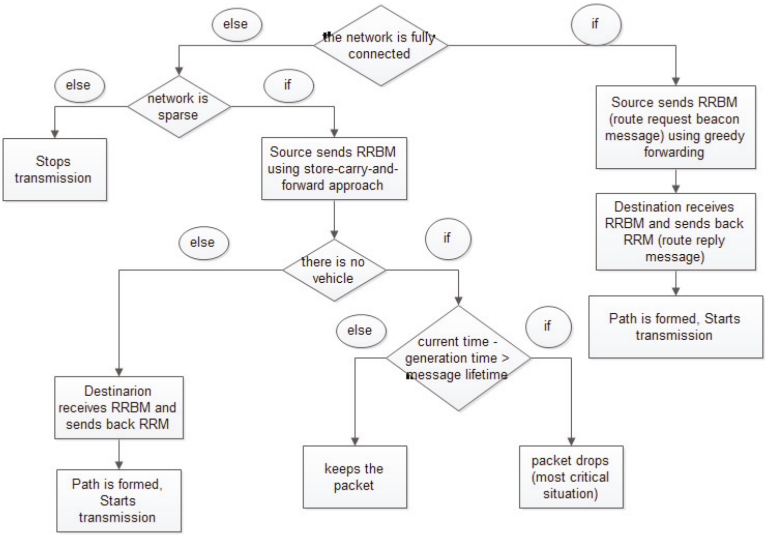


Figure 13. Workflow for anchor-based connectivity-aware routing (ACAR) [45].

4.2.22. Maxduration-Minangle GPSR (MM-GPSR)

GPSR presents some drawbacks because of the frequent communication with vehicles that could be out of range or construct a path with redundancy. To solve the above problems, MM-GPSR routing protocol was proposed in [46]. The enhancement in greedy forwarding first includes determining the allowed communication area, and then computing and comparing the cumulative communication duration of neighbor vehicles; finally, the neighbor with maximum duration is selected as the next hop. When greedy forwarding fails, the perimeter forwarding process is used. Improvements in this case include calculating and comparing angles from source to neighbor nodes and selecting the neighbor with minimum angle as the next hop to forward data.

In order to improve the greedy-forwarding scheme, the cumulative communication duration between the neighbor nodes in the communication range of the source is calculated by using Equation (25).

$$T_i = Ti - 1 + t_i - t_{i-1}, \tag{25}$$

where T_i is the current cumulative communication duration, $Ti - 1$ is the last cumulative communication duration, t_i is the current time of receiving *hello*, t_{i-1} is the time of receiving the last *hello*. The T_i value is compared with nodes in the communication range of the *source*, and the node with maximum T_i is steady and close to the destination, and is selected as the next hop.

Finally, to solve routing redundancy, enhanced perimeter forwarding takes the positional connection between neighbor and destination nodes into consideration. So, the proposal includes finding a next-hop node that does not deviate from *source* to *destination*. To do this, if needed, it draws a line from *source* to *destination*, and then draws lines from *source* to any neighbor node. Each line through a neighbor node forms an angle with the line through the *destination*, and this angle is named as θ. By analyzing and comparing the corresponding θ of all neighbor nodes of the *source*, an optimal next hop is selected.

4.2.23. Connectivity-Aware Intersection-Based Routing (CAIR) Protocol

CAIR [47] is a protocol designed to select a forwarding path as an optimal route that guarantees the best probability of connectivity and lower delay. This is due to constraints of vehicular networks like high mobility, periodic link disconnection, and vehicles with frequently changing density. In this proposal, a vehicle can know its own location and that of its neighbors by sporadically exchanging signalling messages. By using velocity, it is also possible to calculate position prediction, and forwarding nodes can choose the neighbor on the selected path as the next hop whose new predicted position is closest to the destination or the next intersection. CAIR uses a recovery strategy through the idea of store–carry–forward. Equation (26) presents the mechanism for the proposed position prediction.

$$(x_c, y_c) = (x_i, y_i) + (s \cdot \cos\theta, s \cdot \sin\theta), \tag{26}$$

where (x_c, y_c) is the neighbors' current position; (x_i, y_i) is the previous position; $s = (t_c - T_b) \cdot$ speed, where t_c is current time and T_b is previous beacon time; and θ and speed are direction and moving velocity, respectively.

4.2.24. Distance and Signal Quality Aware Routing (DSQR)

DSQR protocol [48] bases its forwarding decisions on mid-area node selection; it evaluates the direction and distance of neighbor nodes, and also considers link quality to elect the best next forwarder node toward the destination node. DSQR is based on the following metrics:

- Forwarding region. DSQR uses the distance of nodes and defines the mid (midrea) and border area of the transmission range. To give higher priority to mid-area nodes, it reduces the breaking probability of the next forwarder, packet error, and delay. If there is no vehicle node located within the mid-area, then the source node adopts the carry-and-forward approach; an example is shown in Figure 14.
- Distance and direction. In geographic protocols, distance is a very important parameter for next-hop selection. Node positions are determined through GPS, where the Pythagoras theorem is utilized for distance evaluation between sources with its neighbor node. In this proposal, using a 3D space for distance calculation was considered, focusing on multilevel flyovers, bridges, tunnels, and over- or underpasses.
- Link-quality estimation. DSQR considers channel-quality measurement at the MAC. To evaluate channel quality, DSQR uses received signal strength (RSS) and the average link quality (ALQ), using past and current channel quality.

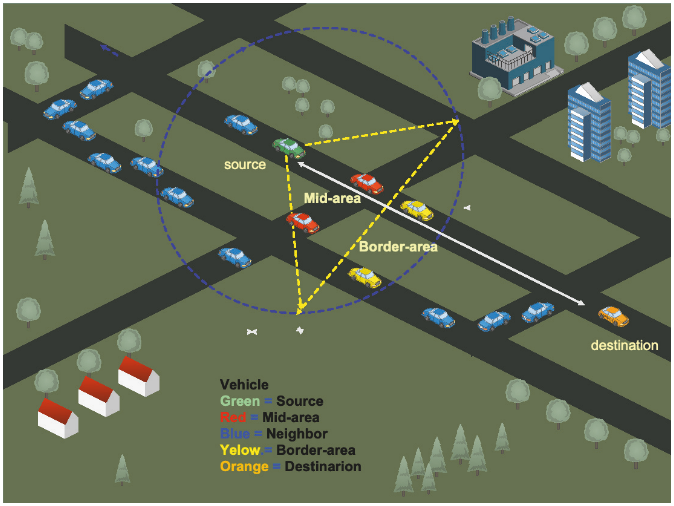


Figure 14. Mid-area and border-area example [48].

The DSQR initiates forwarding selection by looking for that vehicle node that is located in the mid-area; if there are no nodes in that area, then the source adopts the carry-and-forward approach to hold the packet for a specific time interval.

A summary of these proposals is presented in Table 5, where we can see the protocol, the year of the presentation, the metrics used to select the optimal path, the area of evaluation (urban or highway), if they use carry-and-forwarding as an alternative to dropping information in order to minimize losses, and, finally, which simulators were used in order to be evaluated and compared (including network simulator and mobility generator).

Table 5. Multimetric routing protocols in a vehicular ad hoc network (VANET). Number of operations shown with each metric was approximated and based on number of neighbors n, which does not consider any other phase, such as protocol initialization or generation overhead.

Protocol	Year	Metrics Used	Area Evaluated	Carry and Forwarding	Simulators for Evaluation	Delay	% Delivery Ratio
AHP-based Multimetric Geographical Routing Protocol (AMGRP) [35]	2019	Link lifetime ($9n+3$), mobility ($9n+21$), node status ($3n$), and node density (n). **Total ($20n+24$)**	Urban	no	OpenStreetMap (OSM) [49], SUMO [50], OMNET++ (INET) [51]	0.35 s (250 nodes); 1 s (50 nodes)	78%
AODV with predicting node trend (AODV-PNT) [36]	2014	Speed ($2n+2$), acceleration ($2n+2$), movement direction ($2n+2$), and link quality between vehicles ($20n+2$). **Total ($26n+8$)**	Urban	no	SUMO [50], NS-2 [52]	0.6 s (55 nodes)	66%
AODV with multi-RREP (AODV-MR) [27]	2014	Link reliability, link stability and number of hops.	Urban	yes	SUMO [50], NS-2 [52]	0.6 s (50 nodes)	80%
Named Data VANET protocol (NVP) [37]	2016	Distance (TXC) ($3n$), number hops (n) and density (n). **Total ($5n$)**	Urban	no	SUMO [50], NS-3 [53]	2.04 s (500 nodes)	78%
Multimetric Unicast Data Dissemination Scheme (MUDDS) [38]	2012	Link availability (n), distances ($6n$) and Packets Reception Rate PRR ($2n$). **Total ($9n$)**	Highway	no	NS-2 [52]	0.15 s (10–100 nodes)	-
Multimetric Opportunistic Routing (MMOR) [39]	2011	Distance ($7n$), moving direction ($2n$), velocity ($3n$), load ($3n$) and neighbors' density ($3n$). **Total ($18n$)**	Urban	no	NS-2 [52]	-	-
Multimedia Multimetric Map-aware Routing Protocol (3MRP) [10]	2017	Distance ($27n$), density (n), trajectory ($26n$), available bandwidth estimation (ABE) ($7n$) and MAC layer losses (n). **Total ($62n$)**	Urban	yes (local buffer)	OSM [49], SUMO C4R [50], RevSim [54], NS-2 [52]	1.4 s (50 nodes); 1 s (100 nodes)	40% (50 nodes); 29% (100 nodes)

Table 5. *Cont.*

Protocol	Year	Metrics Used	Area Evaluated	Carry and Forwarding	Simulators for Evaluation	Delay	% Delivery Ratio
Multimetric next-hop vehicle selection for geocasting in vehicular ad-hoc networks [41]	2015	Link delay ($6n$), jitter ($4n$), link lifetime ($11n$), velocity ($2n$) and degree ($4n$). **Total ($27n$)**	Urban	no	-	-	-
Fuzzy control based AODV routing (FCAR) [40]	2009	Route lifetime ($32n$) and direction ($17n$). **Total ($49n$)**	Urban	no	SUMO [50], MOVE [55], NS-2 [52]	0.17 s (50 nodes); 0.21 (250 nodes)	-
Reactive routing protocol for VANETs (RRPV) [12]	2014	Number of hops (n), link reliability ($5n$) and co-channel noise ($4n^2$). **Total ($4n^2 + 6n$)**	Urban	no	SUMO [50], NS-2 [52]	1 s (50 nodes)	-
VANET Routing based on real-time road vehicle density [30]	2013	Position (n), direction (n) and density ($6n$). **Total ($8n$)**	Urban	no	NS-2 [52]	-	35%
Pheromone-based vehicle to vehicle (PBV2V) routing [25]	2013	Position ($6n$) and pheromone density ($4n$). **Total ($10n$)**	Urban	no	MOVE [55], NS-2 [52]	-	-
Speed based on demand vector link routing protocol (SODV) [43]	2017	Velocity ($4n$) and number of hops (n). **Total ($5n$)**	Urban	no	VanetMobiSim [56], NS-2 [52]	0.3 s (40 nodes)	26% (40 nodes)
Adaptive geographical routing based on Quality of transmission for urban vehicular networks (AGQOT) [42]	2018	Distance ($6n$) and link connection time ($4nk$). **Total ($n(4k+6)$)** k number of intervals to approximate an integral	Urban	yes	VanetMobiSim [56], NS-2 [52]	1 s (100 nodes); 0.05 s (140 nodes)	25% (100 nodes); 34% (140 nodes)
Greedy curvemetric routing protocol (GCRP) [31]	2018	Position (n), velocity (n), direction (n) and curvemetric distance ($6nk$). **Total ($n(6k+3)$)** k number of vehicles in the forward path	Urban	yes	SUMO [50], OMNET [51]	1 s (100 nodes); 0.05 s (140 nodes)	25% (100 nodes); 34% (140 nodes)
Reliable intervehicular routing (RIVER) [11]	2011	Hops (n) and reliability (n). **Total ($2n$)**	Urban	no	NS-2 [52]	-	-
GPRS-modified (GPRS-M) [44]	2015	Distance, speed, direction for future position ($24n$) and link quality ($2n$). **Total ($26n$)**	Urban and highway	no	JOSM [57], SUMO [50], Bonmotion [58], NS-3 [53]	0.02 s (100 nodes)	79%
Anchor-based connectivity-aware routing (ACAR) [45]	2014	Position ($6n$), direction ($2n$) and density (n). **Total ($9n$)**	Urban	yes	NS-2 [52,52]	0.04 s (100 nodes); 0.02 s (400 nodes)	50% (100 nodes); 100% (400 nodes)
Maxduration-Minangle GPSR (MM-GPSR) [46]	2018	Maximum cumulative communication duration ($3n$) and minimum angle ($18n$). **Total ($21n$)**	Urban	no	VanetMobiSim [56], NS-2 [52]	-	-
Connectivity-aware intersection-based routing (CAIR) [47]	2014	Position ($4n + 44$), speed (n) and density (n). **Total ($6n + 44$)**	Urban	no	VanetMobiSim [56], IDM-LC, Matlab [59], NS-2 [52]	0.75 s (80 nodes)	70% (80 nodes)
Distance and signal quality routing (DSQR) [48]	2019	Link quality estimation ($6n$), and distance ($9n$). **Total ($15n$)**	Urban and highway	yes	NS-2 [52], MOVE [55]	0.0031 s (100 nodes) (500 nodes)	65% (100 nodes); 60% (500 nodes)

5. Discussion

As we see in the summary of Table 5, several proposals of routing protocols exist for vehicular networks. Recent improvements include metrics that are focused on the characteristics of this kind of network. An assumption of all proposals is the use of GPS due to the mobility present in them;

knowing the localization of each node is very important to make the best choice of route. Distance and speed are preferred metrics, because the former can be seen as a progress rate of destination reachability, and the latter accounts for the behavior of the vehicular networks. Then, link life (also called link stability or link quality) is due to a good choice because it follows the route that guarantees perdurable communication to complete the transmission of data. Vehicle density is another metric commonly selected by authors that guarantees the opportunity to have enough options to select the best path. Moreover, Table 5 includes a rough number of operations that the proposed metrics require for a routing decision. Thus, this number of operations, including the "Metrics used" column, is presented as a function of the number of neighbors n. The provided number includes the effort to send or receive any additional signalling needed for it. From our results, metrics like mobility, trajectory, or link quality need more operations because they aim to predict future information. Of course, instantaneous values of these metrics are also possible to use, and usually only need one retrieve operation. In almost all protocols, a node uses a linear-dependent number of operations to make a forwarding decision by means of a weighted multimetric value for each neighbor. If there are not enough neighbors (low density), then some of the routing protocols use a well-known technique called carry-and-forwarding (maintain the packet until a good route could be selected). Other several important considered metrics exist that are mentioned in the summary, such as mobility, hops, direction, acceleration, and trajectory. It is important to study the scenarios and applications before selecting a protocol or in order to improve.

It is important to highlight that all the protocols in Table 5 have only been evaluated using network simulators in order to review behavior at the moment of selecting the next hop or forwarding path. This is mainly because both in cities and rural areas, communication technology is confronted with challenges, as every car must handle communication in a very short time and ensure quality simultaneously, especially when it comes to a real-time request. Conducting real experimentation about novel proposals could present a risk. The simulation is one of the most often used methods for the performance evaluation of VANETs, but by considering the use of a realistic mobility model for evaluation results to correctly indicate the real-world performance of the system [60,61]. However, as seen in [62] ETSI ITS-G5 (GeoNetworking protocol) was implemented and validated in a real environment in order to demonstrate the performance of the communication devices in real V2V with good results. In addition, [63] introduced functionality tests in two vehicular use cases using an information-centric networking protocol support in the ETSI ITS station protocol stack. Real experiments were made in the last few years to advance the implementation of these technologies in new vehicles in order to bring many benefits, like increasing road safety, improving traffic efficiency, and offering cloud services. The next step for these novel proposals is their experimentation in testbeds.

As we see in Table 5, the majority of the proposals were evaluated in urban areas because, due to the presence of obstacles, it is a greater challenge than highways, as there are quick topology changes. This allows the possibility of deploying most of the elements that make up a realistic road, such as traffic lights, stop, multilane roads, and roundabouts. It is also possible to include generating the movement pattern of vehicles in a different typology to be used by the simulator [64]. An urban zone also enables variation analysis of vehicle speed, density, and distance [65]. In the case of highways, routing protocols are not evaluated so deeply because velocities are mostly constants, and the environment normally represents long, sparse, and clear paths [66,67]; many routing protocols use the carry-and-forward method in these cases. Some evaluation in VANETs in highways focuses on propagation modeling, such as in [68].

Related to the research questions in Section 3.1, we concluded that position, direction, and density are the most used metrics, because these are the ones that consider the main characteristics of vehicle scenarios as movement, and consider the presence of other neighbors to make hop-by-hop communication. About the combination, a good proposal of metrics is one such as that proposed in [45], where the authors used position, direction, and density, obtaining good performance in terms of packet-delivery ratio and delay. These metrics are very frequently used and repeated in other proposals, but this special combination has good results in urban scenarios (that are more restricted by the presence of obstacles) regardless of vehicle density of the scenario due to the adaptability provided in the path selection. This helps for a fast-forwarding process for reaching the destination. On the other side, if the goal is to meet an offered QoS over forwarding speed, link quality and stability are some of the metrics that should be included in path selection. In this analysis, in GPSR results, as the protocol with the higher number of comparatives, more than half of the protocols presented were compared with GPSR because GPSR is the base of geographic protocols that are the angular piece in vehicular routing. Finally, in relation to the used simulator, the most used software for analysis is NS-2. Deploying and testing VANETs imply high cost and intensive labor. For this reason, simulations are a helpful alternative preceding actual implementation [69,70]. Many researchers select NS-2 because it is an open-source simulator, has already had many implementations, and it is easy to edit to their needs. NS-2 also allows the use of several mobility generators, such as VanetMobiSim, MOVE, or SUMO, which improve the scenario design, making evaluations more realistic [71,72]. However, several recent investigations have shown a tendency to use Veins and OMNET [73].

As gaps in this literature review, it is important to mention the importance of evaluating new proposals in the same environments, which can include the same simulator and same area (urban or highway) in order to make a fair comparison.

5.1. Nonfunctional Metrics

The main goals of V2V and V2I communications are to improve safety, reduce road traffic, and reduce accidents. So, the main task of a routing protocol is to improve the opportunity to send a message by the best route, delivering data in a faster mode. Nonetheless, an important issue in vehicular communication is if the shared information is correct. In general, all of the traditional aspects of security–privacy, confidentiality, integrity, nonrepudiation, and others, must be applied to VANET communication to prevent compromising traffic safety and causing material damage or even loss of life [74,75]. So, security aspects could be considered nonfunctional metrics. In [76], the authors proposed a communication model to provide vehicle-location privacy. In case that V2I communication is being established, driver privacy must be guaranteed. Trust management is crucial in VANET routing because interchanging false information could cause much damage. Reliable routing and communication are very important, which are analyzed in [77]. Some of these nonfunctional metrics could be introduced in the routing protocols for VANETs in order to guarantee data reliability, as mentioned below.

- Anonymity/Privacy: the objective is to conceal who communicates to whom to a neighbor who observes the interchange of data of the anonymous communication channel.
- Trust: it is important to incorporate mutual trust between vehicles, mainly in the routing process, because one or more malicious neighbors may attempt to disrupt route discovery or data transmission in the network.

When V2I communication is established, information about the vehicle (location, route, etc.) is shared. So, some proposals to maintain a level of privacy were presented, such as [76] that proposed the Pass and Run protocol that first passes information through the VANET (considered in this case was a delay tolerant network (DTN)) before reaching an RSU to maintain vehicle-location privacy. In the DTN, metrics such as distance and direction are taken into account from vehicle source to RSU. In [78], a protocol was presented based on Crowd [79], an approach where each vehicle probabilistically decides to directly send a message to a common receiver or to forward it to a peer, who is asked to repeat the process. The objective is to offer privacy in V2V communication. The proposal was evaluated jointly with AODV and GPSR as VANET routing protocols. This potentially opens a new set of routing protocols where there is a tradeoff between speed and secure forwarding.

5.2. VANET Integration with Other Technologies

One of the most viable communication standards by the Third Generation Partnership Project for vehicular networking is long-term evolution (LTE). LTE standard offers high throughput and lower latency. Its downlink and uplink data rates are 300 and 75 Mbps, respectively [80]. LTE technology improves cost and performance efficiency due to the simplification in network architecture (fewer network elements) and advanced algorithms for resource utilization [81]. Nowadays, cellular networks such as 3G or LTE have wide communication range and coverage, which are ideal characteristics for vehicular-network scenarios. Combinations of VANET technology with 3G or LTE form a heterogeneous network that is adopted for data collection and dissemination to/from vehicles to manage road traffic. Based on this idea, [82] proposed a solution based on speed, location, direction, destination, and LTE link quality. In [80,83], LTE was used in VANET scenarios. In [83], a hybrid solution was highlighted that integrates LTE-A (4G LTE-Advanced), which is a less complex and more cost-effective solution compared to other options. Each vehicle could use its LTE-A interface for V2I communications, offering a reduction in mobility signalling overhead. In [80], a hybrid architecture was proposed that combined IEEE 802.11p-based multihop clustering and LTE called VMaSC-LTE. The principal goals in these heterogeneous network proposals are to achieve a high data-packet-delivery ratio and low delay while keeping the usage of the cellular infrastructure. However, they are not focused on routing design because these proposals use infrastructure-based LTE without direct communication among vehicles, so messages pass through the infrastructure.

The development of Fifth Generation (5G) networks made the internet ubiquitous Internet and the growth of new applications possible. This is also possible in VANET by internet of vehicles (IoV) communication that uses network infrastructure to allow cars to be connected to new radio technologies [84]. It is worth noting that the proposals reviewed in this article have tested by using DSRC framework. However, thanks to LTE device-to-device technology [85] that can be implemented in a decentralized fashion, the performance of all proposals could be significantly improved. LTE D2D has been the perfect candidate to improve communication in VANETs. Since LTE D2D offers improvements in terms of capacity, cost reaction, and spectral efficiency, some car manufacturers are using it to provide applications such as remote monitoring, assisted driving, and infotainment. Thus, extensive simulation tests should be performed for routing proposals under the decentralized LTE device-to-device umbrella. This would help VANET communication meet the 5G requirement in terms of throughput and latency [86] because current performance (under DSRC umbrella) is far from this according to the presented results.

5.3. Dissemination

The other insensitive study routing application is dissemination. The goal of data-dissemination algorithms in VANETs is to deliver information to drivers, passengers, and vehicles, typically in emergency situations. So, it is important to consider that information has to be distributed to all the vehicles in the interest area [87,88]. The main challenge when dissemination is used is how information should be distributed, taking into account characteristics in a VANET like mobility. In VANET, communication V2V, V2I, and Vehicle to Roadside (V2R) are allowed, and information dissemination is important. Flooding is the easiest mechanism but generates the known storm problem in dense scenarios. To reduce this problem, protocols were designed based on smart dissemination. The objective in [89] was to define a distributed dissemination protocol that supports high-rate message flows and does not use beacon messages. This proposal took into account metrics like distance, density, and the number of hops, and it is called timer-based distributed dissemination protocol for VANETs. The authors in [90] proposed a warning service to prevent accidents by alerting drivers about accidents and dangerous road conditions using a dissemination mechanism. The proposal used several metrics in the broadcast-dissemination mechanism, such as density, weighted moving average, and vehicle direction. The investigation in [91] presented a decentralized stochastic proposal called Adaptive Distributed Dissemination (ADD), for the data-dissemination problem using two game-theoretical mechanisms. The goal was to disseminate warning messages to all vehicles inside the region of interest (ROI). Metrics like vehicle location, direction, and velocity were also included. The mechanism to carry the stored message was also used in cases of sparse traffic zones.

The dissemination approach can also function as a technique of information distribution in a vehicular network. This method deals with the avoidance of the storm problem in order to accurately send information. Even though it is a novel and challenging topic in VANETs, we did not consider it with deeper analysis because it is out of the focus of our topic, which is routing protocols that select a path hop-by-hop by using several metrics. As future work, it would be interesting to compare between the two approaches, routing and dissemination.

6. Conclusions

VANETs are the main component of communication framework intelligent transportation systems; therefore, they have been extensively studied from both industry and academia in the last twenty years.

It is expected that vehicles will be equipped with advanced onboard units, multiple communication technologies, and sensor platforms. VANETs provide important information to drivers by using vehicle-to-vehicle communications. Since VANETs are a distributed, self-organized network, a key component in their operation to guarantee their minimal dependence in fixed infrastructure routing plays a crucial role.

In this article, we discussed the importance of developing routing protocols in VANETs and summarized some that are especially proposed for this kind of wireless networks. More precisely, we focused on proposals that use several metrics to select the forwarding path, presenting the importance of these metrics in the behavior of vehicular networks, and how their selection can improve in vehicle communication. We presented the characteristics of these routing protocols (i.e., year of release, area of evaluation, metrics used) and how they are evaluated (i.e., simulators and mobility generators).

In general, after analyzing the contents of Table 5, we concluded that link stability (or link lifetime or stability), position, density, and speed are the more promising metrics in routing protocols for VANETs because of geographical constraints. However, the performance of a routing protocol in vehicles' networks is very related with the mobility model, for that reason, other metrics that provide good performance are direction, trajectory or acceleration that are very related to the mobility of the network.

In a nutshell, depending on the application of VANETs, it is necessary to design specific routing protocols and consider the mobility model to fulfil its requirements. Even though routing in VANETs has received more attention in the wireless-network community, there are still quite a few challenges that have not yet been carefully investigated. New directions in the development of VANET routing protocols include artificial intelligence [92] or trust in communications [93]. As future work, we are gathering statistics of VANET routing protocols reported in the literature to carry out meta-analysis of VANET performance.

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