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Research Article

Enhancing the Performance of 6LoWPAN-Based Wireless Sensor Networks (WSNs) with IEEE 802.11AH (Wi-Fi HaLow)

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6LoWPAN allows IEEE 802.15.4 standard-based wireless sensor networks (WSNs) to be connected to the Internet through the Internet protocol IPv6; however, its performance decreases as the network grows in size due to complications such as the bottleneck problem; therefore this paper aims to improve the performance of 6LoWPAN-based WSNs by using the IEEE 802.11AH standard as a backbone in these networks, since this emerging new technology is suitable for IoT applications, as it can provide a coverage range up to 1,000 m and data transmission rates up to 78 Mbps. The IEEE 802.11AH standard can be used as a backbone by utilizing its characteristics to improve some of the performance parameters of the 6LoWPAN networks such as end-to-end delay, frames delivery ratio, and the network throughput. This paper proposes a heterogeneous network infrastructure consisting of 6LoWPAN and the IEEE 802.11AH standard to enable bidirectional data transmission between the network components and the Internet via the Internet protocol IPv6 with two types of gateways, the edge gateways to connect the entire network to the Internet and the intermediate gateways to connect the 6LoWPAN clusters to the edge gateways. The simulation results demonstrate that the heterogeneous network approach can provide significant improvement gains compared to the 6LoWPAN homogeneous networks, since it shows clear improvements to the packets delivery ratio, the end-to-end delay mean value and the network throughput, subsequently leading to a distinct enhancement in the network's overall reliability.

1. Introduction

The number of devices connected to the Internet is increasing rapidly, accompanied by the integration of the various types of wireless sensor networks (WSNs) in the Internet of things (IoT) infrastructure. These networks could play an important key role in monitoring the areas they are deployed in by collecting data about the status and the variables of these deployment domains, and by transmitting the collected data to the control and monitoring centers via the Internet. These collected data through WSNs enable the decision makers to take the appropriate actions, especially in critical situations and applications like environmental monitoring, healthcare, industrial applications, and smart cities [1].

Therefore, choosing the right wireless networking technologies and protocols play the most vital part in connecting the various WSNs devices to the IoT infrastructure in an efficient, reliable, and productive way. One of the most suitable and used technologies in WSNs is the IEEE 802.15.4 standard [2], due to its low cost and to its easy network deployment. In addition, it has a low-power consumption rate which allows the nodes to operate for a couple of years according to the type of application and usage. The 6LoWPAN technology has been developed to connect the IEEE 802.15.4-based WSNs with the IoT infrastructure via the Internet protocol IPv6 which allows every node to have a unique IP address.

The IEEE 802.15.4 standard is widely used in environmental monitoring, agriculture, industrial, and smart city applications due to the flexibility it provides in monitoring and control applications, with data transmission rates up to 250 kbps and a low-power consumption rate [3].

The IEEE 802.11AH standard has been developed mainly to meet the increasing requirements and demands of IoT applications and its networks, with data transmission rates of up to 78 Mbps and a coverage range up to 1,000 m, also it can support of up to 8,191 devices connected to one access point [4]. The IEEE 802.11AH standard operates in the less interfered sub 1 GHz license-exempt bands [5], and that helps to reduce the interference with the other protocols and standards that use the more crowded 2.4 GHz frequency band like Bluetooth, 6LoWPAN, and Wi-Fi.

This paper is concerned with improving the performance of 6LoWPAN-based WSNs by integrating the IEEE 802.11AH standard in these networks infrastructure. Although the IEEE 802.11AH standard has a better overall quality of service than the 6LoWPAN technology, the latter can support star and mesh topology networks while the IEEE 802.11AH standard can only support star topology, which makes the 6LoWPAN technology more suitable for wide area WSNs. Since the IEEE 802.15.4 standard is more widely used this makes replacing the entire network unpractical, inefficient, and costly. Therefore, this paper proposes a heterogeneous network infrastructure design for 6LoWPAN-based WSNs by using the IEEE 802.11AH standard as a backbone in these networks to improve the end-to-end delay and the delivery ratio parameters. This is justified by the fact that homogeneous networks that use only one protocol or standard are no longer able to meet all the increasing requirements of IoT applications and systems. To achieve this aim, two types of gateways have been proposed; edge gateways that connect the network to the Internet or to the monitoring and control center, and intermediate gateways which enable the bidirectional data transmission between the nodes and the edge gateways. The integration of this network in the IoT infrastructure is done through the 6Lo protocol that enables the use of the Internet protocol IPv6 in resource-constrained networks. Furthermore, network topology and a management system have been proposed which depend on the cluster tree structure, and a flexible method for data aggregation has been proposed accordingly. The simulation of the proposed design is done on a virtual network using the discrete event simulator OMNeT++. The testing and the final results showed an improvement over the homogenous networks since the quality of service has been improved through improving end-to-end delay, frames delivery ratio, and network throughput. In addition, the proposed network can support some of the real-time applications in a better way than the homogeneous networks, and support a big number of sensor and actuator nodes distributed on a large area, while achieving a bidirectional data transmission between its components and the Internet. Thus, it can keep up with the expansion in IoT and WSNs fields and can enable remote and direct access to the nodes by the monitoring and control centers as well as the users.

2. Related Works

The IoT has transformed the concept of the legacy Internet where people create the data to a new form where devices and people now share data creation evolving it into the Internet of Everything (IoE). One of the major concerns was connecting the various types of devices to the IoT networks to enable bidirectional data transmission between the different components of the monitoring and control systems such as sensors, actuators, and decision-making centers.

The issue of connecting the IEEE 802.15.4-based networks to the Internet has been addressed extensively, due to the rise of the IoT concepts and its technologies and the need to merge those networks in the expanding world of IoT. To this end, the possibility of connecting IEEE 802.15.4 networks with narrow-band IoT (NB-IoT), has been investigated by Li et al. [6]. The NB-IoT is an emerging cellular technology for providing wide area coverage, and it was able to improve performance in terms of end-to-end latency and end-to-end reliability. However, it has a data transmission rate that peaks at 250 kbps, therefore one of the more favorable solutions for connecting the low-power IEEE 802.15.4 standard networks to the Internet was using Wi-Fi. Wi-Fi connection offers the most accessibility and interoperability with other devices [7], but it requires more power in spite of providing a larger bandwidth. In addition, it operates on the same 2.4 GHz frequency band as most of the IEEE 802.15.4 standard WSNs, and that can create interference and degrade the network's overall performance, especially in applications where a high quality of service is in demand [8].

A gateway that creates a link between the IEEE 802.15.4-based networks and the Internet by using Wi-Fi as the network's backbone has been proposed by Silveira and Bonho [9]. However, only one gateway was proposed to connect the entire network and for a small number of sensors, without taking into consideration the scalability of the network and the interference that happens between the Wi-Fi and the IEEE 802.15.4 standard, since both of them operate on the crowded 2.4 GHz frequency band. A similar approach was used by Kruger et al. [10], by designing a hybrid gateway based on 6LoWPAN and Wi-Fi to enable end-to-end connectivity between the end devices and the servers. In addition, the paper realizes the interference problem mentioned previously, and it recommends the use of a directional antenna to solve it while making sure that the line of sight of the devices that use the antennas are aligned, but again there were no considerations on the network scalability and performance under the different circumstances, i.e., when the number of nodes and the data flow of the network increase.

Another method to design a gateway for connecting the 6LoWPAN WSN networks to the Internet was proposed by Luo and Sun [11], by attaching a 6LoWPAN adapter device to a PC that operates on a Linux kernel to enable end-to-end communications between the networks components and the Internet. However, it is not clear whether this method is suitable for large-scale networks since all the network data flow has to go through a single point which is a 6LoWPAN adapter. This will lead to congestion in the data flow, especially as the network grows in size.

A hybrid gateway that uses the ETHERNET as a backbone to provide bidirectional data transmission between the 6LoWPAN nodes and the Internet has been proposed by

Honggang et al. [12], and the results show that the gateway fulfills its purpose with stability and adaptability. However, the results are not conclusive since they were derived for five nodes only in the network and the time delay reaches more than 0.8 s, and it keeps increasing as the data transmission rate increases, which makes the proposed network architecture based on this gateway design unsuitable for the networks that are sensitive to time delay.

Multiple studies have been conducted to address the issue of connecting the 6LoWPAN WSN networks to the Internet by designing a hybrid gateway that uses another protocol or standard besides 6LoWPAN; however, while these studies show the possibility of connecting the IEEE 802.15.4-based WSN networks to the Internet by using the Internet protocol IPv6, they do not take into account the bottleneck problem that happens as the network grows in size, since the congestion caused by the escalating data flow causes the quality of service in the network to decline considerably [13].

The IEEE 802.11AH has a better coverage range compared with any other IEEE 802.11-based amendment at a reasonably high-data rates transmission, which makes it a strong alternative to fulfill the needs of the future expansion in the IoT communication requirements and networks [14]. In comparison with low-power WAN (LPWAN) and WPAN technologies the IEEE 802.11AH when implemented properly, enables reliable bidirectional traffic communications, while maintaining a good balance between throughput and distance [15]. This makes it suitable to connect a group of low-power sensors to a server or a network without the need for a power amplifier because the use of the 900 MHz low frequency is beneficial in terms of extending the coverage range and reducing the power consumption [16].

3. General Overview

3.1. WSN. WSN is a group of integrated electronic devices called sensors that are deployed and distributed in a certain area. WSN has the capabilities necessary to gather information and monitor some physical or environmental conditions and parameters in the deployment field [17]. They communicate with each other and with a remote monitoring and control center through a specific networking protocol or standard while reducing the device power consumption as much as possible, taking into consideration the quality of service in the network. Those devices are the sensor or actuator nodes in the WSNs and they may form just a local network that does not connect to the Internet, or they form the things in the IoT infrastructure; however, in both situations, the sensor nodes gather the required data based on two methods:

(1) Sensing and sending the data at scheduled time intervals;

(2) Sensing and sending the data as a response to an event or a query.

In most of the applications, the WSNs are required to use a combination of both methods, also the sensor nodes can be stationary or mobile and that depends mainly on the deployment purpose and application.

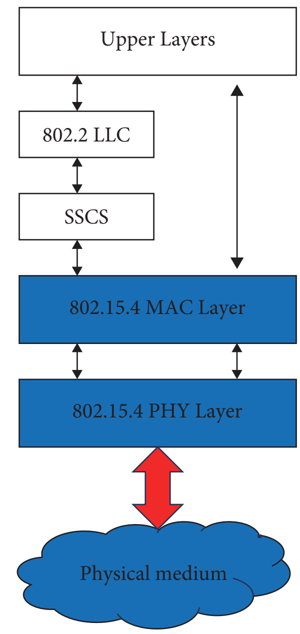

Figure 1: IEEE 802.15.4 Protocol Stack.

WSNs' flexibility and low-power consumption have led to their utilization and success in a lot of fields and applications such as military, healthcare, environmental, agriculture, industrial, and smart city applications [18].

3.2. IoT. The vision of the IoT is based on providing the necessary infrastructures and smart technologies to enable the interaction between the real world and the digital world, allowing any device, anyone, and any network to communicate anytime and anywhere [19]. The main feature of the IoT enabling an unlimited number of devices, users, and services from communicating [20], by using the Internet as a medium to establish a networking environment between the different used communication protocols and standards, therefore the recent years have witnessed extensive research to develop new low-power standards and protocols or to modify some of the existing ones to be more suitable for the future of the IoT networks and systems.

3.3. IEEE 802.15.4 Standard. The IEEE 802.15.4 standard has been developed by the Institute of Electrical and Electronics Engineers (IEEE) for low-rate wireless personal area networks (LR-WPAN) [21], with the aim of creating a communication standard that is flexible, easy to deploy, has low-power consumption, and a low-data transmission rates suitable for WSNs while maintaining a good level of reliability in data transmission. The IEEE 802.15.4 standard has been used mainly in home automation, WBSN, ad hoc WSN, environmental and agriculture applications, and industrial applications.

The IEEE 802.15.4 standard defines the specifications of the physical and MAC layers [22] while leaving the freedom of developing the upper layers (Figure 1) and that has created

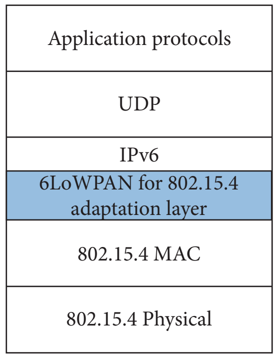

Figure 2: The 6LoWPAN Protocol Stack.

some successful and favorable technologies based on this standard like Zigbee and 6LoWPAN.

3.4. 6LoWPAN. The Internet protocol IPv4 is no longer able to address the increasing numbers of devices and WSNs connected to the Internet to create the IoT infrastructure since it can only address up to 2^{32} devices. Therefore new protocols and standards have been developed for the constrained resources IoT devices to solve this problem, like the 6LoWPAN protocol, which uses the IEEE 802.15.4 standard as its foundation due to its extensive use in the WSNs, allowing it to operate with a coverage range up to 100 m with data transmission rates up to 250 kbps [23, 24]. Using the Internet protocol IPv6 it can address up to 2^{128} devices.

The 6LoWPAN protocol uses a special adaptation layer in the network layer (Figure 2) to define how IPv6 communications are integrated into the IEEE 802.15.4 frames by using the main key elements [25]:

(1) Supporting layer-two forwarding of IPv6 datagrams by enabling the adaptation layer to carry end-level addresses for the ends of an IP hop.
(2) Fragmentation of the IPv6 packets into multiple frames to accommodate the minimum requirements of the IPv6 MTU.
(3) Header compression of higher-layer protocols like user datagram protocol (UDP), transmission control protocol (TCP), and internet control message protocol.
(4) IPv6 header compression through assuming usage of common and shared values, and also by removing fields with fixed information on 6LoWPAN networks.

3.5. IEEE 802.11AH Standard. The IEEE 802.11AH is an emerging new technology that was developed for the low-power wireless networks to meet the requirements of IoT networks and communication between machines, with data transmission rates between 150 kbps and 78 Mbps while providing wireless networking for mobile and stationary nodes with a coverage range up to 1,000 m.

The IEEE 802.11AH standard defines the physical and MAC layers' specifications (Figure 3), it operates in the sub 1 GHz ISM bands while using 1, 2, 4, 8, and 16 MHz as the operating channels bandwidths [26].

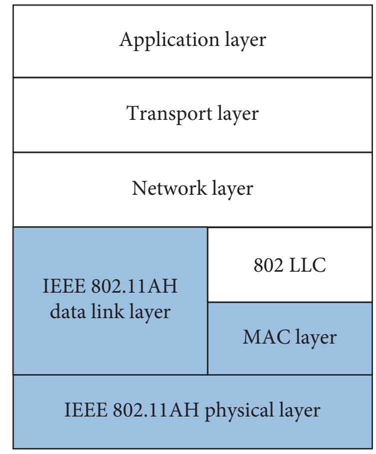

Figure 3: The IEEE 802.11AH Protocol Stack.

The IEEE 802.11AH MAC layer uses the distributed coordination function (DCF) based on carrier-sense multiple access with collision avoidance (CSMA/CA) scheme to access the medium [27], with improved energy-saving mechanisms and algorithms like the traffic indication map (TIM), which enabled it to support up to 8,191 stations, short beacon frames, target wake time (TWT), and restricted access window (RAW).

4. Materials and Methods

4.1. The Proposed Network Architecture. The proposed heterogeneous network consists of a group of distributed sensors and actuators that can communicate by using the 6LoWPAN protocol, also the network has two types of gateways:

(1) Edge gateways, link the entire network to the Internet and send the requests to the appropriate intermediate gateway according to the appropriate destination node.
(2) Intermediate gateways form the backbone of this network provide bidirectional data transmission between the sensors and actuators on one side and the edge gateways on the other side, by collecting the nodes' data and sending it to the Internet through the edge gateways also. They are responsible for sending the requests coming from the edge gateways to their destinations.

4.1.1. The Intermediate Gateway. This gateway consists of two independent parts integrated into it (Figure 4), one that uses the IEEE 802.11AH standard and the other is an IEEE 802.15.4 WSNs coordinator that uses the 6LoWPAN protocol, the two parts share one application layer that connects them to transmit the data from one to another.

4.1.2. The Edge Gateway. The structure of the edge gateway is similar to the intermediate one, hence it has two independent parts (Figure 5) one that uses the IEEE 802.11AH standard and the other connects the gateway to the Internet via the IEEE 802.11 standard (Wi-Fi) or via the ETHERNET.

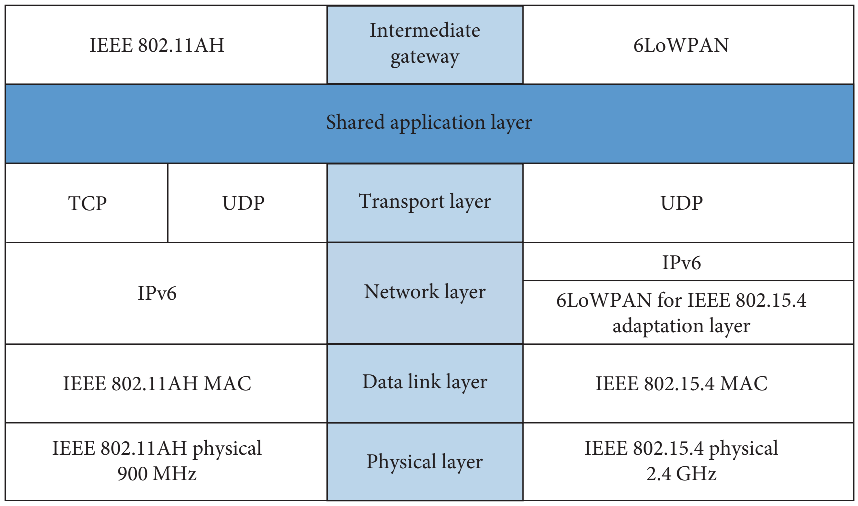

FIGURE 4: The Intermediate Gateway Protocols Stack.

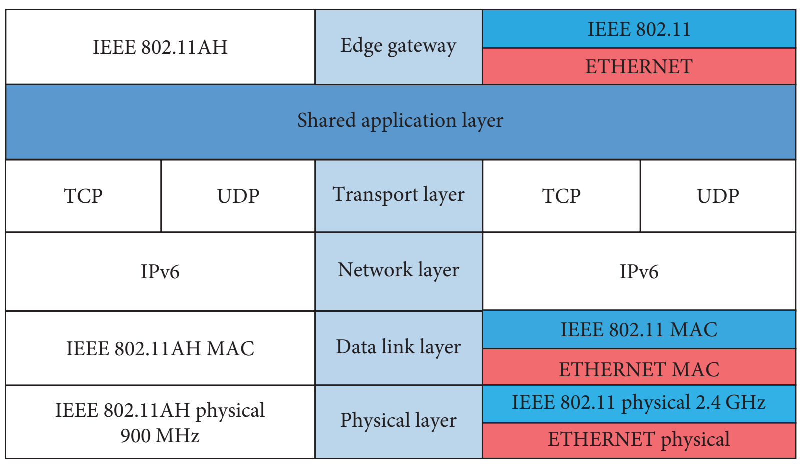

FIGURE 5: The IEEE 802.11AH Edge Gateway Protocol Stack.

Also, another edge gateway was proposed (Figure 6) to connect the homogeneous 6LoWPAN network to the Internet and to make this network a reference for comparing the results with the heterogeneous network.

4.1.3. The Proposed Network Topology. The 6LoWPAN sensors and actuators have been grouped into clusters (Figure 7), and for every cluster, there is an intermediate gateway that connects the cluster with the edge gateway through the IEEE 802.11AH standard, then the edge gateway connects the whole network to the Internet through Wi-Fi or through the ETHERNET.

Using the IEEE 802.11AH standard as a backbone for the network through the intermediate gateway is expected to help with the bottleneck problem. This happens in large-scale IEEE 802.15.4 networks when all the traffic from the nodes have to go through a single point which cannot accommodate all this traffic appropriately, thus the nodes closer to the main coordinator will have a heavier traffic burden [28]. In the homogeneous network case, those nodes are the 6LoWPAN cluster heads and the 6LoWPAN part in the edge gateway. As the number of the nodes and the data flow increase the IEEE 802.15.4 standard bandwidth becomes insufficient and no longer able to handle transmitting all the packets successfully. Because of this the packets get delayed or dropped when the queues are full as a result of the congestion that happens when the pressure on the network starts to accumulate, resulting in a decline in the network performance and reliability. However, by using the IEEE 802.11AH standard as a backbone in the network, the congestion that happens on the cluster heads can be relieved by increasing the network's overall bandwidth, by segmenting the network and then distributing the segments data flows on the higher IEEE 802.11AH standard bandwidth, so resulting in better network reliability.

4.1.4. Bidirectional Data Transmission. The proposed network architecture supports bidirectional data transmission between the nodes and the Internet through a shared flexible application layer to deal with the requests, the nodes' data,

6LoWPAN	Edge gateway	IEEE 802.11 ETHERNET
Shared application layer		
UDP	Transport layer	TCP / UDP
IPv6 6LoWPAN for IEEE 802.15.4 adaptation layer	Network layer	IPv6
IEEE 802.15.4 MAC	Data link layer	IEEE 802.11 MAC ETHERNET MAC
IEEE 802.15.4 physical 2.4 GHz	Physical layer	IEEE 802.11 physical 2.4 GHz ETHERNET Physical

FIGURE 6: The 6LoWPAN Edge Gateway Protocol Stack.

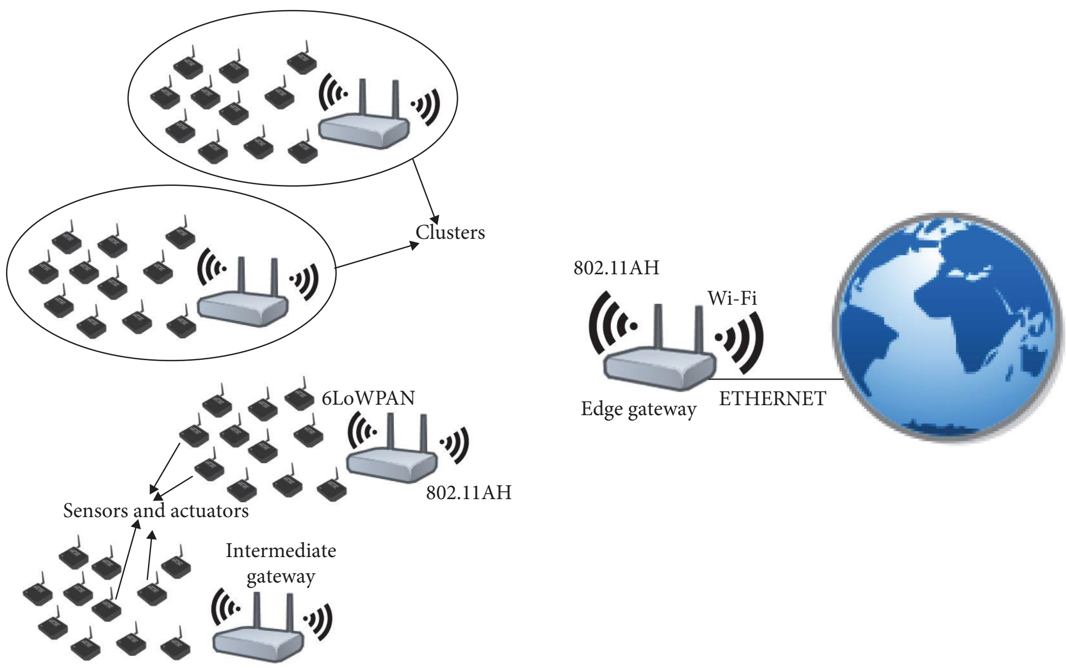

FIGURE 7: The Proposed Network Topology.

and the high-priority messages. In addition, it is responsible for message aggregation and disaggregation.

The 6LoWPAN overall frame can reach at max 127 bytes, on the other hand the IEEE 802.11AH standard frame can carry 7,959 bytes of data as a payload; therefore, multiple 6LoWPAN frames can be aggregated in a single IEEE 802.11AH frame. The aggregation of the messages is done in the intermediate gateway application layer by using two parameters:

(1) The max aggregated messages' number count;
(2) The max aggregation time interval.

Those parameters can be defined at the network setup in accordance with the quality of service required by the deployment domain application, but the high-priority messages are sent directly without waiting for other messages to complete the aggregation requirements, also the intermediate gateway is responsible for the disaggregation of the data sent from the Internet through the edge gateway to the nodes, and to send the right data to the suitably connected node.

The messages aggregation starts when a 6LoWPAN frame arrives at the intermediate gateway application layer then it is taken as a whole to keep all its information and data fields. Afterward, it is placed in the IEEE 802.11AH frame payload field, then if another 6LoWPAN frame arrives it will be inserted in the IEEE 802.11AH frame payload field after the previous one. This procedure will repeat until one of the aggregation conditions is met and by that the aggregated frame will be completed as it is shown in Figure 8.

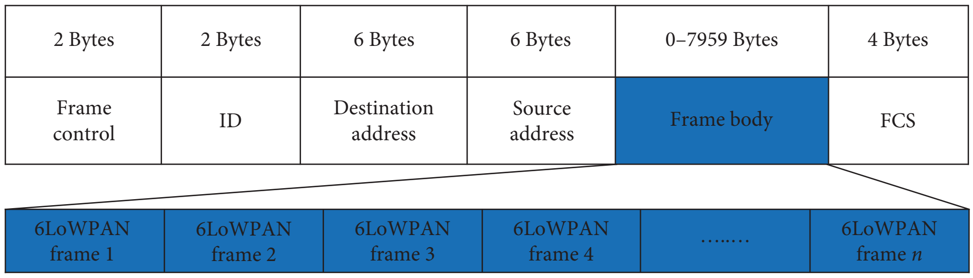

Figure 8: Aggregating multiple 6LoWPAN frames in a single IEEE 802.11AH frame.

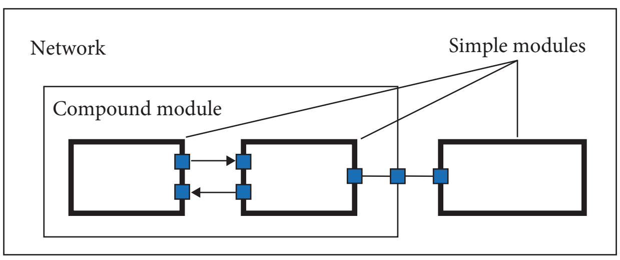

Figure 9: Simple and compound modules in OMNeT++.

4.2. Network Modeling and Simulation

4.2.1. The Simulation Framework. The network modeling and simulation were done by using the Discrete Event Simulator OMNeT++ (Objective Modular Network Testbed in C++) due to its substantial features and frameworks, since it is a multipurpose network simulation framework under the academic public license. Moreover it supports large-scale simulations by using hierarchical models built from combining the reusable models (Figure 9). These models are called simple models and they are written in C++. A number of simple models can be grouped and connected in a compound model to create more complex structures [29] and to create the network simulation.

OMNeT++ uses a special language called the network description language (NED) to let the users define the structures of the modules and their interconnections in the network topology, and also to attach variable parameters to those modules that can be defined at the start of the simulation or in the network simulation configuration file. This makes the simulations of large networks flexible and efficient [30]. In addition, OMNeT++ integrates a graphical editor based on the NED language to ease the creation and design of the network topology and the modules.

The modules communicate by exchanging messages between them through gates connected to wired or wireless links. The single module simple or compound can have multiple gates and the messages can represent simple or complicated data structures. In addition, it represents the frames transmitted between the modules when simulating the network and can be used to deliver the information and data between the various layers of the modules that define and characterize a certain protocol or standard.

OMNeT++ makes the analysis of the results efficient by supporting customizable charts and graphs that can be rendered from the dataset which contains the stored results of the simulation that follows rule-based processing. By following this method, the simulation results in graphs and charts can be automated to show the latest simulation run, also the dataset can derive data from other datasets.

OMNeT++ has multiple contributions to its frameworks and libraries for network simulations. However, the INET framework is considered the main framework for network simulation models, since it has various features and tools to support networks emulation, such as detailed OSI layers and protocols implementations including IPv4/IPv6 network stack, transport layer protocols: TCP, UDP, SCTP, routing protocols (ad hoc and wired), physical layer with scalable levels of details, and modeling of the physical environment with mobility support, also it has wired/wireless interfaces support (ETHERNET, PPP, IEEE 802.11, etc.).

4.2.2. The Simulation Scenarios and Networks. Three different networks have been modeled and simulated to evaluate the proposed new heterogeneous network features and improvements in comparison with the old homogenous network, and they are:

(1) The first network represents the homogeneous network that depends entirely on the 6LoWPAN protocol to be a reference for comparison with the other two networks after concluding the simulations' results. This network does not have any intermediate gateways, just eight 6LoWPAN cluster heads connected to two-edged gateways.

(2) The second network represents the heterogeneous network without packets aggregation, which depends on the IEEE 802.11AH standard as a backbone for the network infrastructure but without aggregating any messages to evaluate the network for the applications that require a high quality of service in regards to the end-to-end delay, the delivery ratio, and the network throughput. Therefore, the cluster heads in the homogenous network have been replaced with intermediate gateways.

(3) The third network represents the heterogeneous network with packet aggregation. This network has the same infrastructure and components as the second network but with the messages aggregation feature

Table 1: The subscenarios parameters.

Subscenario	I	II	III	IV
Simulation run time (s)	100	100	100	100
Queue type	Drop tail	Drop tail	Drop tail	Drop tail
Queue capacity (packets)	100	100	100	100
Packets sizes (bytes)	[10, 30]	[10, 30]	[10, 70]	[10, 70]
Sensors packets intervals (s)	[2, 3]	[1, 2]	[2, 3]	[1, 2]
Actuators packets intervals (s)	[3, 5]	[3, 5]	[3, 5]	[3, 5]
Internet packets intervals (s)	[1, 2]	[0.5,1]	[1, 2]	[0.5, 1]
Max aggregation time (s)	1	1	1	1
Max number of aggregated packets	20	20	20	20

enabled (up to 20 frames and 1 s for time intervals) to better utilize the frame payload size in the IEEE 802.11AH standard. However, the messages aggregation concludes when a high-priority message arrives.

Each network has two edge gateways, one connected to the Internet via Wi-Fi and the other via ETHERNET to test the connection with both technologies.

The networks simulations have been run and concluded for eight different scenarios to test and evaluate the network's response to different payloads, by changing the packets sizes and by changing the intervals between the packets, also to test the performance of the network when the number of the nodes changes in the subnetworks.

The simulation scenarios are divided in accordance with the number of nodes into two main sets, each set containing four subscenarios. In the first main set each network contains 112 sensor nodes and 32 actuator nodes distributed equally on eight subnetworks, each one constituted by 18 nodes. While in the second main set, the number of nodes in each network was increased to 160 sensor nodes and 32 actuator nodes distributed equally on eight subnetworks, each one constituted by 24 nodes.

The subscenarios' parameters are shown in the Table 1. The packets sizes and intervals are randomly generated on a given interval, and also the destinations of packets are chosen randomly. Moreover, some packets are generated in the nodes as a response to the requests arriving from the Internet.

5. Results and Discussion

The simulation results have been analyzed for three metrics to evaluate the performances of the networks, which are:

Packets mean end-to-end delay: the mean value of the end-to-end delay, i.e., the time required for the packet to be transmitted from the source to the destination.

Packets delivery ratio (%): the ratio between the total number of received packets by the destination nodes and the total number of packets sent by the source nodes, expressed as a percentage.

Network throughput: the data transferred successfully from the sources to the destinations via the network in a given time period, measured in bits per second (bps).

5.1. Packets Mean End-to-End Delay. The end-to-end delay simulations' results for the first main set are shown in Figure 10 and their corresponding numerical values are shown in Table 2.

In the first main set of simulations, the homogeneous network showed a slight increase in the end-to-end delay mean value as the intervals between the packets got shorter. Increasing the packets' payloads alone without shortening the packets' intervals had no negative impact on the end-to-end delay mean value. However, the heterogeneous network without packet aggregation showed an overall better performance than the homogeneous network. In addition, increasing the packets payloads while shortening their intervals had no negative impact on its performance. On the opposite, the end-to-end delay mean value has decreased. The heterogeneous network with packets aggregation shows a considerable increase in the end-to-end delay mean value due to enabling the messages aggregation feature.

The end-to-end delay simulations' results for the second main set are shown in Figure 11 and their corresponding numerical values are shown in Table 3.

In the second main set of simulations, the homogeneous network showed a noticeable increase in the end-to-end delay mean value as the intervals between the packets got shorter. Also increasing the packets payloads alone without shortening the packets' intervals had a negative impact on the end-to-end delay mean value this time. However, the heterogeneous network without packet aggregation showed an overall better performance than the homogeneous network. In addition, increasing the packets' payloads while shortening their intervals had no negative impact on its performance this time too. However, the heterogeneous network with packets aggregation shows a decrease in the end-to-end delay mean value in comparison with the first main set.

The simulations' results show that the 6LoWPAN homogenous network performance decreases drastically as the number of nodes increases, accompanied by increasing the packets payloads and shortening their intervals. When the mean end-to-end delay value reaches 0.1246 s, it becomes unsuitable for some applications that have high-quality of service demands, such as power grid control and healthcare applications.

The simulations' results of the heterogeneous network without packet aggregation show better performance and

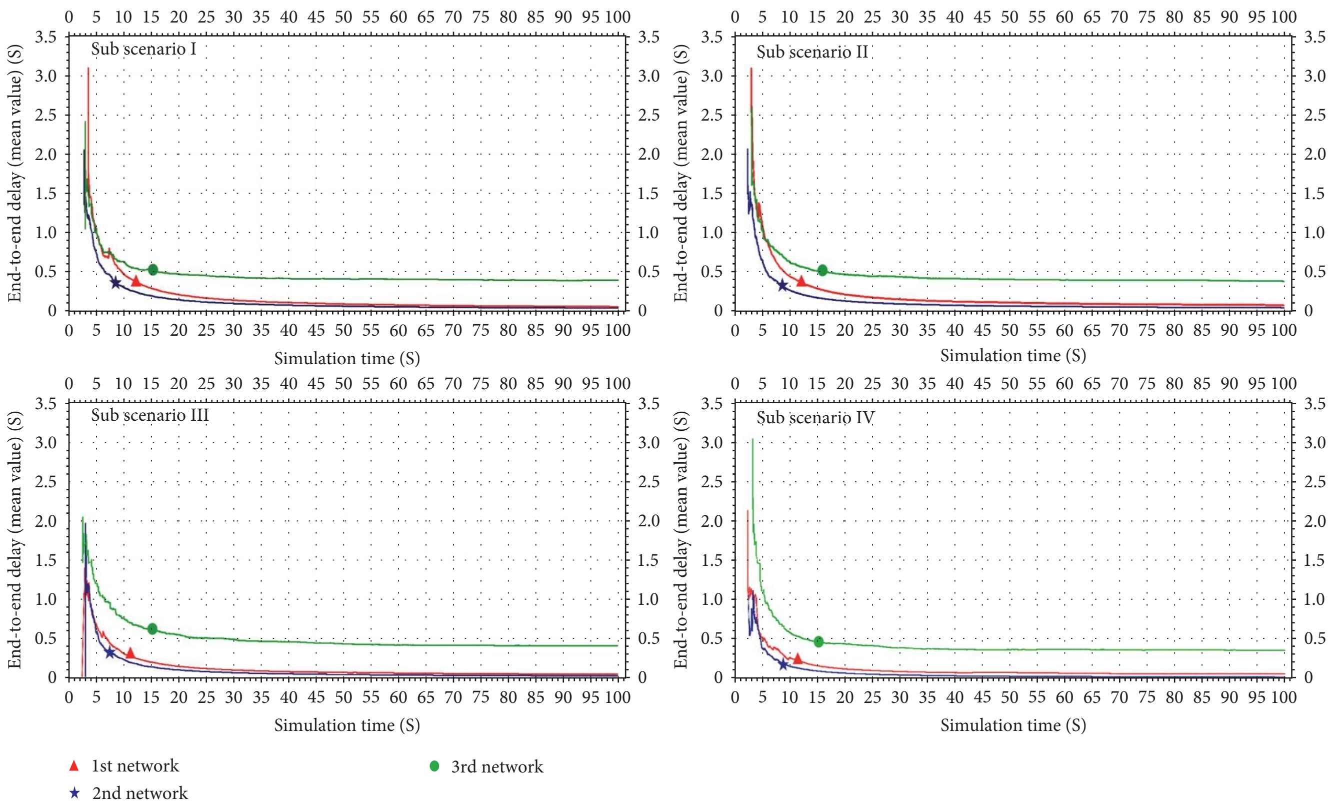

Figure 10: End-to-end delay mean results for the first main set.

Table 2: End-to-end delay mean numerical results for the first main set.

Subscenario first set	I	II	III	IV
Homogeneous network (s)	0.0502	0.0606	0.0454	0.0633
Heterogeneous network without packets aggregation (s)	0.0310	0.0279	0.0249	0.0223
Heterogeneous network with packets aggregation (s)	0.3844	0.3649	0.4088	0.3620

stability, even when the number of nodes increases in comparison with the homogenous network. This is due to using the IEEE 802.11AH standard as a backbone as, since it has a larger data transmission rate than the 6LoWPAN protocol, it was able to minimize the bottleneck problem by distributing the 6LoWPAN network data flow pressure on multiple intermediate gateways, and then by guiding the data flow into a larger pathway, maintained by the IEEE 802.11AH standard, instead of sending the data flow into only the narrower 6LoWPAN pathway. By following this strategy, the time that the packets spend waiting in the queues in the clusters' heads or the edge gateways gets shorter.

Finally, the simulations' results of the heterogeneous network with packet aggregation show a much higher increase in the end-to-end delay mean value due to the waiting time that the packets have to go through until the aggregation conditions are met. However, this does not violate the purpose this feature was implemented for, as long as the network delivery ratio and throughput are not affected. This is shown in the next two sections because the main reason of aggregating the messages is to test the network adaptability to work with applications and services that does not require low-latency standards and requirements.

5.2. Packets Delivery Ratio. The packets' delivery ratio obtained by simulations for the first main set are shown in Figure 12 and their corresponding numerical values are shown in Table 4.

In the first main set of simulations, the homogeneous network showed a slight decrease in the delivery ratio as the packets' payloads got higher without shortening the packets' intervals. However, shortening the intervals between the packets caused the delivery ratio to deteriorate by around 10%. Also increasing the packets' payloads and shortening the packets' intervals at the same time caused the delivery ratio to deteriorate by around 20% in this case. However, both the heterogeneous networks showed clear stability, even when the packets' payloads increased and their intervals got shorter the delivery ratio did not deteriorate compared with what happened in the homogenous network. This

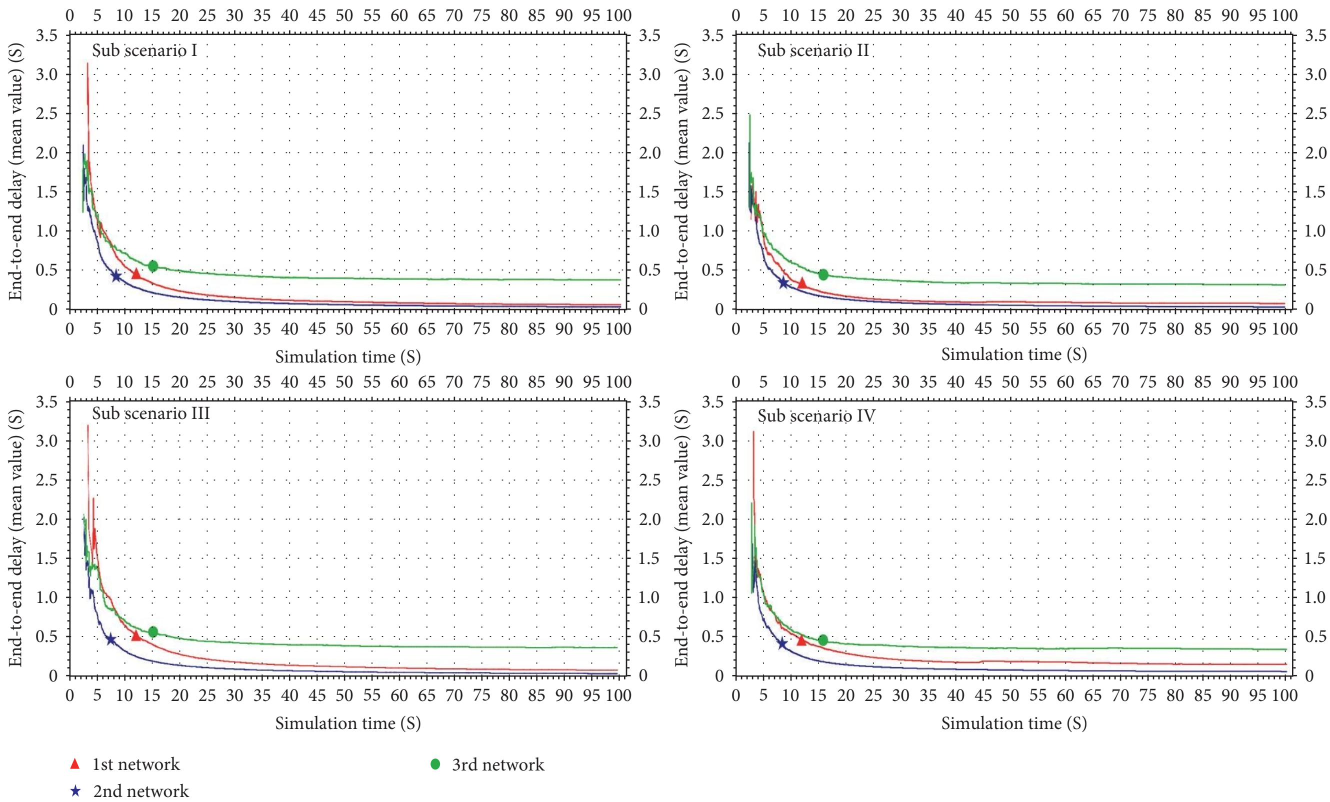

Figure 11: End-to-end delay mean results for the second main set.

Table 3: End-to-end delay mean numerical results for the second main set.

Subscenario second set	I	II	III	IV
Homogeneous network (s)	0.0625	0.0772	0.0751	0.1246
Heterogeneous network without packets aggregation (s)	0.0350	0.0323	0.0323	0.0335
Heterogeneous network with packets aggregation (s)	0. 3788	0.3137	0.3643	0.3188

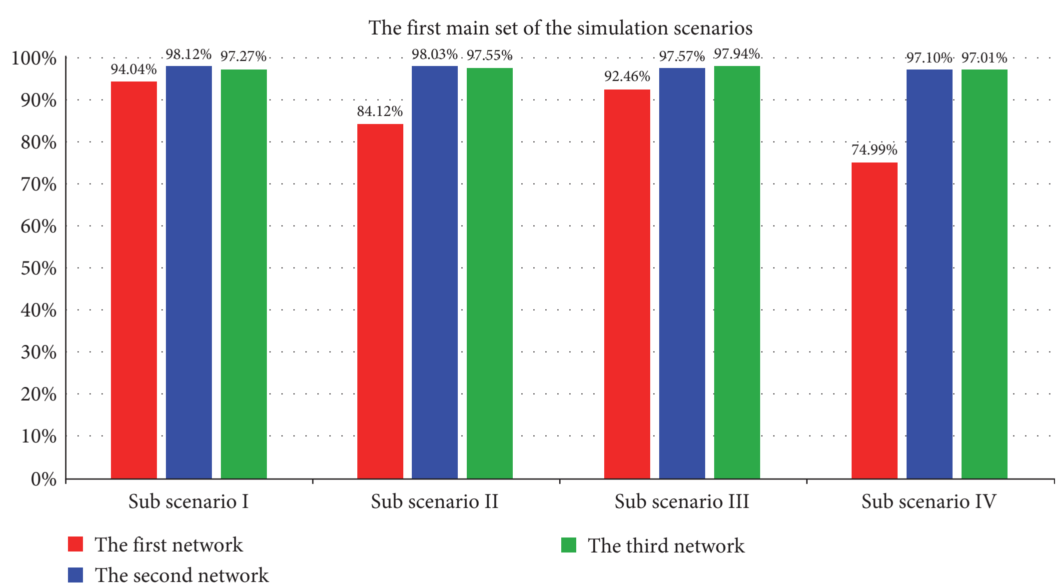

Figure 12: Delivery ratio results for the first main set.

Table 4: Delivery ratio numerical results for the first main set.

Subscenario first set	I	II	III	IV
Homogeneous network				
Packets sent	5,521	8,778	5,503	8,794
Packets received	5,192	7,384	5,088	6,595
Delivery ratio (%)	94.04	84.12	92.46	74.99
Heterogeneous network without packets aggregation				
Packets sent	5,526	8,840	5,514	8,854
Packets received	5,422	8,666	5,380	8,597
Delivery ratio (%)	98.12	98.03	97.57	97.10
Heterogeneous network with packets aggregation				
Packets sent	5,564	8,904	5,524	8,859
Packets received	5,412	8,686	5,410	8,594
Delivery ratio (%)	97.27	97.55	97.94	97.01

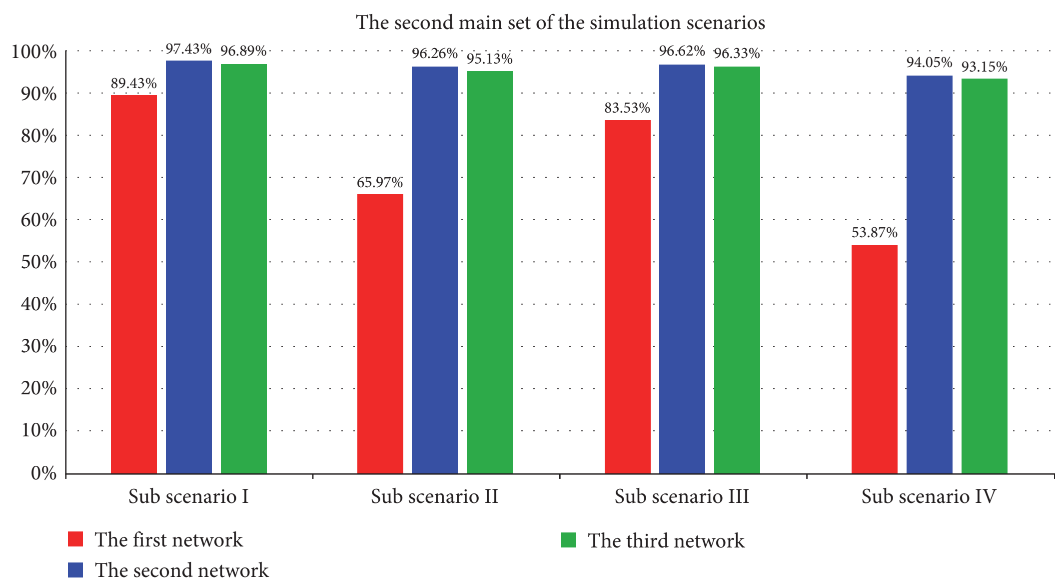

Figure 13: Delivery ratio results for the second main set.

shows that even with the packets aggregation feature the delivery ratio is not affected since it delays the packets only until the aggregation conditions are met.

The packets delivery ratio obtained by simulations for the first main set are shown in Figure 13 and their corresponding numerical values are shown in Table 5.

In the second main set of simulations, increasing the number of the nodes had a big impact on the delivery ratio in the homogeneous network as it measured 53.87% when the packets' payloads got higher and their intervals got shorter. However, this was not noticeable for the heterogeneous networks since the delivery ratio was stable except for the decline of only 3% when the network pressure was at its maximum.

The higher the delivery ratio, the better the network's overall reliability, since it is desired that the maximum number of packets reaches their destination. But that was not the case in the homogenous network, in fact, when the number of the nodes increased accompanied by increasing the pressure on the network the delivery ratio declined severely because the queues in the cluster heads were nott able to comply with all the data flow within a suitable time, and this shows clearly the effects of the bottleneck problem in this network. On the other hand, both the heterogeneous networks showed promising results as the delivery ratio improved significantly and the decline was minor in comparison with the homogenous network, due to using the IEEE 802.11AH standard as a backbone. But, taking into consideration that the loss of an IEEE 802.11AH aggregated frame leads to multiple 6LoWPAN packets loss, the delivery ratio in the heterogeneous network without packets aggregation was slightly better than the heterogeneous network when enabling the packets aggregation feature.

5.3. Network Throughput. The network throughput simulations' results for the first main set are shown in Figure 14 and their corresponding numerical values are shown in Table 6.

Table 5: Delivery ratio numerical results for the second main set.

Subscenario second set	I	II	III	IV
Homogeneous network				
Packets sent	7,453	11,896	7,415	11,852
Packets received	6,665	7,848	6,194	6385
Delivery ratio (%)	89.43	65.97	83.53	53.87
Heterogeneous network without packets aggregation				
Packets sent	7,430	12,048	7,436	12,024
Packets received	7,239	11,598	7,185	11,309
Delivery ratio (%)	97.43	96.26	96.62	94.05
Heterogeneous network with packets aggregation				
Packets sent	7,450	11,972	7,441	11,994
Packets received	7,218	11,389	7,168	11,172
Delivery ratio (%)	96.89	95.13	96.33	93.15

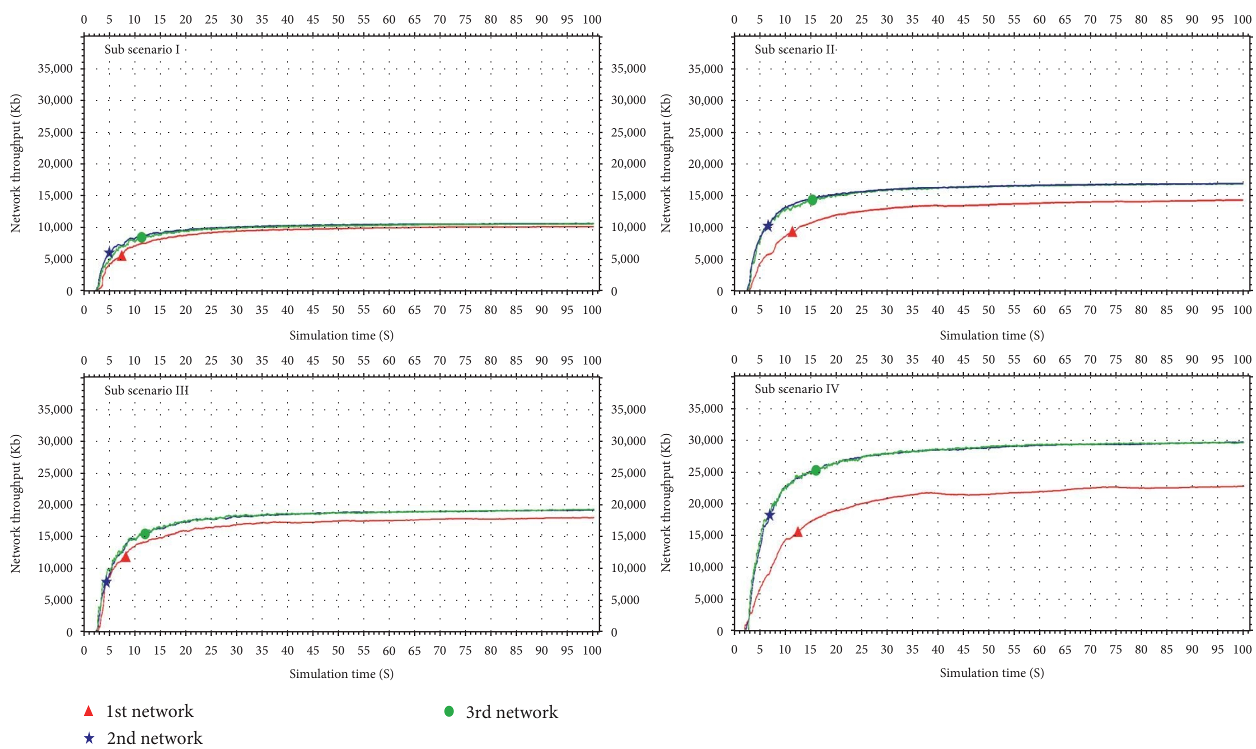

Figure 14: Network throughput results for the first main set.

Table 6: Network throughput numerical results for the first main set.

Subscenario first set	I	II	III	IV
Homogeneous network (kbps)	101.467	142.079	178.184	227.267
Heterogeneous network without packets aggregation (kbps)	106.083	167.541	189.787	297.059
Heterogeneous network with packets aggregation (kbps)	105.511	167.053	191.117	296.583

In the first main set of simulations, the homogenous network throughput was close to the heterogeneous networks throughput values when the pressure on the network was low, but, as the pressure increased by increasing the packets payloads and their intervals, the difference in the throughput values has increased.

The network throughput simulations' results for the second main set are shown in Figure 15 and their corresponding numerical values are shown in Table 7.

In the second main set of simulations, the homogenous network throughput declined severely in comparison with the heterogeneous networks after increasing the number of

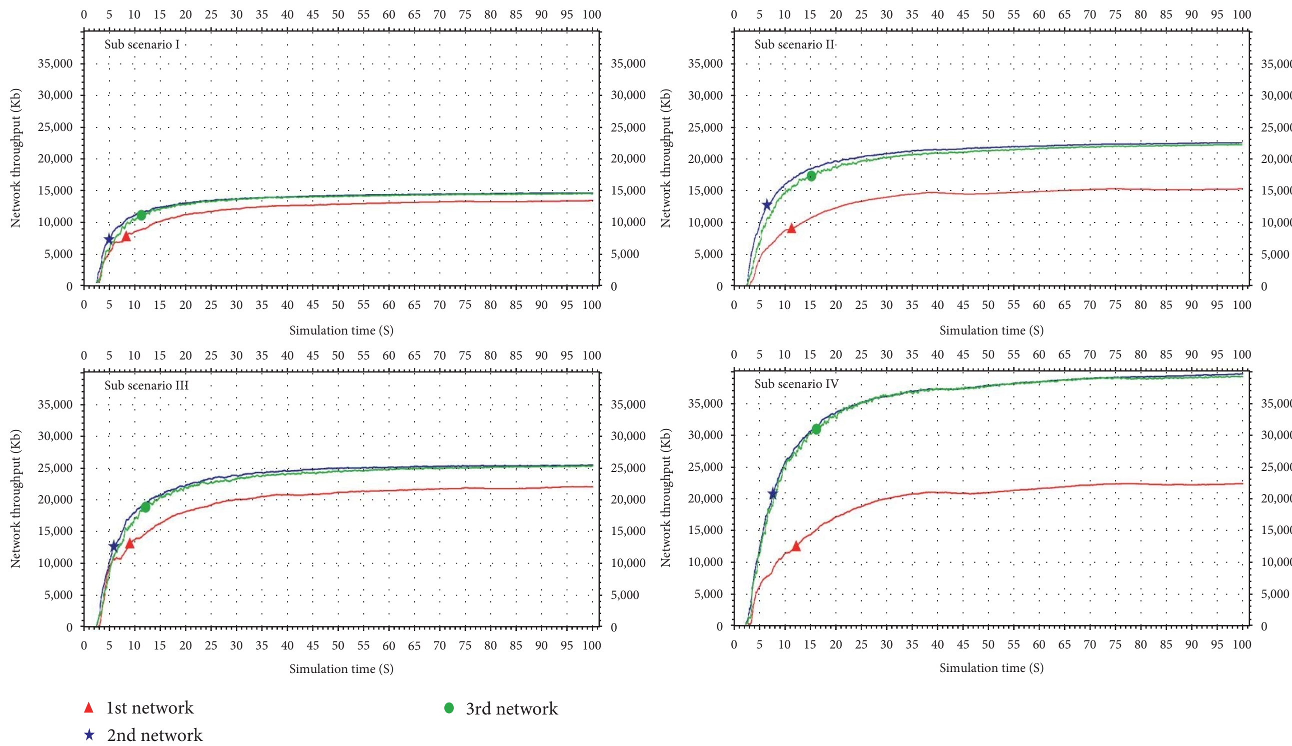

Figure 15: Network throughput results for the second main set.

Table 7: Network throughput numerical results for the second main set.

Subscenario second set	I	II	III	IV
Homogeneous network (kbps)	130.759	153.316	219.710	222.832
Heterogeneous network without packets aggregation (kbps)	142.607	225.651	253.589	395.333
Heterogeneous network with packets aggregation (kbps)	141.492	221.966	252.557	390.906

nodes and when the pressure on the network was at its maximum.

For the comparison among the networks, a higher network throughput is an indicator of good performance when the same conditions are applied. The simulations' results show clearly that the network's throughput has improved significantly in the proposed heterogeneous network, due to the improvement in the network's overall reliability, since more packets are transferred successfully from the source to the destination with lower latency. This is because using the IEEE 802.11AH standard as a backbone has relieved the congestion that happens on the cluster heads when the data flow pressure increases.

6. Conclusions and Future Works

The proposed heterogeneous network architecture in this paper has proved to be more reliable than the typical homogeneous 6LoWPAN network that uses the cluster topology. The proposed architecture can provide a better quality of service in terms of packets' end-to-end delay, packets delivery ratio, and network throughput, due to using the IEEE 802.11AH standard as a backbone, and thus utilizing its bidirectional data transfer rates, which can reach up to 78 Mbps. In addition, operating on the 900 MHz frequency band has minimized the interference with the 6LoWPAN nodes. On the other hand, it should be noted that the results of both heterogeneous networks were close because their infrastructures are the same except for the packets end-to-end delay which is higher in the heterogeneous network with packet aggregation, but this increase in the latency is not undesirable, since it's not originating from a failure or a deficiency in the network but it's forced by choice, due to enabling the packet aggregation feature. This is suitable to use in applications that do not require low-latency demands and at the same time require high reliability, since it has a minimal effect on network delivery ratio and throughput. The new features of the IEEE 802.11AH standard have helped considerably with the data flow congestion that comes from the bottleneck problem in the IEEE 802.15.4 networks, especially when the number of nodes increases and that has led to an improvement in the network's overall quality of service, as it became more robust and reliable.

In future works, the proposed network needs are the energy consumption in nodes and the effects of the routing algorithms on the network overall performance. Furthermore, a method to determine the most suitable number of intermediate and edge gateways in correspondence to the number of nodes needs to be studied and evaluated to make the proposed heterogeneous network deployment more efficient and robust.

Data Availability

The simulations are carried out through OMNeT++ under the academic public license, also all the simulations parameters and details are clearly shown in this paper, which could be used to reproduce the simulations related to these paper findings.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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