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Strengthening Road Safety and Mobility at the Urban Level with the Aim of Digitizing and Shaping Smart Cities Through Emerging Vehicular Communications C-V2X, DSRC, and VLC

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Abstract: The simulation results presented based on the proposed system demonstrated significant improvements in communication reliability, packet loss reduction and signal stability, highlighting its superiority in real urban traffic conditions. Using the IEEE 802.11p standard and a modular dual-antenna architecture, the system maintained a latency below 10 ms over distances of over 3 km, without noticeable signal loss. GNSS synchronization ensured precise vehicle positioning and dynamic signal optimization. There are results and approaches that highlight the limitations of IEEE 802.11p in dense traffic scenarios; the current approach has reduced packet loss to below 5%. Its integration also allows compatibility with future technologies such as 5G and C-V2X, guaranteeing scalability and long-term relevance. The proposed prototype sets a new standard in vehicular communications, combining high performance with a flexible and extensible architecture, making it a viable solution for large-scale deployments in smart cities, supporting the transition to safer and more sustainable transportation infrastructures.

Keywords: smart city; urban congestion; vehicle-to-vehicle; vehicle-to-infrastructure; visible light communications; 5G

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1. Introduction

According to data from the World Health Organization, road traffic accidents annually result in injuries to approximately 50 million individuals, with over 1 million fatalities. Road traffic accidents are also the primary cause of death among young people aged 15 to 35. Beyond the tragic loss of life, the economic burden on national economies is significant, representing an estimated 3% of Gross Domestic Product (GDP) [1].

In response, the United Nations (UN) General Assembly adopted a resolution on 31 August 2020, aimed at enhancing global road safety by setting a target to halve road fatalities by 2030. In alignment, the European Union (EU) approved the Road Safety Policy Framework 2021–2030—Next Steps towards Vision Zero in 2021, which supports the UN target and reaffirms the EU's long-term goal of achieving zero road fatalities and serious injuries by 2050.

Analysis from the Organization for Economic Co-operation and Development (OECD), International Transport Forum indicates that although road fatalities have decreased over the past decade, the decline rate has been under 10% per decade among studied countries, underscoring the need for innovative approaches to meet the 50% reduction target by 2030. A report from the U.S. Department of Transportation's Research and Innovative Technologies Administration demonstrates that implementing road safety applications based on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication could reduce traffic crashes by as much as 81%, including reductions of 83% in light vehicle collisions and 72% in heavy vehicle crashes. The EU's Europe on the Move publications and the EU Road Safety Policy Framework 2021–2030 prioritize mobility that is connected, clean, and safe [2]. Within this framework, a principal research focus has been the development of vehicular communication technologies to support road safety applications and urban mobility initiatives. The European Green Deal aims to transform Europe into a climate-neutral continent by 2050, focusing on significantly reducing greenhouse gas emissions, increasing energy efficiency, and promoting sustainable transportation. However, the interdependence between this agreement and vehicular communication systems, as well as road safety, remains underexplored, despite their significant potential to simultaneously address environmental and safety challenges. The lack of an integrated approach limits the understanding of how advanced vehicle communication technologies, vehicle-to-everything (V2X), can substantially contribute to achieving the Green Deal's objectives. Vehicular communication systems, particularly V2X solutions, enable real-time data exchange between vehicles (i.e., V2V) and between vehicles and infrastructure (i.e., V2I). These technologies enhance road safety by reducing accident risks, optimizing traffic flow, and enabling automated responses to hazards or congestion. From an environmental perspective, smoother traffic flow minimizes idling times and unnecessary accelerations and braking, directly reducing fuel consumption and CO_2 emissions. Nevertheless, the environmental benefits of V2X implementation are often overlooked in environmental policy discussions. Within the framework of the European Green Deal, significant emphasis is placed on sustainable transport, including the accelerated adoption of Electric Vehicles (EVs) and the development of multimodal infrastructure. Implementing V2X technologies is essential for unlocking the full potential of EV charging networks. For instance, smart charging stations that integrate V2I communication can optimize energy distribution and grid balancing by providing real-time information on energy demand and availability. Furthermore, predictive traffic management systems, using vehicle data, can identify and recommend energy-efficient routes, thereby reducing congestion and carbon emissions. Another overlooked aspect is the connection between road safety and environmental objectives. Road accidents result in significant societal losses, including unnecessary energy consumption linked to emergency interventions, damaged infrastructure, and traffic congestion. By improving road safety through intelligent V2X systems, the number of accidents and associated emissions could be significantly reduced. Thus, vehicular communication technologies are not merely technological advancements but essential solutions for achieving safer and more sustainable transportation systems. In conclusion, aligning V2X technologies with the objectives of the European Green Deal is imperative. Policymakers must recognize the importance of smart infrastructure, connected transport networks, and V2X systems as key enablers of eco-driving, emission reduction, and improved road safety. Promoting investments in these areas represents a major opportunity to achieve environmental and road safety goals simultaneously, serving as a crucial step toward a sustainable and efficient future. The European Green Deal has also established ambitious targets for carbon-neutral road transport by 2050 and a 55% reduction in emissions by 2030, aiming to drive transformative advancements in technologies and services, including connectivity, digital information systems, and sustainable shared mobility solutions [3,4].

A review of the current state of global research highlights the progressive implementation of Cooperative Intelligent Transport Systems (C-ITSs), in which vehicular communications are an essential component. These systems are designed to integrate all road users—both drivers and pedestrians—into an interactive network for real-time information exchange. This communication includes several types of interactions, such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), pedestrian-to-infrastructure (I2P/P2I) and vehicle-to-pedestrian (V2P) [5]. Initially, these systems were developed to optimize traffic control mechanisms, thus contributing to increased road safety and accident prevention. However, technological progress has led to the emergence of advanced communication infrastructures and autonomous vehicles, which can handle large volumes of data. These advances pave the way for innovative solutions, but they also pose major challenges, such as high implementation costs, the need for complex infrastructure, the harmonization of different technologies produced by different manufacturers, and alignment with various global standards. The development of emerging, potentially disruptive technologies, such as fifth-generation (5G) cellular communications and prototype sixth-generation (6G) systems, brings both opportunities and challenges for improving vehicular communications. In addition, another innovative direction explored in this research is the use of visible light communication (VLC) technology. This opens up new possibilities for implementing efficient, scalable, and more future-proof systems [6,7].

The core innovation of the proposed system, from which simulation algorithms are subsequently presented, consists of the integration of a dual-antenna architecture and adaptive transmission power settings. This ensures robust and low-latency communications, covering an extended area, with three control units supporting all traffic arteries over a distance of approximately 3 km. The system also uses advanced software tool chains for MAC-level data processing, GNSS synchronization for precise vehicle positioning, and dynamic signal optimization. Unlike conventional solutions, the presented prototype has a modular design that allows for smooth upgrades to future technologies, including 5G and C-V2X, thus ensuring long-term applicability. Tests conducted in real urban traffic conditions, including heavy traffic areas and traffic-lighted intersections, demonstrated superior performance in terms of signal stability, low packet loss rate, and high data throughput.

This study offers the main modality to scale or turn to a vehicular communication system based on IEEE 802.11p [8], optimizing urban traffic conditions in real life, with high-density and mobility model dynamics. In the proposed methodologies, the main metrics used to evaluate the performance of the systems include the following: packet loss rate, which is less than 5%; the distance, which is up to 3 km; communication delay, less than 10 ms in heavy traffic conditions; and signal stability, which varies between −42 dBm and −52 dBm, ensuring robust connectivity. It is the maximum distance from the transmission which is most important, so the assistants will cover the four main zones, with an intense circulation, approximately 3 km from the emitter, and the distance between the communication systems within a range of 900–1200 m. These values reflect the system's ability to function efficiently in complex urban environments.

The article is detailed in an explicit way that aims to integrate GNSS synchronization into a dual architecture, in addition to rigorous testing methodologies in complex urban environments, in order to offer innovative features, such as improved precision, reliability, and efficiency for the vehicular communication system. Therefore, the present proposal is aimed at enhancing the existing hardware component, which has been recently projected, with special features to optimize different operations associated with this application, with analysis made in real time. Section 2 will describe in detail the model and its essential aspects that are fundamentally important in order to analyze the best techniques. Section 3 continues to highlight specific contributions to the research, including innovative architecture, research, and experimental findings. Further on, Section 4 summarizes the main conclusions, offering a clear perspective and the impact of the relevant studies, while

Section 5 formulates a broad conclusion, offering a summary of the most suitable solutions proposed for future studies. With a well-defined structure, the article contributes to the forward-looking area of smart transport, consolidating the basis for implementing scalable vehicle systems.

2. Materials and Methods

In radio communications, two critical aspects warrant careful consideration: the security of wireless links under diverse operating conditions and the potential health risks associated with prolonged exposure to radio transmission antennas. As wireless communication technologies evolve, ensuring the confidentiality, integrity, and availability of transmitted data becomes increasingly vital. Wireless links are inherently vulnerable to interception, signal interference, and unauthorized access due to their open nature. Threats such as man-in-the-middle attacks, signal jamming, and unauthorized breaches can compromise sensitive information and disrupt critical communication systems, particularly in applications such as vehicular communication networks, public safety operations, and industrial automation. To address these vulnerabilities, it is essential to implement robust encryption methods, authentication protocols, and advanced intrusion detection systems to safeguard wireless transmissions effectively. Another significant concern relates to the potential health implications of radiofrequency (RF) exposure, particularly from high-energy transmission antennas. Regulatory frameworks, such as those established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), are designed to ensure safe exposure limits; however, long-term effects remain a topic of ongoing investigation. Prolonged proximity to RF-emitting antennas, such as those found in cellular networks and broadcasting systems, raises questions about potential biological impacts, including thermal effects and tissue heating. While current scientific consensus suggests that exposure within regulatory limits poses minimal risks, continued research is critical, especially as next-generation technologies, such as 5G networks, operate at higher frequencies. In conclusion, addressing the security challenges of wireless communications while carefully monitoring and mitigating potential health risks is paramount. A balanced approach that combines strict cybersecurity measures with adherence to established health and safety standards is essential to fostering trust, reliability, and safety in modern radio communication systems.

The advancement of radio communications and the proliferation of new mobile devices have driven substantial societal transformations, a trajectory that continues with the deployment of 5G cellular broadband networks and the anticipated development of 6G technologies. However, ongoing enhancements in radio signal coverage, quality, and stability and increased data volume and throughput have led to saturation within the radio and microwave spectrum. One primary strategy to address this issue has been to subdivide the radio spectrum allocated to mobile communications into distinct bands tailored to specific applications, including transportation, road safety, and public security—areas of focus in this study.

Modern vehicles are now equipped with an array of autonomous sensors, cameras, and radars, enabling the adjustment of active safety modules. Radar sensors, which operate using microwaves, are capable of detecting external objects and assessing their position, distance, size, and speed. Camera-based systems serve to identify and warn of potential hazards and are frequently integrated with radar systems. For instance, monocular cameras possess a Field of View (FOV) between 50° and 60° and a range extending beyond 150 to 200 m, supporting applications such as pedestrian detection, road lane analysis, speed limiter identification, traffic sign recognition, and assistance in driving and parking maneuvers [9].

In in-vehicle communications, electronic subsystems are essential for optimizing the function of all vehicle components. A key standard in this domain is the Controller Area Network (CAN) bus, which enables the transmission of short messages across the network, facilitating communication among Electronic Control Units (ECUs) at data transfer rates up to 1 Mbps. The CAN bus is specifically designed to support the self-diagnosis, troubleshooting, and efficient handling of communication issues. CAN communications employ the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol, with messages identified by unique 11-bit identifiers that encompass data processed and transmitted across the network and subsequently received by connected nodes [10].

Beyond the CAN bus, the Local Interconnect Network (LIN) standard serves as a localized network facilitating interconnection and communication among intelligent sensors. The LIN is predominantly used to manage light sensors, door and window control, and operates on a master–slave architecture. For higher-speed communications, the FlexRay bus provides superior fault tolerance, enhanced efficiency, and improved reliability compared to CAN; however, implementing FlexRay is more costly and often necessitates infrastructure redesign. FlexRay's communication speed can reach up to 10 Mbps, making it particularly valuable in modern vehicle applications. Additionally, the Media Oriented System Transport (MOST) standard supports multimedia transport within the vehicle. MOST employs a ring topology and synchronous data transmission, enabling the transfer of audio, video, voice, and other data via optical fibers or electrical conductors [11].

According to vehicle accessibility protocols, internal networks such as CAN and LIN offer limited access to users and are intended for manufacturers and developers only. Any unauthorized external intervention may compromise the condition of the vehicle. These networks are not externally accessible via analysis and control devices, even for specialized personnel in dealerships or service centers. The on-board diagnostics (OBD) system is used to facilitate user-level access to computerized diagnostics. This system allows on-board diagnostics directly on the vehicle, using a standard communications port that provides real-time data, fault reports, technical status, mechanical parameters, and the wear of mechanical and electrical components, depending on the type of vehicle. The information obtained from inside the vehicle is a reliable and viable source for use in external communication environments. A relevant example is the integration of such data into traffic control and management systems, which could benefit from information directly from vehicles. This would allow critical situations to be managed, helping to improve mobility and road safety [12].

A key direction of wireless communications in the vehicular domain is the precise identification of vehicle position and analysis of vehicle movement dynamics. Many vehicle applications rely on position analysis and management systems such as the Global Positioning System (GPS). GPS, a system of American origin, is characterized by a network of geostationary satellites that communicate directly with GPS receivers, providing precise information about the location and positioning of an object. A GPS receiver uses high-frequency radio signals, a synchronized clock, and a database with the exact locations of each satellite, thus being able to calculate the distance to other satellites. According to studies, data accuracy can be substantially improved by using Differential GPS (DGPS) and a Wide Area Augmentation System (WAAS) [13]. New generations of vehicles can use 'estimated track' systems, which become functional in situations where GPS-based navigation is not available, such as in areas without coverage, tunnels, or mountainous gorges.

Another global positioning system is Galileo, of European origin, which operates similarly to the American GPS, but is civilian-controlled and provides information to both the general public and the military. The Galileo program became fully operational in 2020, with 30 dedicated satellites. Glonass, a global satellite navigation system developed by

Russia, consists of 24 dedicated satellites and operates on the same principles as GPS and Galileo. China's Beidou system also includes 42 dedicated satellites. There are now devices capable of receiving signals from multiple positioning systems simultaneously, which helps increase the accuracy and quality of the signal for vehicle positioning analysis [12,14].

Evaluation of Radio Technologies Applied in the Context of Vehicles

Radio technologies for vehicular applications address transportation challenges through cooperative C-ITSs and dedicated solutions. C-ITSs leverage (V2V) and (V2I) communications to enhance traffic safety, reduce road accidents, and lower CO_2 emissions. These systems enable vehicles to detect potential hazards—such as obstacles, construction zones, hazardous surfaces, or accidents—and to communicate this information to drivers and nearby vehicles.

Vehicle-to-everything systems alert traffic participants to dangers via visual or auditory signals, facilitating the rapid activation of braking systems to avoid collisions. The V2X infrastructure comprises on-board units (OBUs) and roadside units (RSUs), which include ITS central stations (ICSs). European standards recommend ITS-G5, based on the IEEE 802.11p protocol, as the wireless communication standard for V2X. RSUs, installed on road infrastructure, act as intermediaries between vehicles and infrastructure, playing critical roles in traffic management, such as at traffic lights or signal-controlled pedestrian crossings [15].

The central ITS controller, integrated within a larger control system, disseminates information to other controllers. The OBU requests data on the current route, directional changes, or the locations of emission zones. In cases of route obstructions, the central system can suggest alternative paths to enhance vehicle safety. Compared to traditional vehicle sensors or non-cooperative DSRC systems, these C-ITS solutions offer greater coverage and reliability, detecting obstacles and hazards over extended distances. Communication among vehicles utilizes ITS-G5, with information transferred to control areas via LTE/4G/5G cellular networks. Additionally, V2X systems enable the sharing of collected data with stakeholders such as automotive manufacturers, road operators, local authorities, and administrative-territorial institutions. Deploying these technologies in road transport can significantly mitigate road accidents and reduce vehicle-related CO_2 emissions [16,17].

Interoperability and harmonization across diverse ITSs are crucial for achieving comprehensive V2X coverage within existing road infrastructure. At the European level, the European Commission initiated M/452 standardization efforts in 2009, involving the three European Standardization Organizations (ESOs): the European Telecommunications Standards Institute (ETSI), the European Committee for Standardization (CEN), and the European Committee for Electrotechnical Standardization (CENELEC). These initiatives aimed to establish a cohesive framework of standards, specifications, and guidelines to facilitate the deployment of cooperative intelligent transport systems (C-ITSs) across Europe.

Initially, the CEN and ETSI adopted the IEEE 802.11p standard, while the CENELEC expressed certain reservations. Over time, international collaboration has expanded, bringing in the International Organization for Standardization (ISO), the Institute of Electrical and Electronics Engineers (IEEE), and the Society of Automotive Engineers (SAE) to support the global harmonization of C-ITS standards. This collaborative effort led to the ESO's approval of the ETSI EN 302 665 and ETSI EN 302 663 standards, both of which are based on IEEE 802.11p, incorporated into the IEEE 802.11 standard in 2012 [18–22].

The main characteristics of the IEEE 802.11p standard are summarized in Table 1, as referenced [23].

Table 1. The main features of IEEE 802.11p standard.

Standard Attributes	IEEE 802.11p
Data transmission rates	3, 4.5, 6, 9, 12, 18, 24, 27 Mbps
Modulation modes	BPSK, QPSK, 16-QAM, 64-QAM
Coding error correction modes	Convolutional coding with K = 7
Coding rate	1/2, 2/3, 3/4
Symbol length	8 µs
Waiting interval	1.6 µs
Bandwidth	10 MHz
Frequency range	5.850–5.925 GHz

The origin of the development of this standard derives from the US Federal Communications Commission's (FCC) proposal in 2000 to allocate 75 MHz of the 5.9 GHz spectrum (5850 MHz to 5925 MHz) for vehicle-to-infrastructure communications. This initiative aimed to implement road safety applications, reduce congestion and improve vehicular traffic networks. The allocated spectrum has been divided into seven channels of 10 MHz each, with the first 5 MHz not being used and reserved as guard channels. Crucially, this radio band is free, not subject to FCC usage fees, but there are restrictions on the conditions and technologies of use. In 2004, the IEEE 802.11p standard was developed, which was intended to describe the functions and services required by WAVE stations to ensure interoperability in a short time frame, the exchange of messages in reliable communication, and the provision of critical data in vehicle-to-vehicle communications, without the need to connect to a Basic Service Set, as was the case with 802.11. The 802.11p standard can be limited to the 802.11-specific MAC and PHY levels, which were dedicated to single-channel operations [24].

Differently, DSRC, which deals with higher-level approaches, includes IEEE 1609.x, where 1609.3 defines how to establish and manage connections and 1609.4 facilitates higher-level operations for multiple channels without directly involving the PHY. These approaches aim to simplify the process by installing a set of radio units to form and maintain a group with a high level of cooperation. Thus, radio units can communicate directly with each other, provided they are part of the same group, filtering outside transmissions. This type of group is defined as a Basic Service Set (BSS), with several protocol mechanisms to ensure robust and secure communication at its level. The main purpose of these changes was to efficiently configure the whole group without conforming to the standard load, which simplifies BSS operations, having an ad hoc approach adapted to the vehicular environment. A BSS can be interpreted as a group of 802.11 stations connected to an access point, configured to communicate with each other using the wireless network, called a BSS. The BSS mechanism focuses on controlling and accessing the resources provided by an access point, allowing the radio unit to filter the information transmitted by other radio units in the coverage area of the access point. A radio unit first analyses the signal received from an access point and then associates it with a BSS, including the association or authentication process. The ad hoc mode can be defined in the 802.11 standard, which establishes connections with the BSS infrastructure and is referred to as an IBSS—Independent BSS. An IBSS requires a high level of attention, is extremely complex during configuration, and is dedicated for use in vehicular communications. A BSS can be identified by users by SSID—Service Set Identification, equivalent to the name generated by a Wi-Fi hotspot. The SSID is associated with a BSS known to radio units at the MAC level and is represented by a field of approximately 48 bits, similar to a MAC address [25,26].

Each Basic Service Set (BSS) requires a unique identifier, called a BSSID, which is distributed to all users. In an Independent BSS (IBSS), the MAC address is locally generated and consists of a random number of forty-six bits, except for one bit independently set to 0 and one locally set to 1. At the MAC level, the radio unit relies on the information in the Address 1 field when receiving a set of data from the physical layer (PHY) to make appropriate decisions. Address 1 may include a group of addresses, and the BSSID ensures that the transmission generated by a station is maintained in the same BSS. In some special situations, such as when a BSSID becomes a wildcard, it includes all bits with the value 1. The current 802.11 standard imposes certain restrictions on the process of using management frames, depending on the demand of the subtype identified as sample. It should be noted that the IEEE 802.11p standard is largely inspired by 802.11a, with a channel width of about 10 MHz, compared to 20 MHz [27].

The basic 802.11 standard uses 10 MHz channels, and their implementation involves doubling the parameters compared to orthogonal frequency division multiplexing (OFDM), used in 802.11a. This adaptation of the 802.11a standard helps to manage the increase in radio-channel-induced delay spread (RMS Delay Spread). In vehicular environments, a guard interval of around 20 MHz is not considered wide enough to prevent interference in the transmission process.

Thus, the IEEE 802.11p communications standard performs reliably under ideal traffic conditions, but does not excel in handling large numbers of users, and performance drops significantly under dynamic traffic conditions, which can lead to critical situations. These problems are attributed to both its ad hoc nature and the decentralization of the protocol, which necessitates the need to explore alternatives for information exchange within ITS. The use of other types of networks, including mobile communication technologies, should also be considered. Consequently, vehicular environments are becoming an essential component of mobile communications, but bring new requirements, in particular in terms of inter-vehicle safety. Vehicle dynamics pose many challenges for future physical layer (PHY) developments. The 802.11p standard has been adjusted to address these specific requirements (Figure 1).

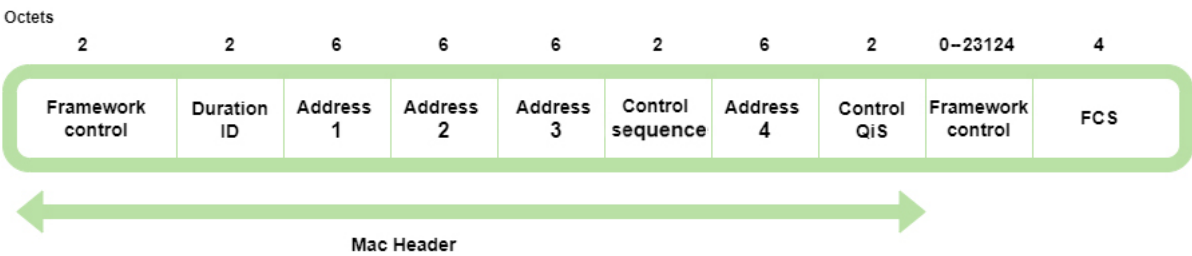

Figure 1. The framework format on OSI layer 2 of the 802.11p communications standard.

As noted in source [28], IEEE 802.11p is acknowledged as the sole standardized wireless technology for vehicular communications that meets the stringent low-latency demands of under 100 ms for transmitting road safety information and messages. Conversely, contemporary technologies in LTE, 4G, or 5G cellular networks can process and send data with even lower latency, approximately 20 ms or less. LTE, in particular, provides high data-transfer rates, achieving a minimum of 100 Mbit/s for downloads and 50 Mbit/s for uploads, coupled with low latency [29].

We can say that the LTE standard, highlighted by 3GPP, is capable of supporting very high terminal speeds, allowing speeds of up to 350 km/h or even 500 km/h, depending on the frequency band, although communication performance tends to decrease with increasing speed [30]. Recent research, such as that reported in [29], has evaluated the applicability of LTE and ITSs, concluding that LTE meets all ITS standard requirements and can, in some aspects, exceed 802.11p. For example, LTE can handle a substantial connection for about 700 ITS users, compared to 802.11p's capacity of 400 users, and offers a longer range of 2000 m compared to 800 m for 802.11p.

However, during instances of transmission and connectivity overload, LTE struggles to consistently meet the strict requirements of ITSs. Study [31] discusses LTE's ability to support dedicated road safety applications, although these are limited in terms of cooperativity. When the LTE network becomes overloaded, it fails to deliver the anticipated results. In comparison, study [32] examines the UMTS cellular system alongside LTE and 802.11p, but only in a single scenario. This study concludes that UMTS does not meet C-ITS requirements, while LTE shows potential but cannot yet provide the consistent low latency specific to 802.11p communications. Consequently, 802.11p cannot currently be replaced by LTE due to significant deployment and cost disadvantages.

Within the European Union, the following ITS-G5 frequency bands are distinguished:

ITS-G5A: with a frequency range spanning 5.875 and 5.905 GHz, dedicated to ITS applications related to road safety and traffic management;

ITS-G5B: with a frequency range spanning 5.855 and 5.875 GHz, reserved for ITS applications except for road safety applications, and mainly used locally [31];

ITS-G5C: with a frequency range between 5.470 and 5.725 GHz, intended for RLAN, BRAN, or WLAN use. The operation of this band is conditional on Dynamic Frequency Selection (DFS) and BSSIDs are not allowed;

ITS-G5D: with a frequency range spanning 5.905 and 5.925 GHz, reserved for future ITS developments.

The G5-CCH main control channel and service channels, such as G5-SCHI and SCH2, are directly linked to the ITS-G5A and are specifically designed for road safety. Other examples include the SCH3 and SCH5 channels, which are used in road efficiency applications. As indicated in Table 2, the transmission power limits vary between 23 dBm (approximately 200 mW) and 33 dBm (around 2 W), with data rates ranging from 6 Mbit/s to 12 Mbit/s (G5-SCH2) [33].

Table 2. Channel allocation in Europe—ETSI EN 302 663.

Frequency Band	Channel Type	GHz Frequency Range	802.11 Frequency Channel	Standard Transfer Rate	E.I.R.P. (Effective Isotropic Radiated Power)
ITS-G5A	G5-CCH	5.895–5.905	180	6 Mbit/s	33 dBm
	G5-SCH1	5.875–5.885	176	6 Mbit/s	33 dBm
	G5-SCH2	5.885–5.895	178	12 Mbit/s	23 dBm
ITS-G5B	G5-SCH3	5.865–5.875	174	6 Mbit/s	23 dBm
	G5-SCH4	5.855–5.865	172	6 Mbit/s	0 dBm
ITS-G5D	G5-SCH5	5.905–5.915	182	6 Mbit/s	0 dBm
	G5-SCH6	5.915–5.925	184	6 Mbit/s	0 dBm
ITS-G5C	G5-SCH7	5.470–5.725	94 -145	limiting	30 dBm (DFS master) 23 dBm (DFS slave)

In the ITS-G5 frequency bands, except for ITS-G5C, dynamic frequency selection is prohibited, preventing the selection of the least congested channel. The 802.11p wireless standard requires pre-established frequency channels and detailed channel control (G5-CCH) to provide multiple service channels (G5-SCH).

In summary, 802.11p is recognized as the leading candidate for radio communications dedicated to intelligent transport systems, being highly reliable for active safety applications due to very low delays, a range of more than 500 m, and the ability to communicate directly with source and end nodes without the need for additional network infrastructure, thus facilitating distributed communication. Unlike conventional Wi-Fi technologies, these nodes communicate without generating a BSS, allowing for rapid information exchange. For NLOS (non-line-of-sight) scenarios, such as congested areas or urban intersections, as well as for extending the coverage area, roadside infrastructure units (RSUs) are installed that provide advanced security and management functionality. The main impediment is that the deployment of such a nationwide RSU network is considered economically unjustified by the authorities, and the existence of cellular networks discourages the deployment of such systems. In addition, the high mobility of vehicles causes a considerable fading effect and a significant amount of packet collisions. Research also points to an additional problem related to simultaneous communication with two nodes in different coverage areas, leading to radio packet collisions close to the receiver, a phenomenon known as a hidden node.

Thus, although 802.11p behaves reliably under ideal traffic conditions, various bottlenecks occur in real dynamic situations and it does not provide an efficient solution for managing large numbers of users. Fifth-generation communications present complementary solutions to the challenges faced by IEEE 802.11p in vehicular communications, which will be addressed in this paper.

3. Cooperative Solutions Based on V2V-V2R for Congestion Control and Advanced Communications in Urban Traffic

It can be argued that a crucial aspect of C-ITSs is the capability of road users and infrastructure to obtain precise data on the position, movement, and routes of objects, as well as their status and mobility levels. This capability falls under the concept of cooperative awareness (CA). This functionality is essential for the correct and autonomous operation of ITS applications and services, enabling collision risk detection and the prevention of adverse events by accurately knowing the position of vehicles and information in the area. Continuous information and feature sharing among road users, facilitated by direct point-to-point communications, produces cooperative awareness messages. The services and capabilities offered by cooperative awareness (CA) are essential for the ITS road infrastructure, in contrast to other communications that do not get directed to the dedicated network. As discussed above, the sending and receiving of CAMs is conducted through the CA core service.

The function of CA is to regulate the frequency at which CAMs are generated and the intervals between them. According to ETSI EN 302 637-2 [34], the minimum and maximum frequencies are set at 1Hz and 10Hz, respectively. Within these limits, the basic services provided by the CA can adjust the generation frequencies according to changes in their own layer, such as changes in position or speed, and channel mobility, controlled by Decentralized Congestion Control (DCC). These generation frequencies are essential to guarantee a swift CAM response time of under 50 milliseconds, ensuring accurate message interpretation regardless of the ITS stations' transmitting locations.

The use of a timestamp is essential to ensure timely synchronization, regardless of the users of the road infrastructure, which is fundamental to the process described. When a cooperative awareness message follows a specific structure, the identification and synchronization process becomes simpler. This message type incorporates the ITS Packet Data Unit (PDU) header, which includes the protocol version, message type (CAM, DENM, DCC), and originator ID, among other information stacks. These elements can be used optionally or individually by the ITS station, enabling the vehicle to recognize multiple stacks and containers with high-frequency information.

Applications and their complexity may require the number of containers to be supplemented by the addition of additional information elements and frames. The primary container can hold essential ITS station details, such as location, time, geographical coordinates, and the positions of nearby common nodes for all ITS station types (ITS-S vehicle, stationary or personal ITS-S, direct or indirect). The high-frequency operational container carries data from the dynamic environment and manages rapid ITS station changes, including speed, direction, and band adjustments.

3.1. Development of a Cooperative Architecture Based on the 801.11p Standard for Interconnecting Road Infrastructures

Communication over short distances at 5.9 GHz (DSRC) relies on the IEEE 802.11p standard and has emerged as a feasible solution for various applications including V2V, V2R, and V2I, alongside aiding the advancement of autonomous vehicles. DSRC employs orthogonal frequency division multiplexing (OFDM), which is grounded in the wireless local area network (WLAN) standard IEEE 802.11a. In terms of preventing data collisions, DSRC utilizes carrier sensing collision avoidance multiple access (CSMA/CA). As a type of short- and medium-range wireless communication, it integrates well with road safety system concepts.

In the ultimate phase, the examination focused on synchronizing and assigning specific transmission slots in multi-hop networks with heightened mobility scenarios, refining IEEE 802.11 MAC communication for road-focused systems. While there were constraints on MAC protocol establishment performance, a self-competition trend emerged among neighboring nodes and data transmissions, resulting in certain constraints in the IEEE 802.11 context. Additionally, ad hoc data routing through the ad hoc distance vector (AODV) proved beneficial for message integrity in DSRC applications.

The depiction in Figure 2 presents the structural layout of the DSRC module, revealing a return loss below 0 dBm across all RF ports. Assessments conducted on the DSRC receiver spanned from −95 to 20 dBm, with a margin of ±2 dB under challenging operational circumstances.

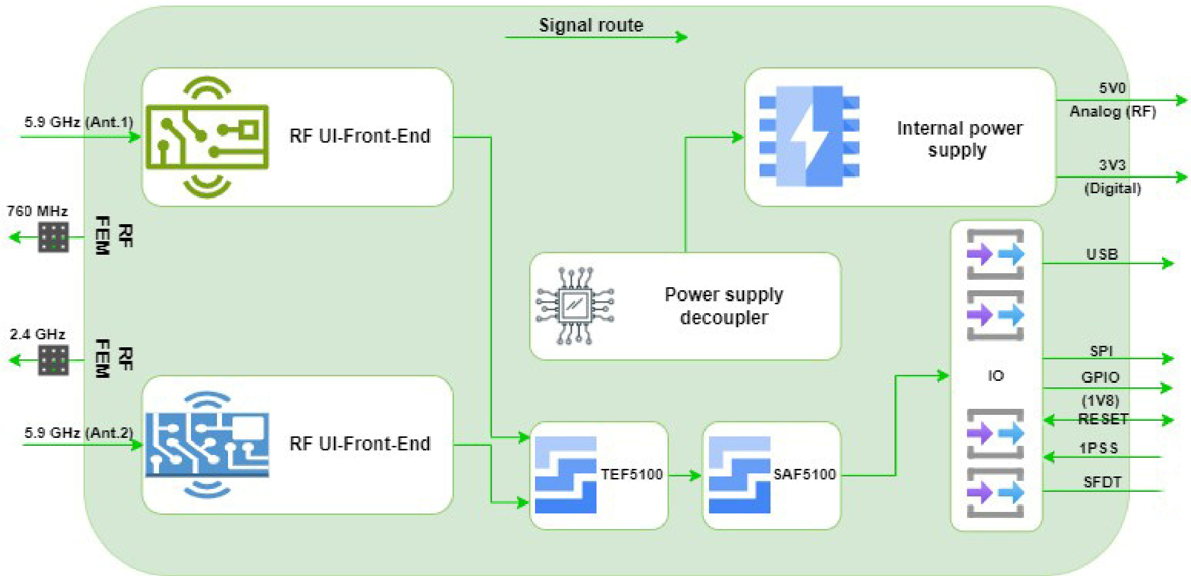

Figure 2. Communication architecture of OBU control unit Mk5 system—DSRC.

Demonstrating the adaptability and maneuverability of the physical layer (PHY), grounded on an IEEE 802.11p compliant radio transceiver, was emphasized through the incorporation of sophisticated data processing algorithms within the modular receiver. The interface between the PHY and RF facilitated enhanced radio configurations, simplifying the deployment of either single-channel or dual-radio DSRC systems. The RF subsystem boasted the capability to transmit via distinct antenna ports tailored for 5.9 GHz frequency bands, with one end positioned to encompass a broad coverage area. Access to RF outputs was provided through separate receive (Rx) and transmit (Tx) pins while maintaining compatibility with the 760 MHz and 2.4 GHz frequency bands. Leveraging these frequency bands necessitated RF front-end circuitry and an off-board UI for seamless integration into a radio system.

When configured in a dual-radio setup, the module showcased remarkable PHY adaptability, functioning as two distinct PHY modules, each functioning on its own radio channel. Leveraging U-Blox technology for both single and dual antennas, the receiver sensitivity operated at 5.9 GHz in DSRC mode with a 10 MHz bandwidth. At these input levels, the packet error rate (PER) stood below 10% for a PSDU length of 1000 bytes. Receiver sensitivity was evaluated with input signals directly fed into the antenna ports at ambient temperatures ($\pm 6^{\circ}$).

Each transmission underwent fading due to the Pure Doppler effect, with the second antenna experiencing an 11 Hz Doppler, disrupting channel phase synchronization. The Rx signal indicated zero flux power, with the maximum input level and receiver operating level set at -20 dBm (PER may surpass 10% for input levels beyond this threshold). Consequently, the received sensitivity was gauged by an input signal directly fed into the antenna ports, where each transmission contended with Pure Doppler fading. Moreover, the second antenna introduced an 11 Hz Doppler, thwarting premature channel synchronization. The Rx signal denoted signal strength relative to time zero. The receiver's maximum input level stood at -20 dBm (PER can oscillate between 10 and 15% under mobile conditions across all input levels). The characteristics and transfer rate, contingent on device mobility, are anticipated to endure minimal degradation under ideal circumstances. However, in scenarios marked by congestion and heightened mobility, interactions could transpire at distances of approximately 1000 m.

The primary container possessed the capacity to store essential information for ITS stations, encompassing details like location, time, geographic coordinates, and proximity to neighboring common nodes across various ITS station types (ITS-S vehicles, stationary or personal ITS-S, both direct and indirect). Meanwhile, the high-frequency operational container managed data pertinent to the dynamic environment, overseeing rapid alterations in ITS stations such as velocity, trajectory, and frequency band adjustments.

As mentioned earlier, compliance with both standard requirements and strict legislation in force was imperative for the V2X system. In the first phase of performance evaluation, measurements were carried out on the road infrastructure around the university campus in Suceava over a distance of over 3 km on the roadway.

The demonstration of the efficiency of communication systems based on the 802.11p standard aimed at exposing the interconnection aspects between vehicles and infrastructure with the transmission of periodic messages validating their position and the degree of traffic congestion in the monitored area.

Enhancing radio performance involved utilizing dual antennas for transmission and reception, while the MAC layer operated on the SAF5100's ARM processor, providing various operational modes. Transmit power ranged from -10 dBm to +22 dBm, adjustable in 0.5 dB increments per antenna port. Synchronization is critical for V2X systems due to position detection and accuracy requirements. Therefore, the MK5 incorporated a GNSS receiver supporting GPS, GLONASS, and Galileo, ensuring synchronization even in areas with weak GNSS signals like densely populated urban areas.

The GNSS receiver in the MK5 delivered precise position updates and relative data, achieving speeds of up to 10 corrections per second. It maintained a horizontal accuracy of about 2 m and ensured timing accuracy equivalent to 25 ns. As detailed in the previous chapters, the system ports had various uses, in particular the serial port for connecting an external GNSS receiver. The MK5 ran a GPS server (Daemon) in the background, constantly maintaining the connection and automatically reconnecting the system in case of interruptions, thus ensuring uninterrupted data transmission. This facility allowed applications direct access to GPS data, including for optimizing the operation of the GPS receiver during the test phase.

3.2. Exposure of the Test Area to Real Mobility and Heavy Traffic Conditions

As stated in the manuscript, we attempted to highlight the degree of usefulness in introducing emerging cooperative systems into road infrastructure based on the 802.11p standard with the maintenance of a de-congestion rate in heavily trafficked urban areas.

Therefore, a set of practical scenarios applied to real traffic cases in the city of Suceava in the vicinity of the university campus were considered, with the possibility of performing measurements over a distance of more than 3 km of the roadway and passing through all possible road forms, traffic-lighted intersections, non-traffic-lighted intersections, two-lane access roads, one-lane roads in each direction, or one-way road sectors.

In Figure 3, we see the layout of the test area that simply surrounded the university campus, and the area for controlling and managing the data taken from the traffic for efficient management. The scenarios were run in a comprehensive manner addressing different cases and aiming to highlight traffic behavior under different circumstances of the 802.11p standard.

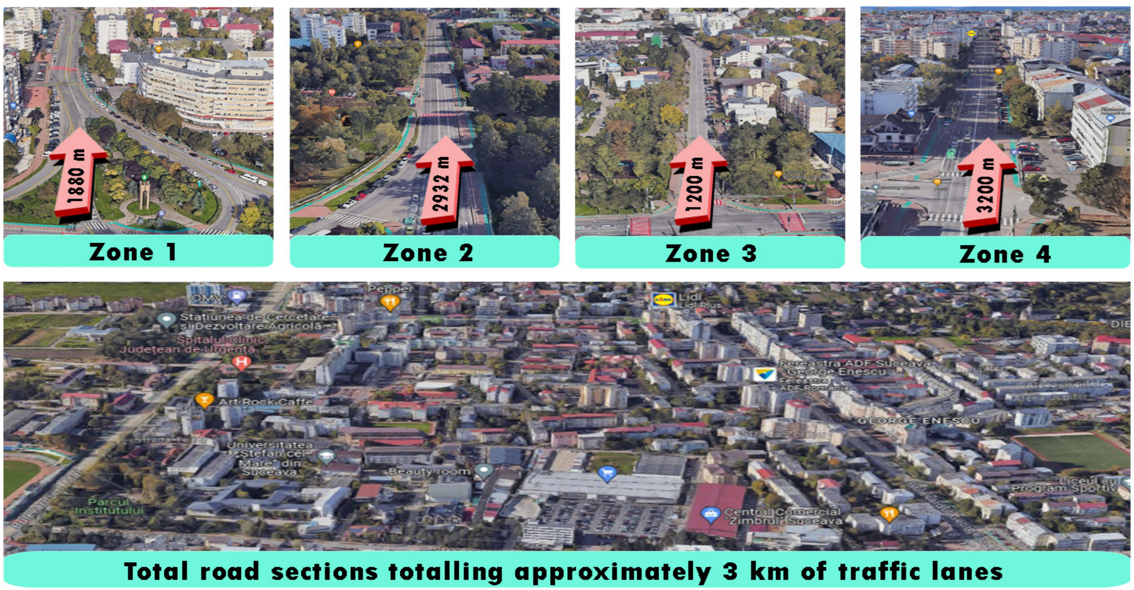

Figure 3. Areas analyzed and road sections used in the assessment of traffic conditions.

The selected test areas, Zones 1 to 4, represent diverse urban traffic conditions, offering relevant scenarios for evaluating the proposed architecture. These zones included various urban environments such as residential, commercial, and mixed-use areas, each with distinct traffic patterns. Residential areas, for instance, are influenced by daily activities like school transportation and local access. Commercial areas experience high traffic volumes due to economic activities, deliveries, and pedestrian flows. Mixed-use zones or campuses combine residential and commercial characteristics, reflecting the traffic dynamics of multifunctional spaces. Zone 1, Zone 2, and Zone 3 were predominantly congested during morning hours (8:00–11:00 AM) and experienced traffic peaks again in the afternoon (3:00–5:00 PM). Zone 4, situated at the intersection of Zones 1 and 3, became heavily congested between 4:00 and 5:30 PM, serving as an access road where redirected traffic converged. The selection of these zones ensured a comprehensive evaluation of the proposed system under varying traffic conditions and urban scenarios, providing insights into its behavior and performance.

This selection was made to reflect the diversity of traffic conditions encountered in typical urban environments. In addition, the chosen areas were evaluated according to characteristics such as infrastructure density, frequency of congestion incidents, and connectivity to other areas. The elaboration of these criteria underlines the relevance of testing in these locations, reinforcing the practical value of the study for improving urban traffic management. By clarifying these aspects, the contribution of the study is extended, demonstrating that the data presented are not only local, but can be extrapolated to better understand general traffic conditions in similar urban environments. In order to see how the road infrastructure presented in the article behaves, Table 3 has been outlined to present the vehicle flow for each artery analyzed in the manuscript. Therefore, there are the following vehicle variations for each traffic artery and its characteristics.

Table 3. Information on the number of vehicles that the infrastructure allowed and the number that transited the areas within 10 min.

Time Intervals	Zone 1 Two-Lane Road /Vehicles	Zone 2 Two-Lane Road /Vehicles	Zone 3 One-Lane Road /Vehicles	Zone 4 Two-Lane Road /Vehicles
08 a.m.	348	458	473	430
09 a.m.	397	530	520	563
10 a.m.	344	588	400	600
13 p.m.	420	632	484	843
14 p.m.	478	699	491	749
15 p.m.	523	734	500	837
16 p.m.	595	833	544	989
17 p.m.	687	980	590	1138

Taking into account the traffic information, we can present the following aspects. The number of vehicles transiting those areas is within the allowed limit, with the mention that there may be deviations of 10–15% from the number presented in the above table because the number of vehicles transiting those areas was directly related to the other traffic events, and these can be unpredictable, imperceptible, and only pre-empted with great difficulty. The complete information is exposed in the form of an explanatory graph to differentiate each area, see Figure 4.

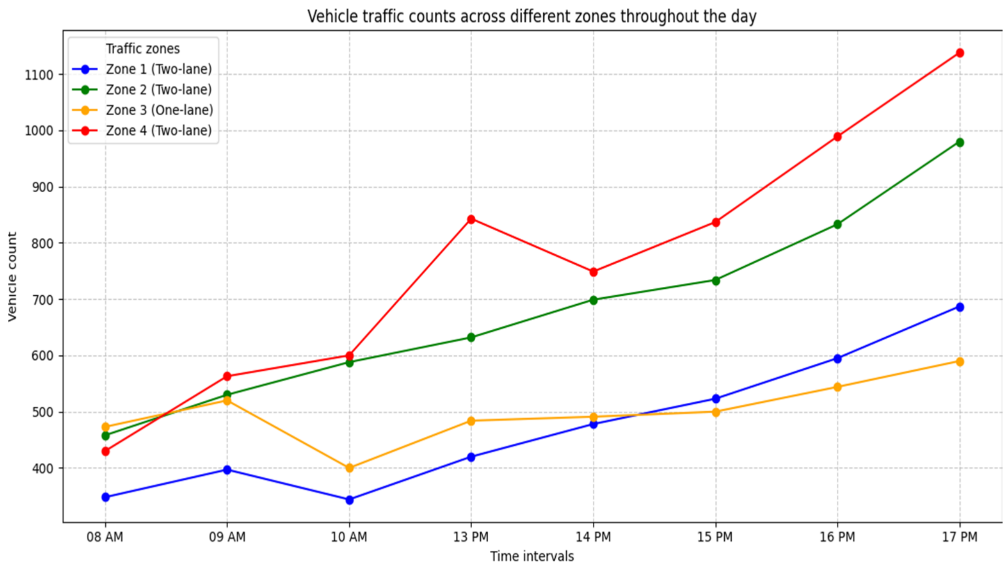

Figure 4. An illustrative graph showing the variation in the traffic patterns between zones, with Zone 4 recording the highest peak during the evening (5 p.m.).

For such conditions, we had to consider the design of a prototype system able to adapt both to the requirements of the standards, but also to the strictness of the road legislation, without neglecting the component of traffic volatility and aspects related to the mobility of cars on certain road sectors, especially since we are talking about urban traffic, and the distances over which communications are offered must be as flexible as possible even if in some cases they exceed 700–800 m in a straight line or more than 500 m from the control point from which the infrastructure is managed.

3.3. Technical Description and Phasing of the Development of the Software and Hardware Platform for Connected Vehicles

To develop the proposed prototype system to achieve V2X communications and to avoid deviation from the standard or issues that directly contravene the information set out in the legislation in force, all the elements and parameters supporting the duality of a system based on two types of GPS and that could transfer information over distances of more than 50–100 m were monitored at laboratory level.

It is important to mention that the proposed prototype used the IEEE 802.11p standard, with the integration of hardware modules such as the MK5 GNSS receiver that supported position synchronization through systems such as GPS, GLONASS, and Galileo. As for the software tools, libraries were used for data processing at the MAC layer level of the SAF5100 and a dedicated GNSS server was used to ensure the flow of information. The tests were carried out using dual antennas, configured for 5.9 GHz frequencies, with an adjustable transmission power between −10 dBm and +22 dBm, increasing the accuracy of the transmissions. They were applied in real urban mobility conditions, over a distance of over 3 km, including various scenarios such as traffic-lighted intersections and heavy traffic areas. Thus, the experimental methodology provides a solid basis for analyzing performance under various conditions, and its detailing in the article would increase the practical value and applicability of the conclusions.

When the mixed ports of the system were exposed for information retrieval through the serial port and the connection of the external GNSS receiver, the modules dedicated to V2X communications could run a common GPS tracker server in the background, and by calling from the console the IP address, which responds to each item in the network, we received a link with the information transmission and the data stream that the proposed system mediated. We are talking about a connection between two or more vehicles, these having extremely high dynamics about the standard and the information that such a GPS-based system can retrieve.

According to the architecture in Figure 5, elements were introduced that took into account the interconnected devices, including the vehicles, the interface modules, and the connections between them, be it 4G, 5G, or LTE. Each component in the diagram responded to the demands and rigors of the 802.11p standard to develop an emerging system capable of providing valuable traffic information and delivering timely and vital data to other participants to reduce congestion, road accidents, or prevent adverse events. It should be kept in mind that when performing outdoor test scenarios in a fully mobile environment, data transmission, and reception were performed with two or more antennas, these were directly correlated with the MAC layer within the ARM processor of the SAF component and may have had a variety of pre-functionalities and direct data collaboration modalities. We can say that there was also a minimum power, a transmission practice, which was around the values of 10 dBm, its maximum power being over +20 dBm, at the antenna port level.

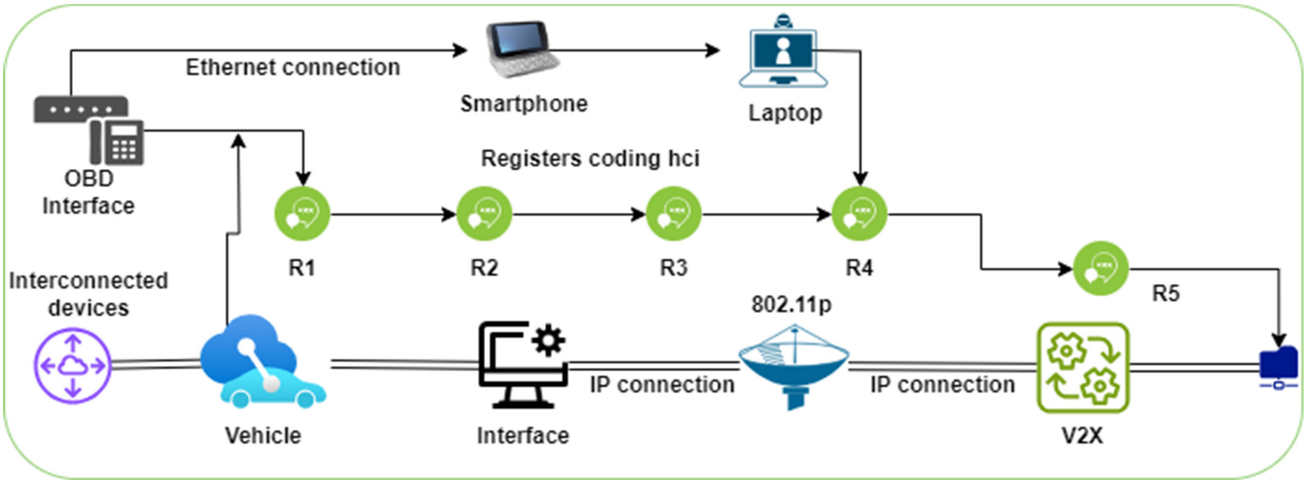

Figure 5. A diagram of the design of the 802.11p urban communications prototype.

We consider this transmission power as a possible permanent and stepwise control at each stability threshold, as this element allows better position detection and peak-to-peak synchronization. If we consider a GNSS-based receiver, it can incorporate other positioning and detection systems, even Beidou, GLONASS, or even Galileo, which can perform collaborative iterations to maintain the synchronicity process in conditions where the GNSS radio signal becomes imperceptible, especially in heavily trafficked areas or areas with urban agglomerations, high-level buildings, or areas with passages.

Thus, we had to consider the design of an architecture based on a GNSS radio module for urban areas with procedures taken over in extreme conditions by a Glonass/Galileo variation, especially when there are constant updates regarding position or relativity, the correction speeds must be extremely high, exceeding, in some cases, 30 corrections/second, and the horizontal accuracy must be about 5 m, which is equivalent to about 20–30 ns. Architectural implementations of systems of this time are always based on a controller or master module through which the network and CAN ports are interfaced; data acquisition and assimilation at the network level will be performed through an iterative sequence between the basic information received through the 802.11p routing server and the time sequences at which data are extracted from the sequential debugging procedures.

Libraries dedicated to the process of data retrieval and filtering passed through the literal area through those hci stacks where the information profile and how it influences the connection was established. When we talk about connectivity, we consider that this is a typical point-to-point connectivity, and, thus, simultaneous nodes were realized on the network in order to transmit information step-by-step between the services identified at the architecture level. We can say that the identified services had a unique ID, which is universal, written in about 128 bits (UUID) for messages of interest and 256 bits (UUID) for additional characteristics that an item in the network has and is not part of the registered ones. Each identifier was characterized as a unique ID and a pseudo ID, 1×1321 or 2×3312, directly reflecting its position, priority if any, and also elements of the amount of information it contained as a bearer.

3.4. Setting Descriptive Scenarios and Length Analysis for Bit Rate Propagation Segments

When we generated a first set of information to expose in the designed prototype to highlight the reliability and configurable aspects of the system, iterative initialization procedures were run at the internal routine level for devices defined as standard; the address had the standardized form of a group of octets from an IP address, which was formed, in turn, using approximately 6 digits, and the standard value of which could be identified as a serial number to be identified as normative; and a pre-identifier was generated with four instances encrypted at the redundant stack level based on the calibration standard in the last MAC substrate. This was taken over as a dedicated local network in the interconnection of each IP address layer.

To have conclusive measurements, we needed to obtain the information as accurately as possible for the bits, which were divided into about four segments, with a unique quantization and a propagation area or buffer segment for each of the phases they were at when they interconnected with the signal carrier. We can say that the length for each segment could directly influence the bit rate at the CAN port level and therefore it was necessary to generate a new iteration for the bearer through a CAN identifier.

In order to obtain a compliant bit transfer, we needed to analyze the partitioning of the buffer segments for each mode phase in the clock signal rate being used as a barometer between the clock signal selection mode and the CAN port interface that was set at the vehicle level, which was in many cases $f_{CANCLK} = 60$ MHz. Subsequently, we also considered the aspects that defined that prescalar value product by which the ratio between the CAN clock frequency and the serial clock frequency f_{SCLK} was emphasized, this being based on the amount of time of the CAN protocol relative to the total amount of time, the progression of this value, defined as follows, being extremely important:

$$f_{SCLK} = f_{Tr} = \frac{f_{CANCLK}}{Prescalar\ value} \tag{1}$$

where f_{Tr} is transmission frequency.

In order to obtain a sequential configuration of the propagation mode, and for this aspect, thresholds were set for each phase buffer in direct relation to the length between the transmission and the waiting duration between the two transmitting and receiving entities of the signals, being defined as follows:

$$\text{Bit Rate} = \frac{f_{Tr}}{(Nr\_Tq)} \tag{2}$$

This aspect exposes the bit transfer rate in relation to the number of time quanta, obtaining by this ratio the number of time quanta, and the definition of the segment length can also be represented in the following form:

$$Nr_{Tq} = 1 + br_{segprop} + br_{pseg1} + br_{pseg2} \tag{3}$$

Arguably, the parameters should be chosen so as to achieve the desired maximum CAN bit rate, although a valid combination using time segment settings compatible with a standard CAN is also possible. CAN bit rates of 256 kbit/s and 500 kbit/s can be achieved even under non-ideal conditions. Taken as a whole, all these aspects treated individually were part of a standardized configuration in order to achieve the expected transfer rate performance and validations within the thresholds presented above. We can say that these transfer rates also depended on the CAN bus being able to support them, including keeping a high reliability without losses. The main goal was to highlight how to create an emergent communication network within smart cities, to provide sufficient information in traffic or to other participants, and to send these data to the road infrastructure. The current scenarios only tested at the demonstration level the transmission of information in the areas shown in Figure 3.

$$\text{Bit Rate} = \frac{f_{CANCLK}}{N_{Trq}} \tag{4}$$

The maximum bit rate of a CAN bus system depends on the number of time quanta N_{Trq} and the frequency of the CAN clock f_{CANCLK}. This illustrates how increasing the number of time quanta decreases the maximum bit rate. Adjusting N_{Trq} is a balance between achieving the desired bit rate and maintaining proper synchronization across the network.

The architecture shown in Figure 6 includes a simplified design of two components, one dedicated to 802.11p-based communications.

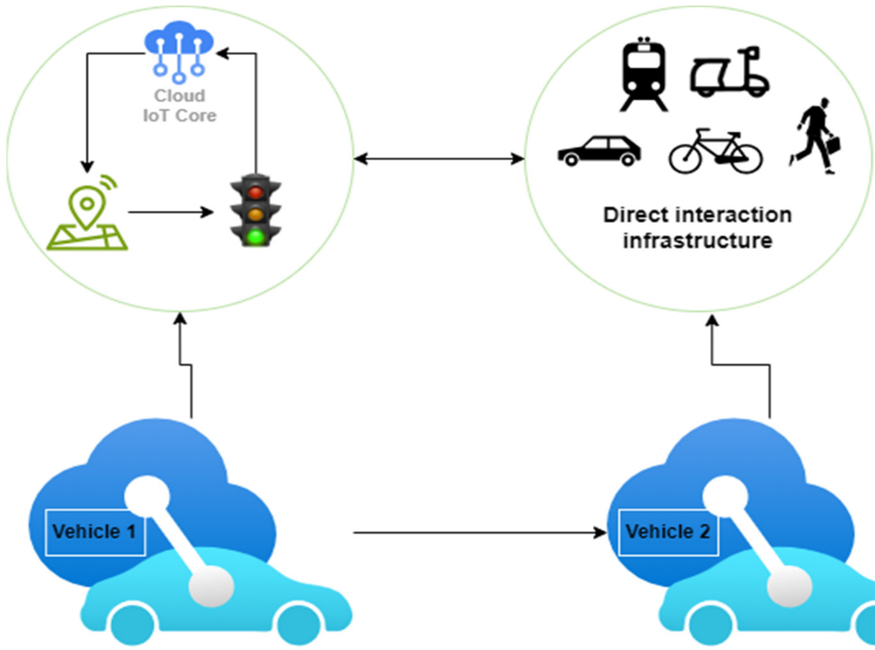

Figure 6. V2V/V2I scenario cooperative data collection and transmission system.

The aim is to achieve stable communication through the complementary combination of these two types of communication. This technological integration can lead to the development of a prototype that offers a solution with superior performance to each technology, capable of handling and transmitting a large amount of information securely to the receiver.

3.5. Testing the Reliability of the Designed Architecture at Urban Infrastructure Level

When we talk about such systems based on 802.11p or the RADAR standard, we also need related elements to support signal accuracy, even Kalman filters. Therefore, to increase the quality of measurements, the use of GPS multisensor packages or the use of video sessions can be an alternative. At the time the tests for the areas under discussion were started, the predictability of the measurement data was leading to a standard deviation between 1 and 3 m, but this can be treated as a special case. The vehicles transmit a prioritization and awareness message of the form X83Z3 in a repetitive loop with a congestion/accident cause code, which starts from the control point and branches out to the whole measurable area. When talking about the absolute and varying mean errors concerning speed, the trend was somewhat upward because of their proportional relationship to the distance or speed of the vehicles. Four test scenarios will be presented for each presented area, and the communication distance, number of transmitted packets, signal strength, number of transmitted/received messages, transfer rate, and operating distances of the proposed prototype will be highlighted.

The mean absolute error varies with speed and tends to increase because of its proportional relationship with travel distance and speed. These scenarios aimed to emulate the ideal functionality of a dedicated system for managing intersections and facilitating communication flow based on 802.11p. Testing the capabilities and limitations of a system utilizing 802.11p encourages the development of new concepts and coding methods within the standard's structure and message transmission format. The quality of the transmitted information relies on the GPS signal's strength and accuracy, as well as the filtering methods employed in the network. In these scenarios, standard filtering was used, and system corrections were provided by GPS antennas, reducing position uncertainty by about 2–3 m for each coordinate. However, this type of filtering proved insufficient under the given conditions, particularly when traversing varied environments and conducting complex measurements in high-mobility scenarios.

In subsequent scenarios, the absence of tall buildings was noted, but the distance to the transmitting area increased substantially, resulting in consistent signal degradation. In the medium to low dynamic range scenarios, with distances ranging from 260 m to 450 m, packet delivery rates decreased, while reception accuracy improved. Another critical factor was that data packets might face more severe collisions in congested areas or at intersections.

Recent research does not concentrate on practical and applied modeling for path loss analysis and testing under extreme conditions. Instead, it addresses packet performance at specific intersections using a theoretical path-finding model and route measurement. In extreme conditions, nearby buildings impacted the line-of-sight (LOS), but communication remained dependable even beyond 100 m from the transmission area, with an effective radiated power (EIRP) of 50 dBm, which is below the 45 dBm limit set for these applications in Europe. In controlled scenarios, communication was sufficiently reliable and stable at distances of 60–100 m, with an EIRP ranging from 22 to 33 dBm, below the imposed limit. We can say that the measurement process started from the control area of the campus, more precisely, right in the center of the simulated area, and aimed to highlight the behavior of the proposed prototype, which is based on the 802.11p standard, visualizing from 50 m to 50 m or from 100 m to 100 m when transmitting data packets with awareness and warning messages. Table 4 shows the scalability of the standard, but also how it remained stable throughout the measurements. For a better interpretation of the information regarding the way in which the areas presented are part of the experimental and simulation process, where we have Area 1 with two runways and distances between 50 m and 470 m, we observed that the message had diminished, but still remained perceptible by the receiver in terms of maintaining transfer rates, see Figure 7.

Table 4. Test scenarios for Zone 1 from point of transmission to reception; data interpretation, data transfer, signal, message.

Zone 1 Two-Lane Road	Packets/nr	Signal [dBm]	Message [B]	Transfer Rate kBps
Distance—50 m	22	−42.03	112	61,212
Distance—100 m	38	−44.12	101	68,944
Distance—200 m	31	−46.43	83	58,195
Distance—250 m	18	−46.75	76	64,350
Distance—350 m	11	−47.31	70	61,212
Distance—470 m	8	−48.11	42	68,944

In the case of Table 5, some instability can be observed in certain areas, this is a much more stressed area in terms of vehicles, buildings, and urban agglomerations, which is reflected in the number of packets, which decreases sharply in extremely remote areas in relation to emission.

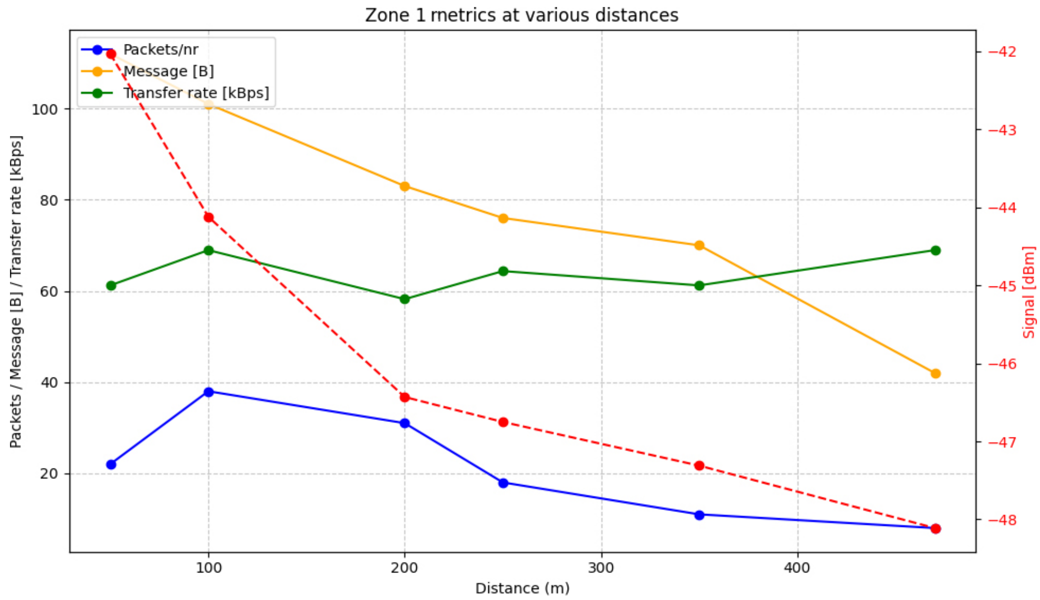

Figure 7. Graphical representation for Zone 1 showing information on distances or loss values of data packets in relation to measurement distances.

Table 5. Test scenarios for Zone 2 from point of transmission to reception; data interpretation, data transfer, signal, message.

Zone 2 Two-Lane Road	Packets/nr	Signal [dBm]	Message [B]	Transfer Rate kBps
Distance—50 m	40	−42.11	112	63,431
Distance—100 m	32	−43.88	93	65,858
Distance—150 m	29	−43.91	90	56,387
Distance—250 m	23	−45.44	83	63,766
Distance—300 m	21	−46.18	80	66,336
Distance—400 m	16	−47.84	71	65,854
Distance—550 m	9	−49.17	51	56,572
Distance—650 m	4	−51.03	43	63,481
Distance—733 m	1	−52.88	38	62,561

The presentation of the information in the tables is also made in graphic form, in which the aspects regarding Areas 1 and 2, and also the parameters related to them as a result of the measurements, are shown by plotting in Figures 7 and 8, respectively. The number of packets transmitted decreases significantly with increasing distance. From 40 packets at 50 m, this number decreases to a single packet at 733 m. This indicates a clear degradation of network performance at long distances, which highlights the physical limitations and interference in signal transmission.

The signal (measured in dBm) decreases from −42.11 dBm at 50 m to −52.88 dBm at 733 m. This trend is representative of the natural attenuation of the signal with increasing distance. It is noteworthy that between 250 m and 400 m the signal varies with a more moderate slope, suggesting a critical point of attenuation in this area. The transfer rate (kBps) remains relatively constant up to 300 m, but fluctuates thereafter, indicating increased instability in the transmission as the distance increases. This instability is significant for critical scenarios where latency plays a critical role. The message size (B) varies between 112 B at 50 m and 38 B at 733 m. The reduction in size indicates data loss and a limited ability to support high-volume transmissions over long distances.

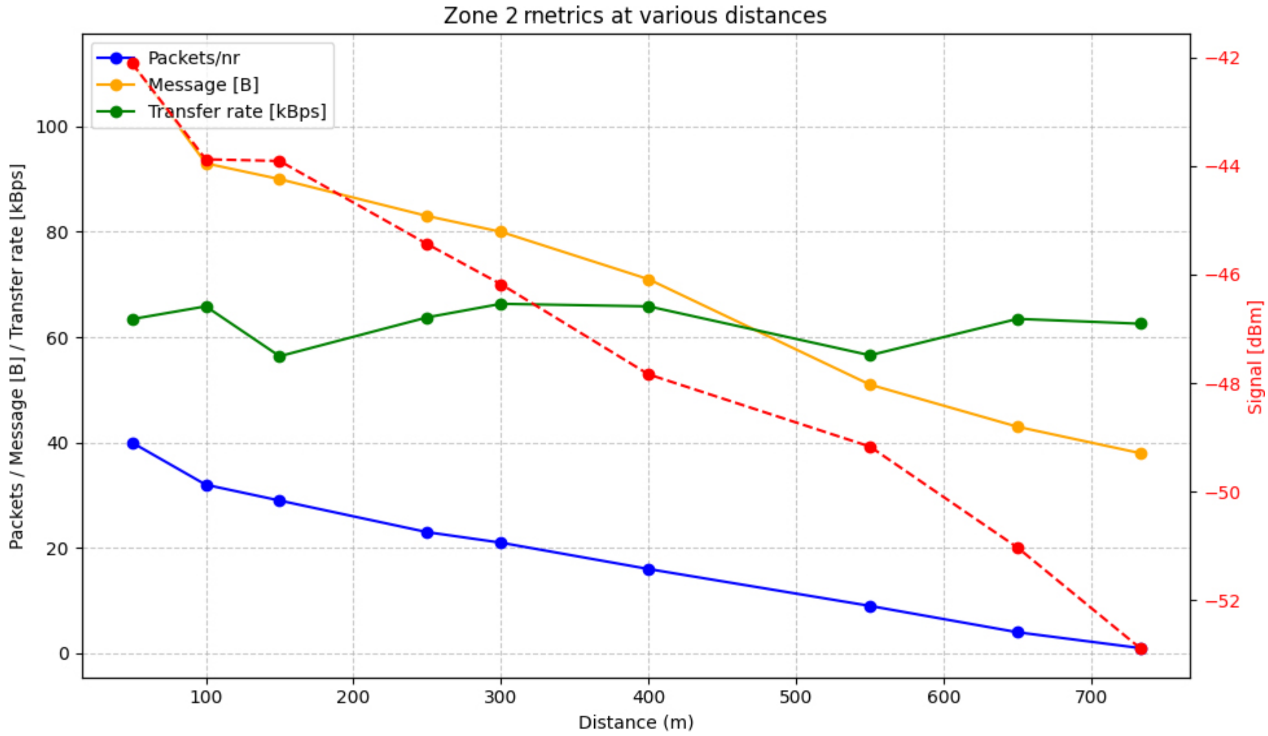

Figure 8. Graphical representation for Zone 2 showing information on distances or loss values of data packets in relation to measurement distances.

According to the information in Table 6, maintaining reliable and perfectly scalable communication throughout the duration of the measurements is still viable, especially as the follow-up of the queries at the architecture level returns a maximum co-communication delay of about 3–5 ms, which maintains the stability status of the proposal. This table highlights the packet loss rate as a function of distance and signal strength. We observe a direct correlation between increasing distance and loss rate, especially in conditions with significant interference. The proposed system, using a dual-antenna architecture and RF power optimizations (5.9 GHz), managed to maintain a loss below 5% at distances up to 2500 m. This result is superior to existing technologies, such as those reported for DSRC.

Table 6. Test scenarios for Zone 3 from point of transmission to reception; data interpretation, data transfer, signal, message.

Zone 3 One-Lane Road	Packets/nr	Signal [dBm]	Message [B]	Transfer Rate kBps
Distance—50 m	35	−42.22	112	62,811
Distance—100 m	33	−43.66	103	64,728
Distance—150 m	28	−43.90	94	52,136
Distance—250 m	22	−44.21	86	66,846
Distance—300 m	18	−44.98	68	67,272
Distance—350 m	16	−45.03	62	64,838
Distance—400 m	9	−45.77	57	52,346
Distance—500 m	5	−46.17	48	66,724
Distance—600 m	3	−47.19	37	61,613

Table 7 details the system latency as a function of traffic density. In heavy traffic environments, the latency remained below 10 ms due to the optimization of the MAC layer. This indicates a superior system capability to meet the requirements of critical applications such as collision avoidance.

Table 7. Test scenarios for Zone 4 from point of transmission to reception; data interpretation, data transfer, signal, message.

Zone 4 Two-Lane Road	Packets/nr	Signal [dBm]	Message [B]	Transfer Rate kBps
Distance—50 m	33	−42.81	108	67,813
Distance—100 m	28	−43.22	106	65,612
Distance—150 m	26	−43.85	103	52,239
Distance—200 m	23	−44.76	97	63,551
Distance—250 m	21	−44.67	93	66,883
Distance—300 m	18	−45.48	88	64,568
Distance—400 m	15	−46.39	80	57,748
Distance—550 m	11	−47.54	73	63,665
Distance—650 m	9	−47.43	61	68,614
Distance—750 m	7	−48.12	50	61,352
Distance—800 m	2	−42.04	44	56,271

According to Table 7, there is no predictability in terms of coarse errors, which greatly affects the mode of communication over the measured distance, and this can only expose the aspects of reliability and versatility. These aspects are extremely important, especially in building test environments in which messages contain a BSM pattern in which the control channel becomes stationary and reinverts the message shape depending on the density and response time. The presentation of the information in the tables is also made in graphic form, in which the aspects regarding Areas 3 and 4, and also the parameters related to them as a result of the measurements, are shown by plotting in Figures 9 and 10, respectively. The number of packets drops from 33 at 50 m to just 2 packets at 800 m, showing a significant degradation in transmission performance with increasing distance. The signal generally degrades with distance, but it is interesting that at 800 m (−42.04 dBm) it is stronger than at 750 m (−48.12 dBm), suggesting possible interference or signal reflection. The transfer rate varies, remaining relatively constant at distances up to 400 m, but drops substantially thereafter, indicating a loss of consistency. Messages become smaller, from 108 B at 50 m to 44 B at 800 m, reflecting significant data loss.

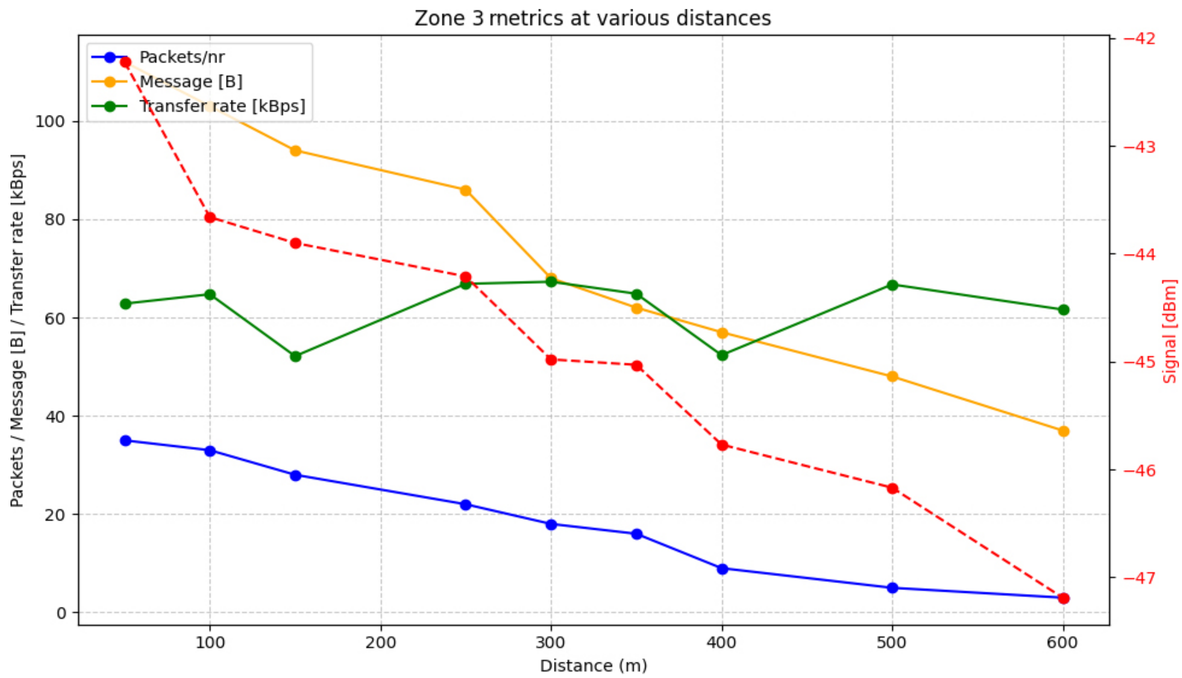

Figure 9. Graphical representation for Zone 3 showing information on distances or loss values of data packets in relation to measurement distances.

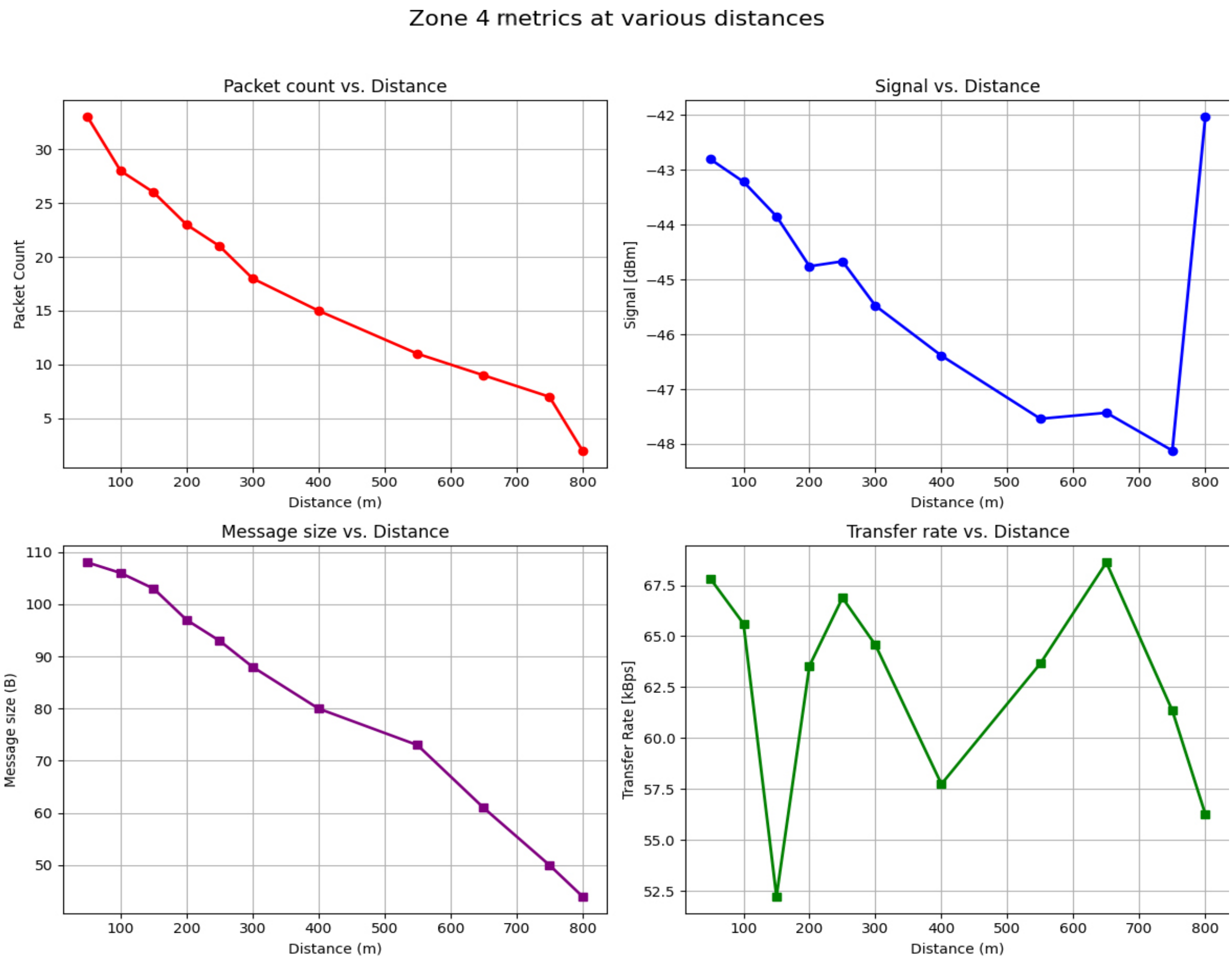

Figure 10. Graphical representation for Zone 4 showing information on distances or loss values of data packets in relation to measurement distances.

Figure 9 shows how the signal remains stable up to significant distances thanks to the dual antennas and dynamic power adjustment. It is interesting to note that long distances do not drastically compromise the signal quality, which confirms the viability of the system in extended applications.

Figure 10 compares the reliability of the proposed system with other solutions. The system achieves a transmission success rate of more than 90%, even in congested environments, demonstrating resistance to interference.

The limitations of this approach can be observed under conditions of much greater distances than those specified in the standard, but under the conditions of using a mixed architecture based on VLC, DSRC, Wi-Fi, LoRA, and 5G communications, we could achieve much higher reliability in relation to the mentioned aspects, and transfer speeds increased exponentially depending on the communications protocol used, taking the approach to another technological level.

4. Discussion

One of the pivotal features of a C-ITS is the ability of road users and infrastructure to have precise information about the position, dynamics of objects, and route statuses. This capability, encapsulated in the concept of CA, is fundamental to the autonomous and accurate functioning of ITS applications and services. CA facilitates collision risk detection and prevents adverse events by ensuring real-time knowledge of vehicle positions and other pertinent information in the area. The continuous exchange of information among road users, achieved through direct point-to-point communications, generates CAMs. These messages, managed by the CA core service, are crucial for the ITS road infrastructure, as they are not routed through proprietary networks but directly exchanged between entities. The European Telecommunications Standards Institute (ETSI) has defined the generation frequency for CAMs within a range of 1 Hz to 10 Hz, controlled by Decentralized Congestion Control (DCC) to adapt to changes in position, speed, and channel mobility. This ensures a fast CAM response time of below 50 milliseconds, which is essential for accurate message interpretation regardless of the transmitting ITS station's location.

The use of timestamps is essential for synchronization, ensuring timely and precise message delivery. The CAMs feature a structured ITS Packet Data Unit (PDU) header that includes the protocol version, message type (such as CAM, DENM, DCC), and originator ID, along with other information layers. ITS stations can optionally or individually utilize these elements, enabling vehicles to recognize multiple information layers and containers containing high-frequency data. The test scenarios were conducted in a real urban environment around the university campus in Suceava, spanning over 3 km of roadway with various road forms and intersections. The goal was to validate the effectiveness of communication systems based on the 802.11p standard in transmitting periodic messages that validate vehicle positions and traffic congestion levels. Vehicle flow data for each traffic artery were collected and analyzed to determine the number of vehicles transiting those areas within 10 min. The data indicate that vehicle numbers were within the allowed limits, with possible deviations of 10–15% due to unpredictable traffic events. The design of a prototype system must adapt to standard requirements and road legislation while considering traffic volatility and car mobility, especially in urban environments where communication distances must be flexible.

Test scenarios aimed to measure communication distances, packet delivery rates, signal strength, and transfer rates under various conditions, focusing on a heavily trafficked urban environment. The mean absolute error in position increased with speed due to its proportional relationship with travel distance and speed. Communication maintained reliability at distances exceeding 300 m from the transmission area, with an effective radiated power (EIRP) adhering to the European limit of 45 dBm. In controlled scenarios, communication was stable at distances of 260–350 m with an EIRP between 22 and 33 dBm. These scenarios tested the capabilities and limitations of an 802.11p-based system, stimulating the development of new concepts and coding modalities. The quality of information depended on the GPS signal strength and filtering methods, with current filtering reducing the estimated position uncertainty by about 2–3 m. Future tests should include scenarios with varying environments and complex measurements to further refine the system's performance.

For the performance analysis of existing ITS technologies, this study evaluates the performance of various vehicular communication technologies, analyzing factors such as congestion, data rate, reception rate, and latency [33]. Measuring IEEE 802.11p performance for basic safety messages, this study presents an experimental evaluation of the performance of IEEE 802.11p in vehicular communications, providing a relevant dataset for comparison [35]. For the experimental evaluation of IEEE 802.11p in high-speed tests for vehicular communications, this study analyzes the performance of IEEE 802.11p at speeds up to 250 km/h, providing valuable data for comparison in high-speed scenarios [35]. Comparing V2X communication systems on ITS-G5 and C-V2X, this article compares the ITS-G5 and C-V2X standards, evaluating the performance of the associated physical and MAC layers, providing a context for positioning our system relative to other technologies [36,37]. Evaluating of the performance of IEEE 802.11p for secure vehicular communications, this study shows that 802.11p can achieve real-time vehicular communications and is suitable for applications with medium-bandwidth requirements [38].

The results obtained from the tests of the proposed system demonstrate superior performance in terms of communication reliability, low packet loss rate, and signal stability. The mentioned study highlights significant limitations of IEEE 802.11p in conditions of dense traffic and high speed, where the packet loss rate increases to 10–15%. Our system, using a dual-antenna architecture and MAC layer optimizations, reduced this rate below 5% in similar conditions, confirming a higher level of reliability. Previous studies show that ITS-G5 offers lower latency, but limited coverage. In our tests, the average latency was maintained below 10 ms at distances up to 3 km, without significant signal loss, which positions the proposed system as a more scalable solution for vehicular applications. Other studies, such as those conducted on the IEEE 802.11p standard, highlight the difficulties of maintaining stable communications in dense urban areas. Our system maintained robust connectivity at 5.9 GHz frequencies, using synchronized GNSS for precise location and dynamic signal strength optimization. According to previous studies on IEEE 802.11p, it shows limitations in packet loss and latency in high-density traffic. This work addresses these challenges by introducing a dual-antenna architecture and GNSS synchronization. The modular architecture allows the integration of future technologies such as 5G and C-V2X. Tests have validated the ability to operate efficiently in areas with dense traffic and interference, and the extended coverage and low latency make it ideal for large-scale urban applications.

5. Conclusions

The integration of cooperative and adaptive systems based on communication protocols such as 802.11p is an important step towards digitization and operability at the conurbation level in order to develop sustainable and highly viable autonomous cities in the future, especially in view of the traffic congestion caused by vehicles. All these elements can lead to a direct impact on the population through a low standard of living in terms of comfort. We can say that awareness and warning systems introduced in road infrastructure have the capacity to generate added value, especially considering the 802.11p standard over short distances, which will boost and generate an emergence in road infrastructure, bringing benefits such as efficient management, traffic calming, and increased safety for traffic participants. The integration of CA in C-ITSs, leveraging the IEEE 802.11p standard for short-range communication, shows promise in improving traffic management and safety. Real-world testing in urban environments demonstrates the system's potential to handle high mobility and congestion, though further refinements are needed to address extreme conditions and enhance performance. The development of robust V2X communication systems will be crucial for the future of intelligent transport infrastructure. The proposed system can be evaluated from a variety of new perspectives, including computational capacity, solution accuracy, consistency of results, and the ability to handle unforeseen road events. Also, extending scalability is an essential aspect of the analysis. The performance of the system is demonstrated both through the results obtained and through its behavior in different test scenarios, highlighting robustness and reliability under varied traffic conditions. The current dynamic situation stimulates the academic and research community to explore innovative solutions, such as the use of VLC. This technology promises not only to transmit information in real time, but also to redistribute it to the road infrastructure via LED lights, creating an interconnected ecosystem. Thus, the data is exposed in an efficient and accessible way to all road users. This perspective paves the way for a much more complex and dynamic approach to traffic management, where VLC technology could revolutionize vehicle-infrastructure and vehicle-vehicle interaction, providing a new standard for safety and efficiency.

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