

Article

Energy Aware and Quality of Service Routing Mechanism for Hybrid Internet of Things Network

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Abstract: Wireless Multimedia Sensor Networks (WMSNs) based on IEEE 802.11 mesh networks are effective and suitable solutions for video surveillance systems in detecting intrusions in selected monitored areas. The IEEE 802.11-based WMSNs offer high bit rate video transmissions but are challenged by energy inefficiency issues and concerns. To resolve the energy inefficiency challenges, the salient research studies proposed a hybrid architecture. This newly evolved architecture is based on the integration of IEEE 802.11-based mesh WMSNs along with the LoRa network to form an autonomous and high bitrate, energy-efficient video surveillance system. This paper proposes an energy-aware and Quality of Service (QoS) routing mechanism for mesh-connected visual sensor nodes in a hybrid Internet of Things (IoT) network. The routing algorithm allows routing a set of video streams with guaranteed bandwidth and limited delay using as few visual sensor nodes as possible in the network. The remaining idle visual sensor nodes can be turned off completely, and thus it can significantly minimize the overall energy consumption of the network. The proposed algorithm is numerically simulated, and the results show that the proposed approach can help in saving a significant amount of energy consumption while guaranteeing bandwidth and limited delay.

Keywords: wireless mesh network; energy efficiency; quality of service (QoS); energy-aware routing; IEEE 802.11; Internet of Things (IoT) network



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1. Introduction

The rapid rise of the Internet of Things (IoT) [1–3] has led to considerable growth in the demand for video surveillance systems. Wireless Multimedia Sensor Networks (WMSNs) based on IEEE 802.11 mesh networks are effective and suitable solutions for video surveillance systems in detecting intrusions in specific monitored areas. While IEEE 802.11-based WMSNs support high-bitrate video transmission, they are inefficient in terms of energy consumption. The inefficiency in energy use is caused by the fact that the visual sensor node's radio interface is constantly on, even when it is neither transmitting nor receiving data. Therefore, the idle listening (IL) state results in a great deal of energy wastage [4,5]. In order to resolve such energy inefficiency issues, we conducted research [6] and proposed a new hybrid IoT system through a convergence of WMSNs based on IEEE 802.11 mesh networks with the LoRa network to form an autonomous and high bitrate, energy-efficient video surveillance system capable of detecting and tracking an intruder. Using the advantages of a LoRa network (i.e., long-range, low cost, and low power consumption), we proposed in [6] that the LoRa network be used as an always-active network for preliminary motion detection and activation of visual sensor nodes in the network. Based on the sensed information, the LoRa network activates visual sensor nodes that are involved in surveillance and routing a video stream to the gateway, as well as completely turning off visual sensor nodes that are not required. Thus, using

this mechanism, an ample amount of energy can be saved. The hybrid IoT network is shown in Figure 1, and a detailed description and operation of the hybrid IoT network is presented in [6].

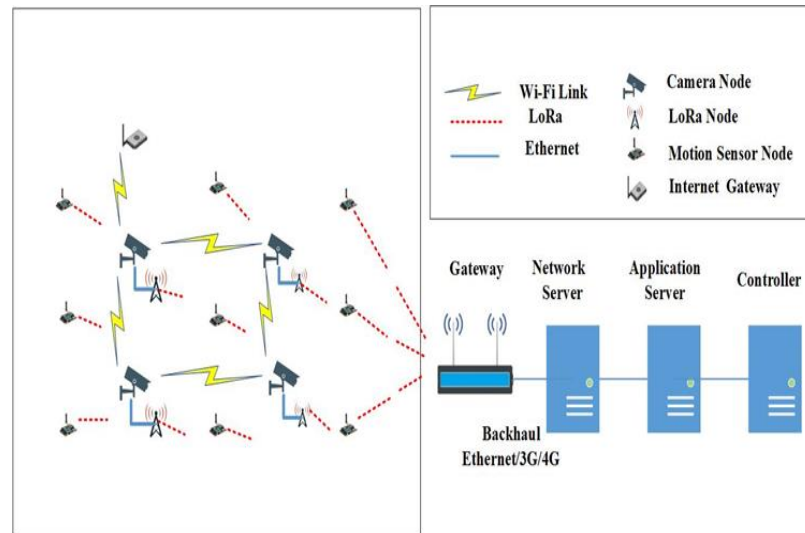


Figure 1. Hybrid IoT network architecture (Reprinted with permission from reference [6]. Copyright 2020 IEEE).

The hybrid IoT network architecture simply enables the management of the energy consumption of the visual sensor nodes by switching them on and off as needed, and there should be a mechanism to determine which nodes turn on and off in the network. It is known that video surveillance applications require that the video captured by the visual sensor nodes in the mesh network is transferred to the gateway node using a routing mechanism. As a result, the involved visual sensor nodes must remain turned on and the remaining idle nodes must be turned off. In order for the routing mechanism to be energy efficient, energy awareness should be taken into consideration in the network protocol design of the mesh-connected visual sensor nodes. It is essential to determine which few amongst the visual sensor nodes are needed for surveillance and are involved in routing a video stream to the gateway without compromising QoS requirements. This allows for those involved nodes to be turn on, while turning off completely as many idle nodes as possible to save the global energy consumption of the network.

Additionally, multi-hop wireless mesh networks suffer from the interference phenomenon, and providing quality of service is challenging in these networks since two links cannot transmit simultaneously if they interfere with each other [7–14]. In order to support a wide range of QoS requirements, a routing mechanism needs to have a complex model in which the wireless network has multiple QoS metrics. Therefore, providing a guaranteed QoS is a great challenge due to the inherent limitation of the wireless mesh.

Following the above, this paper proposes an energy-aware and QoS routing algorithm for mesh-connected visual sensor nodes in a hybrid IoT network. This is an advanced feature extension of a previous research paper [6]. The routing algorithm allows routing a set of video streams with guaranteed bandwidth and limited delay under the assumption that the end-to-end packet transmission delay is proportional to the number of hops in a path while optimizing the energy consumption of visual sensor nodes in the network. After evaluating the performance of the proposed routing mechanism through simulation, this research showed that the proposed routing algorithm provides guaranteed bandwidth and limited delay with a significant reduction in energy consumption.

The key contributions of this paper are the following:

- We propose an energy-aware and QoS routing algorithm for mesh-connected visual sensor nodes in a hybrid IoT network, as proposed in our previous work [6].

- We propose an optimal routing algorithm that provides guaranteed bandwidth and limited delay while minimizing total energy consumption. The energy efficiency is achieved by completely shutting down as many visual sensor nodes as possible without compromising performance.
- We formulate the problem as an integer linear program (ILP) and used a branch-and-bound algorithm for obtaining the optimum solution.

The rest of the paper is organized as follows. Section 2 presents the existing research on energy optimization and QoS routing in wireless multi-hop networks. Section 3 introduces the system models on which this research is mainly based. Section 4 presents the mathematical formulation of the problem and our solution. Section 5 analyzes the performance of the proposed routing algorithm and compares the results with other algorithms from the literature. Finally, Section 6 presents concluding remarks.

2. Related Works

Existing research on energy optimization and QoS service routing in wireless multi-hop networks are drawing significant attention in the research community. The authors in [15] presented a routing protocol that supports the transmission of multimedia stream in WMMSN. The routing protocol makes packet forwarding decisions based on the position of sensors nodes to the destination of the nodes. The mechanism uses the load balancing technique in a multipath-to-destination to distribute the load and increase the lifetime of the network. Similarly, the authors in [16–19] employ load balancing techniques in networks for increasing the lifetime of a network. Most of the proposed solutions are based on uniformly distributing a load over the network, thereby maximizing the lifetime of the networks without compromising the performance. However, distributing load uniformly over a network is not necessarily energy efficient in terms of the global energy saving of the network. This is because the mechanism forces nodes in the network to remain turned on even if it is transmitting a small amount of data. Therefore, this research focused on global energy consumption savings in multi-hop mesh networks, while maintaining a certain amount of QoS.

The authors in [11] proposed a throughput and energy-aware routing mechanism for IEEE 802.11-based mesh networks. It is a centralized routing mechanism, which requires a global view of the network. The proposed solution is based on integer linear programming to maximize the number of nodes that can be turned off while guaranteeing throughput. However, the solution applied an iterative algorithm in order to find the optimum solution that left as many routers as possible switched off.

The authors in [20] proposed a routing mechanism that allows flows to be aggregated over a minimum number of nodes for any set of source and destination nodes in a multi-hop wireless network. The authors proposed a solution based on integer linear optimization to route flows over a minimum number of nodes while respecting QoS in terms of throughput. Aggregating a set of flows over a minimum number of nodes allows some flows to take a longer path to their destination. Considering the ideal wireless channel, a longer path incurs longer delay in the flows to the destination. Therefore, in the case of large node deployment; it has a significant negative impact on delay-sensitive applications such as video transmission.

Therefore, this paper proposes a centralized energy-aware and QoS routing algorithm for mesh-connected visual sensor nodes in a hybrid IoT network, as proposed in [6]. The routing algorithm allows the routing of a set of video streams to the gateway with guaranteed bandwidth and limited delay (with the assumption that the end-to-end packet transmission delay is proportional to the number of hops in a path) while using as few visual sensor nodes as possible in the network. This allows for only those nodes that are involved in the surveillance and routing to be turned on, while turning off (or putting in a complete shutdown mode) the idle nodes that are not involved in the routing and surveillance.

Table 1 shows a summary of the related research by different authors and our proposal according to energy consumption reduction, interference considerations, and QoS guarantees.

Table 1. Related work overview and our proposal.

Reference	Global Energy Consumption Reduction	Increase Life Time	Interference Considerations	QoS Guarantees
Jung et al. [16]	Not considered	Yes	No	Not specified
Medjah et al. [15]	Not considered	Yes	No	Limited delay, Packet loss ratio
Li et al. [17]	Not considered	Yes	No	Not specified
Thangaramya et al. [18]	Not considered	Yes	No	Not specified
De la Oliva et al. [11]	Yes	Not considered	Yes	Throughput
Laube et al. [20]	Yes	Not considered	Yes	Throughput
The proposal	Yes	Not considered	Yes	Throughput, Limited delay

3. System Model

This section presents the wireless network model and interference models upon which our work is based and the assumptions that are considered.

3.1. Network Model

We represent mesh-connected visual sensor nodes in the hybrid IoT network by a directed graph $G = \{V, E\}$, where V is the set of visual sensor nodes, and E is the set of wireless links between the set of those nodes. We consider single radio mesh-connected visual sensor nodes and that all the visual sensor nodes are in a static condition. The visual sensor nodes can be source nodes, relay nodes, and gateway nodes. For a given pair of nodes in the network, there is a link $(i, j) \in E$ if both are in the transmission range of each other. We consider the same transmission range for all nodes in the network.

3.2. Interference Model

The wireless network interference between nodes can be represented by a conflict graph [21] with respect to the network graph. The conflict graph $CG = (V', E')$ is an undirected graph in which the vertices represent links of the network G , and the edges represent the interference relation between the wireless links. The model that is used to compute the conflict graph is the N-hop interference model. In this model, a node interferes with its neighbors up to a distance of N-hops. This paper uses the 2-hop interference model as used in [22]. We represent a set of mutually interfering links by a maximal clique [23] in the conflict graph (i.e., a complete sub-graph of CG). By computing the maximum cliques from the conflict graph, we obtain the sets of links that cannot be active simultaneously in the network. Consequently, only one conflict graph node in a clique (one link in the connectivity graph) may be active at once. Accordingly, the sum of the rates of the conflict graph nodes in each maximal clique cannot exceed the capacity of the channel. Therefore, cliques can be used to derive necessary and sufficient constraints to accept or reject the flow requests based on the bandwidth available in the multi-hop wireless network [23].

4. Problem Formulation and Optimum Solution

In this paper, we study how to reduce the energy consumption in the mesh-connected visual sensor nodes in the hybrid IoT network without compromising performance. We do not focus on reducing energy consumption on each visual sensor node but rather on the global energy consumption of the network. This is done by concentrating flows to a few visual sensor nodes as much as possible while guaranteeing bandwidth and at the same time not allowing each of the set of flows to take a path length longer than a maximum desired value so as to guarantee the delay as well. This allows as many visual sensor nodes as possible that are not used and involved in the video surveillance to be selectively turned off. Therefore, the objective of this paper was to design an optimal routing mechanism that could minimize the number of active visual sensor nodes involved in routing a set of flows

to gateways, while complying with QoS constraints in terms of bandwidth and delay (in terms of path length).

We formulated the problem as an integer linear program (ILP) [24]. The objective was to find the minimum number of visual sensor nodes needed (activated) under QoS constraints in terms of bandwidth and delay.

To describe the model, we introduce the notation for the parameters and variables as follows.

E : the set of links

V : the set of visual sensor nodes

C_l : the set of cliques

K : the set of flows in the network

$d_{i,j}$: the capacity reserved on link (i, j)

$C_{i,j}$: the total capacity available on link (i, j)

(S_k, G_k) : the source and the gateway of flow k

B_k : the minimum capacity requested by flow k

x_i : equal to 1 if the node is used to route flow, 0 otherwise

$x_{i,j}^k$: equal to 1 if (i, j) is used to route flow k , 0 otherwise

p_m : path length limit of each of the flows

The objective function:

$$\text{Min } \sum_{i \in V} x_i \quad (1)$$

Subject to the following constraints:

$$\sum_{(i,j) \in C_l} (d_{i,j}/C_{i,j}) \leq 1, \forall C_l \in C_l \quad (2)$$

$$\sum_{(i,j) \in E} x_{i,j}^k - \sum_{(j,k) \in E} x_{j,k}^k = 0, \forall k \in K, \forall j \in V - \{S_k, G_k\} \quad (3)$$

$$\sum_{(i,S_k) \in E} x_{i,S_k}^k = 0, \forall k \in K \quad (4)$$

$$\sum_{(S_k,i) \in E} x_{S_k,i}^k = 1, \forall k \in K \quad (5)$$

$$\sum_{(G_k,i) \in E} x_{G_k,i}^k = 0, \forall k \in K \quad (6)$$

$$\sum_{(i,G_k) \in E} x_{i,G_k}^k = 1, \forall k \in K \quad (7)$$

$$\sum_{(i,j) \in E} x_{i,j}^k \leq 1, \forall k \in K, \forall i \in V - \{G_k\} \quad (8)$$

$$\sum_{k \in K} x_{i,j}^k \cdot B_k = d_{i,j}, \forall (i,j) \in E \quad (9)$$

$$\sum_{(i,j) \in E} x_{i,j}^k \leq p_m, \forall k \in K \quad (10)$$

$$x_i = \begin{cases} 1, & \text{if } d_{i,j} + d_{j,i} > 0 \\ 0, & \text{otherwise} \end{cases} \quad \forall i \in V, \quad (11)$$

$$x_i \in \{0, 1\}, \forall i \in V$$

$$x_{i,j}^k \in \{0, 1\}, \forall (i,j) \in E, \forall k \in K$$

Equation (1) is the objective function that minimizes the number of visual sensor nodes that can be used (activated) in the network. Equation (2) is the capacity constraint that makes sure that flows are routed with respect to the residual capacity of the cliques. Equation (3) ensures the flow conservation rules. Equations (4) and (6) ensure that a flow should not loop back to its source and leave its destination. Equations (5) and (7) force the source and the destination to be used. Equation (8) shows the single path constraint and that a flow should not split into several paths. Equation (9) represents the capacity reserved on a link as the sum of the capacity reserved by each flow on that link. Equation (10) puts a limit on the path length of each flow. Each flow path should not be longer than p_m hops so that the delay is limited. Finally, Equation (11) ensures a node is used if it receives or sends

traffic. As can be seen from the Equation (11), the constraint is not linear. Since most of the linear programming solvers require linear formulations of the objective functions and constraints, it is therefore necessary that the non-linear constraint should be converted to the equivalent linear constraints. Using the techniques as in [25] and a constant wireless capacity assumption, the linearization of the constraint in Equation (11) is the following:

$$C * x_i - \sum_{(i,j) \in E} d_{i,j} \geq 0, \forall i \in V \quad (12)$$

$$C * x_i - \sum_{(j,i) \in E} d_{j,i} \geq 0, \forall i \in V \quad (13)$$

$$\sum_{(i,j) \in E} (d_{i,j} + d_{j,i}) - B \cdot x_i \geq 0, \forall i \in V \quad (14)$$

Constraints (12) make sure that a node is used ($x_i = 1$) if there is a video stream going out of the node. Constraints (13) also makes sure that a node is used ($x_i = 1$) if there is a video stream going into the node. Constraints (14) ensures the node is not used ($x_i = 0$) if there is no video stream passing through the node.

In order to solve the optimization problem, we use the branch-and-bound method [24].

5. Performance Evaluation

In this section, we evaluate the performance of the proposed algorithm. First, we assess its energy performance in terms of the number of nodes that can be spared and switched off. Next, we evaluate the maximum path length taken from each of the submitted flow sets (with the assumption that the end-to-end packet transmission delay is proportional to the number of hops in a path). The maximum route length considered is the maximum path length taken by a flow from the set of flows generated. Further, the proposed algorithm is compared with two other algorithms for mesh networks.

Shortest path algorithm: An algorithm that routes flows (video streams) over the shortest available path between the source and the gateway. The algorithm is defined for a single flow in [22], but it is extended to consider a set of flows in this paper.

Aggregation algorithm: A routing mechanism that aggregates flows over a minimum number of nodes [20]. Both the aggregation algorithm and shortest path algorithm take into account inter-flow and intra-flow interference.

Proposed Algorithm: An algorithm that allows flows to be routed over a limited number of nodes without allowing each flow to take a path length longer than a maximum desired value (P_m). This limits the path taken by each flow and therefore benefits delay-sensitive applications such as video streaming. We have chosen this path length (P_m) to be the diameter of the network, i.e., the length of the shortest path between the farthest node and gateway in the topology.

This paper considered a 6×6 grid network consisting of 36 nodes. The distance between neighboring nodes was 250 m. The nodes had a transmission range of 250 m and an interference range of 500 m. We considered the grid network with one gateway located at one of the corners of the grid. The shortest path between the farthest node and the gateway was 10 nodes ($P_m = 10$). We generated a set of flows from 1 to 10 (1, 2 sets, 3 sets of flows, etc.), and each flow was generated with a randomly selected source, and the bandwidth requirement of each flow was set to 0.5 Mbps. We considered constant capacity between wireless links and varying values of capacities for the simulations ($C = 5$ Mbps, $C = 10$ Mbps, $C = 15$ Mbps). We also considered an ideal wireless link. We used MATLAB for generating and calculating parameters from the network and used CPLEX studio [26] to solve the formulated optimization problem. All computations were performed on a computer equipped with 2.8 GHz Intel Core i7 and 16 GB RAM.

The comparison of the proposed algorithms in terms of energy consumption against the shortest path algorithm and the aggregation algorithm is presented in Figures 2–4 for varying values of wireless channel capacities ($C = 5$ Mbps, $C = 10$ Mbps, $C = 15$ Mbps).

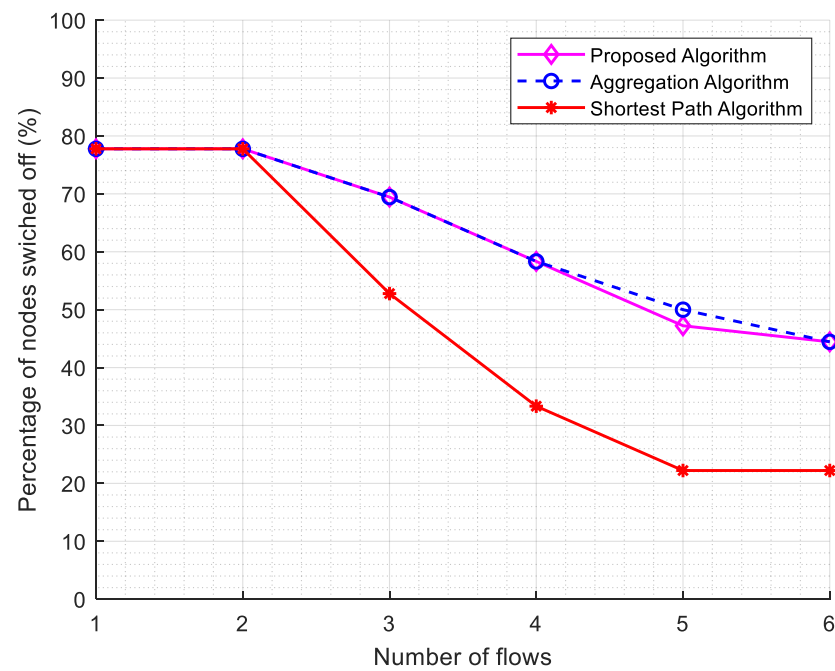


Figure 2. The percentage of spared nodes (nodes that can be switched off) variation according to the number of set of flows generated for wireless capacity equal to $C = 5$ Mbps.

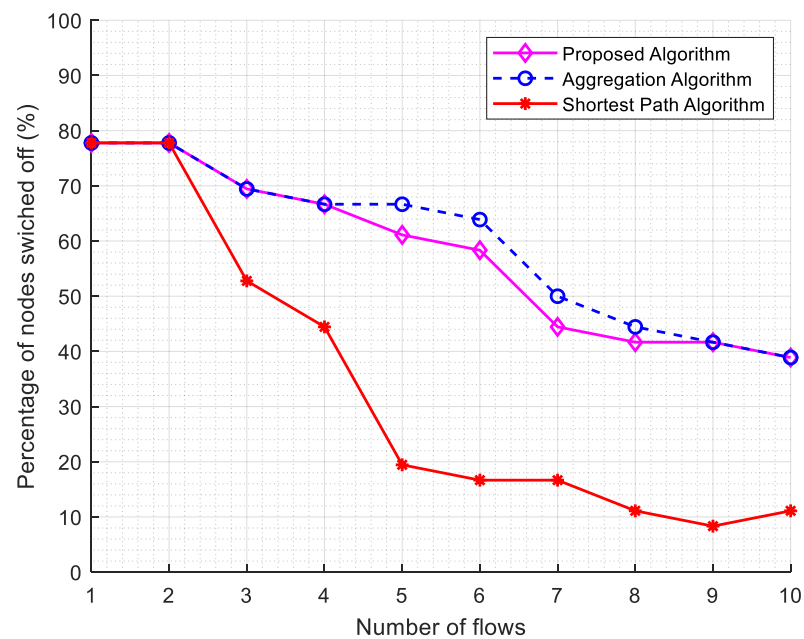


Figure 3. The percentage of spared nodes (nodes that can be switched off) variation according to the number of set of flows generated for wireless capacity equal to $C = 10$ Mbps.

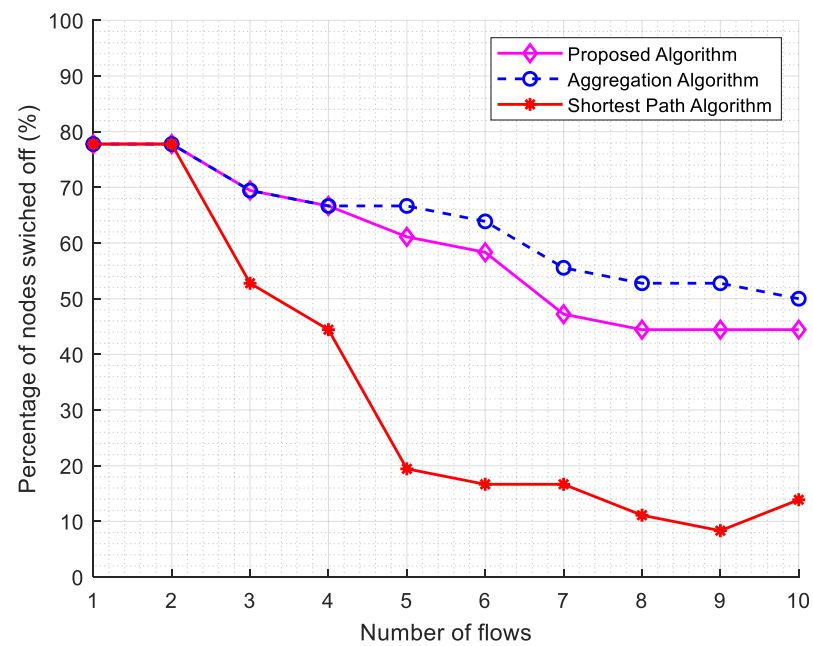


Figure 4. The percentage of spared nodes variation according to the number of set of flows generated for wireless capacity equal to $C = 15$ Mbps.

The comparison of the proposed algorithm in terms of maximum route length against the shortest path algorithm and the aggregation algorithm is presented in Figures 5–7 for varying values of wireless channel capacities ($C = 5$ Mbps, $C = 10$ Mbps, $C = 15$ Mbps).

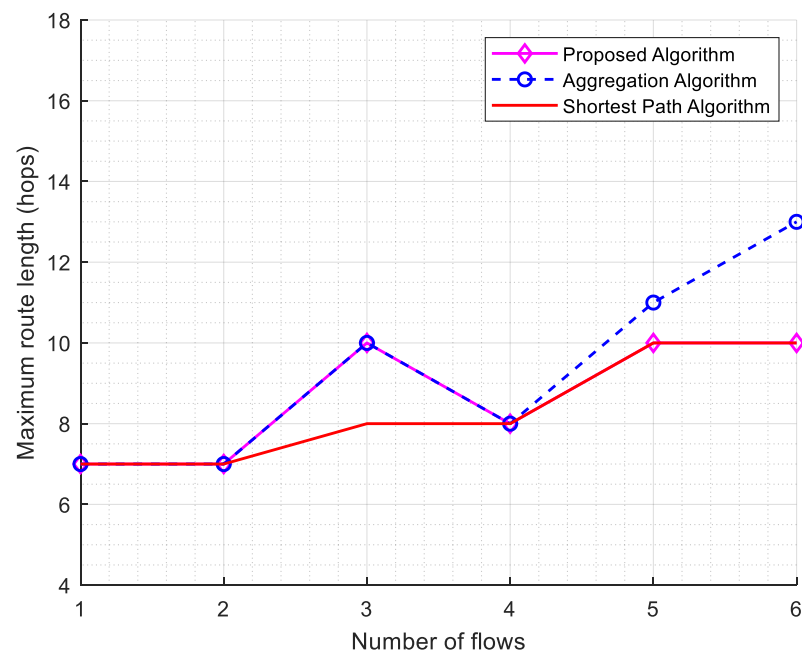


Figure 5. The maximum path length variation according to the number of set of flows generated for wireless capacity equal to $C = 5$ Mbps.

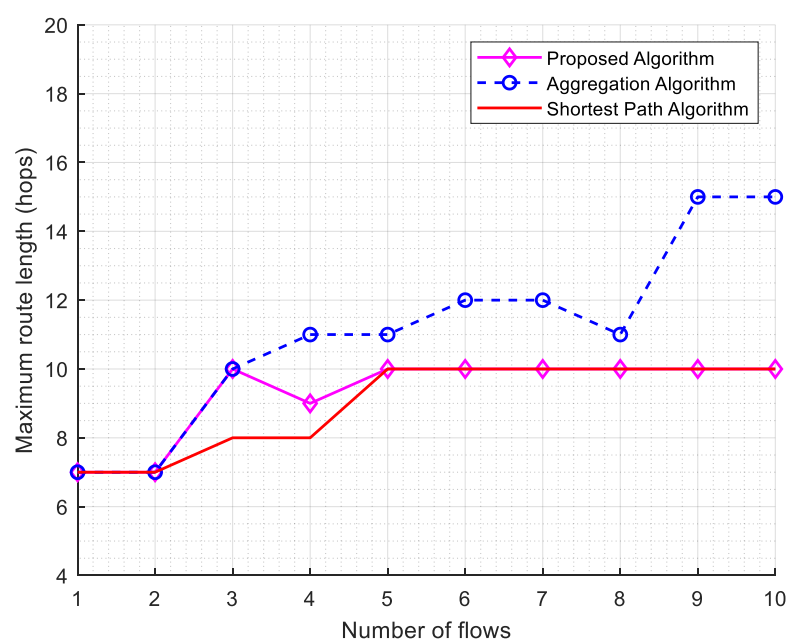


Figure 6. The maximum path length variation according to the number of set of flows generated for wireless capacity equal to $C = 10$ Mbps.

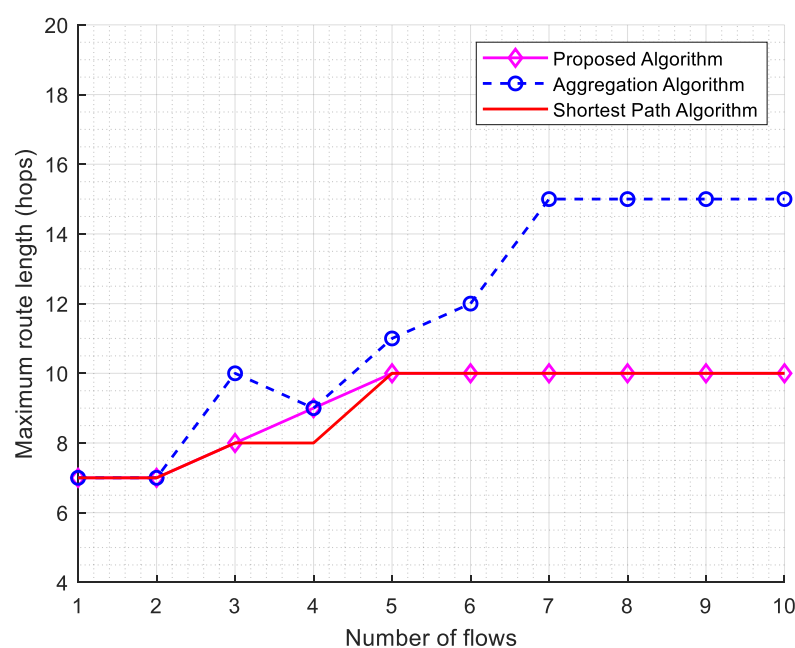


Figure 7. The maximum path length variation according to the number of set of flows generated for wireless capacity equal to $C = 15$ Mbps.

As can be seen from Figures 2–4, the proposed algorithm and the aggregation algorithm greatly outperform the shortest path algorithm in terms of energy saving, while the aggregation algorithm performs slightly higher than the proposed algorithm. Taking Figure 4 as an example, the shortest path algorithm can use 80% of the nodes in the mesh network to support 10 submitted flows, whereas the proposed algorithm and the aggregation algorithm require 54% and 50% of the nodes in the network, respectively, to provide the same service. The aggregation algorithm slightly outperforms the proposed algorithm in terms of the overall energy consumption reduction, but it provides very poor performance in terms of delay. However, the slight decrease in energy performance in the

proposed algorithm is at the expense of guaranteeing and limiting the delay of flows to the gateway (Figures 5–7). Another point, which is noticeable from Figure 2, is that we submitted more than six sets of flows, but the algorithms do not accept flows of more than six sets of flows. This shows that all the algorithms have the same flow acceptance rate.

As can also be seen from Figures 5–7, the aggregation algorithm allows flows to take longer path lengths (in terms of number of hops) to the gateway, which makes it have a longer delay compared with the proposed algorithm and the shortest path algorithm to the gateway. As it is shown in Figure 7, the aggregation algorithm uses a maximum path length of 15 nodes to reach to the gateway, whereas the proposed algorithm and the shortest path algorithm use a maximum route length of 10 nodes to reach the gateway.

From the above discussion, it can be concluded that there is a clear tradeoff between QoS and energy saving. For video surveillance applications that have strict QoS requirements, the proposed approach reduces a significant amount of global energy consumption while guaranteeing QoS in terms of bandwidth and delay.

6. Conclusions

This paper proposed an energy-aware and QoS routing algorithm for wireless mesh-connected visual sensor nodes in a hybrid IoT network. The routing algorithm allows routing a set of video streams with guaranteed bandwidth and limited delay with the assumption that the end-to-end packet transmission delay is proportional to the number of hops in a path, while involving the minimum number of active visual sensor nodes in the network. We formulated the problem as an integer linear program (ILP), and for finding the minimum number of visual sensor nodes to be used (activated), we imposed bandwidth and delay constraints. We used a branch-and-bound algorithm to solve the integer linear programming optimization model. The proposed approach was evaluated via simulation and compared with previous approaches from the literature, such as an aggregation algorithm and a shortest path algorithm. A clear tradeoff was observed between energy saving and QoS. The simulation results show that the proposed approach achieves considerable overall energy savings while guaranteeing QoS in terms of bandwidth and delay. The proposed approach allows as many visual sensor nodes as possible to be completely turned off to reduce the global energy consumption of the network. Putting nodes in a complete shutdown mode has the add-on benefit of reducing wireless interference between wireless nodes. The work considered mesh-connected visual sensor nodes with a single gateway, but it could be extended to consider a different number of gateways to assess the variation of the different performance metrics. The study can also be extended to develop feasible heuristic solutions for networks involving a large number of nodes.

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