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Developing new connectivity architectures for local sensing and control IoT systems

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Abstract
While improvement can be done in every component of the Internet of Things (IoT) as an evolving technology, this work focuses on connectivity. Currently, the main in-building connectivity technology for IoT enterprise deployments is the low rate wireless personal area network (LR-WPAN). However, despite the low power and complexity, the two main issues of the LR-WPAN are very slow data access and short coverage range. To address these issues, 802.11ax can be a promising alternative due to its new IoT-oriented features that explicitly target the resource-constraint requirements. This work proposes and implements two IoT connectivity architectures to deploy the 11ax protocol stack in the sensor motes for sensing the environment and also in the backhaul link to collect and relay the sensed data to the remote processing server. The LR-WPAN is also implemented to be utilized as the baseline and reference point for comparison purposes. Furthermore, a decision model with two integrated modules is proposed to measure and evaluate the performance of the proposed architectures on the basis of the IoT requirement factors that directly contribute to IoT efficiency. The model includes an extensive set of IoT use cases to demonstrate the capabilities of the proposed architectures and determine their contribution to performance enhancement of the IoT systems.

Keywords Internet of Things · Decision model · IoT applications · IoT requirement factors

1 Introduction

The Internet of Things (IoT) is an important worldwide technology with different requirements that are still evolving. IoT has a wide range of applications including industrial and home automation, medical and health care, smart cities, traffic management, ecosystem monitoring, and beyond. In these applications, a complete IoT system represents the integration of four distinct components: sensors/devices, connectivity, data processing, and user interface [1]. In essence, IoT is a network of connected things which makes the connectivity a critical component for providing seamless and distributed connection between IoT devices. Moreover, connectivity is highly important as it can control the overall IoT system performance by directly influencing the performance of the other three components. However, as a result of the ongoing growth in the number of connected devices to IoT systems, their connectivity remains a critical challenge [2].

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Due to the wide number of IoT applications, requirements, and use cases, there exist many connectivity technologies that can be chosen for IoT deployments. Accordingly, the IoT connectivity technologies can be broadly divided into two solutions as either long- or local-range [3, 4]. The main local-range IoT connectivity solution for in-building enterprise deployments is the 802.15.4 standard [5–7]. It is used in many industrial, commercial, and residential IoT deployments due to low power consumption, complexity, and cost. It defines the physical (PHY) and media access control (MAC) layers of low rate wireless personal area networks (LR-WPAN) [8, 9]. The LR-WPAN only allows 54B data length in the application layer [10, 11], which is too small for IPv6 packets [12]. To solve the issue and perform efficient IPv6 communication over LR-WPAN, the IPv6 over LR-WPAN (6LoWPAN) is used, which defines an adaptation layer above the LR-WPAN MAC layer [13]. The 6LoWPAN, in addition to fragmentation and reassembly of IPv6 packets, can perform header compression to reduce the transmission overhead of the packets and meet the size requirements of IPv6 [12]. It provides two compression techniques called internet protocol header compression (IPHC) and header compression (HC1) to compress the IPv6 headers down to only a few octets and reduce the protocol overheads [10, 14].

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Despite the advantages, the very low data rate (up to 250Kbps) and short coverage range are the main challenges of the LR-WPAN [15]. IoT is a constantly evolving technology that embraces a vast number of other technologies. Therefore, it is clear that to provide seamless and continuous access to IoT systems, no single connectivity solution is ideally suited to serve all the IoT use cases. In this regard, the 802.11 standard as an essential component in today's networking can be a promising alternative. The recently developed 802.11 standards, including 802.11ax high efficiency (HE) and 802.11ah (HaLow) are the IoT-oriented solutions. The 802.11ah is long-range and low in power and data rate. However, it is not commonly used in the IoT deployments because it operates on the 900 MHz frequency band for which there is no global standard [16]. In contrast, 11ax operates in 2.4 GHz (in addition to 5 GHz) which is commonly used in the systems that can operate worldwide. Moreover, 11ax includes new features that explicitly target the IoT requirements which turn it an attractive choice for IoT connectivity in enterprise environments [17, 18]. There are several power-saving schemes in 802.11ax, among which are target wait time (TWT) and 20 MHz-only mode [19–22]. The power-saving is particularly important for IoT sensors and devices with constraint power [21]. To further support IoT requirements, 11ax utilizes orthogonal frequency-division multiple access (OFDMA), a technology borrowed from the long term evolution (LTE) in the form of multi-user multiple inputs multiple outputs (MU-MIMO) and MU-OFDMA [23]. While MU-MIMO provides multiple-user access by using different spatial streams, the MU-OFDMA subdivides the channel into multiple sub-channels called resource units (RUs) and assigns them to different devices [22]. Both MU-OFDMA and MU-MIMO can improve performance by reducing certain transmission overheads [23]. Moreover, the 11ax standard promises reliable data delivery in a high-density area which, according to Cisco, is the area where more than 30 devices are simultaneously connected to a single access point [24]. This capability is highly important for the scalability of the IoT systems to avoid risks to the growth and preserve the stable connectivity of the IoT devices.

Given all the 11ax IoT-oriented benefits, which particularly target the resource-constrained devices, will open up new directions for researches. However, due to being a new standard, the benefits for IoT systems remain in the theoretical level as no work has been done to implement and evaluate the standard in the IoT systems to determine the practical optimization level in IoT business models and devices. Therefore, the prime motivation in this work is to determine the contribution of 11ax to the efficiency of the IoT systems both as the protocol stack of the sensor motes as well as the backhaul link to remote servers. Moreover, the 6LoWPAN adaptation layer has been mostly utilized in the LR-WPAN networks for efficient IPv6 communication. However, there is no work with regard to the implementation of the 6LoWPAN on top of the 11ax protocol stack for IPv6 communication in the IoT systems. This prompts our second motivation to determine the functionality and possible benefits that the 6LoWPAN can bring to the 11ax-based IoT systems.

This work specifically aims at the connectivity component for indoor local sensing and control IoT applications such as home automation and industrial monitoring. In this regard, four main contributions are summarized as follows. First, we propose a connectivity architecture called 6LoWPAN over high-efficiency and low rate wireless personal area networks (LoHELR). The LoHELR is applicable as the backhaul link of the IoT systems to connect the sensor motes to the remote processing server. Second, we propose a second connectivity architecture called 6LoWPAN-enabled high efficiency (LoHE). The LoHE takes full advantage of the 11ax standard by placing its protocol stack in the entire IoT systems from the sensor motes and their access link to the remote server. Third, to evaluate the LoHELR and LoHE, we propose a decision model with two integrated modules for data management and evaluation purposes. It provides a simulation-driven analysis of the proposed architectures based on the IoT requirement factors. Fourth, the LR-WPAN IoT system is also developed and implemented to be utilized as the baseline and reference point for comparison purposes with the proposed architectures.

The remainder of this work is organized as follows. In Section 2, the related works are discussed. Section 3 presents the details regarding the proposed architectures and decision model. The results and discussions are provided in Section 4. Section 5 concludes the work.

2 Related works

The IoT applications cover large areas of interest that are still evolving in different aspects. The connectivity is one of the IoT components that can take the full advantages of other evolving technologies. Any advances in either wire, wireless, or cellular 4G/5G technologies can become a part of IoT connectivity if it can meet the IoT requirements. The authors in [25] consider the 802.11-based networks as a common scenario for the future of IoT systems. In this regard, they develop a WLAN aware cognitive MAC (WAC-MAC) and compare its efficiency to the LR-WPAN standard. The effects of a varying number of sensor nodes and beacon intervals are measured in terms of delay, energy, and throughput with no considerations for 11ax and 6LoWPAN. A mathematical model is provided in [26] to evaluate the performance of 802.11b/g standards for further comparison with the LR-WPAN. The throughput performance is measured under a different number of nodes and data arrival rates. Unfortunately, while 11ax and 6LoWPAN are not evaluated, other critical IoT requirement factors involving in the performance variations are also are not measured. An analytical model based on Markov chains is provided in [27] to evaluate the co-existence of 802.11 and ZigBee in IoT systems. The performance of accessing the channel is measured under different connection density configurations while no assessment is made on the 11ax and other IoT factors. The authors in [28] compare 802.11 and WirelessHART with LR-WPAN to determine the resulting interference levels and sensitivity thresholds for different channel overlapping configurations. The 802.11 g interference on the performance of LR-WPAN devices is also measured in [29, 30]. A suite of hybrid communication including 802.11a/b/g, WiMAX, and Ethernet is provided to compare the performance with the LR-WPAN in [31]. Throughput, delay, and loss rate are measured under the different sizes of packets. Despite that, the work does not take into account any other IoT factor or 11ax-based connectivity. A comparison of LR-WPAN with 802.11ah is provided in [32] to measure the throughput, association time, and delay as the number of sensor nodes changes.

In order to determine if LR-WPAN meets the requirements of a wireless body area network (WBAN), a traffic-adaptive priority-based MAC protocol (TAP-MAC) is proposed in [33]. The model is simulated and the performance is measured and compared with the original LR-WPAN in terms of throughput, delay, and energy consumption under a different number of sensor nodes varying in the range of 10 to 60. In this regard, the connectivity is only based on LR-WPAN and the 11ax and other important IoT requirement factors are not evaluated. In [34], multimedia sensor networks are investigated to evaluate the performance of delay-sensitive real-time IoT applications. The packet delivery ratio and latency are measured for different data transfer rates, number of nodes, and number of retransmissions. The sensor network with 802.15.4–2015 standard is also investigated in [35] using a testbed to measure the delivery ratio for different payload sizes.

The 6LoWPAN evaluation in LR-WPAN in terms of header compression efficiency is provided in [36]. A modified and improved IPv6 header compression (MIHC) is proposed to be compared with the original IPHC and also with no-compression using the Cooja simulator in Contiki. To evaluate the throughput, delay, and round trip time performances, the payload size varies in the range of 5 to 85 bytes. However, the evaluation is without regard to the 11ax and other IoT effective requirement factors. The 6LoWPAN efficiency regarding the WBAN requirements is also investigated in [37]. Throughput, packet error rate, delay, and energy consumption are measured for different packet generation rates and the number of nodes. The 6LoWPAN performance is also investigated in [38] in the presence of a UDP server with different packet sending rates varying in the range of 0 to 256 without consideration to other IoT factors.

Some works also attempt to extend the local-range connectivity of IoT services to wide area networks (WAN). A new access router using the WiMAX standard is proposed in [39] for being tightly coupled integration with the LR-WPAN. The total carried traffic under different arrival rates is measured to evaluate the performance. However, 11ax and other IoT factors and metrics are not investigated. The IoT connectivity investigated in [40] is based on the low-power wide-area network (LoRaWAN). A scheduling algorithm is proposed for synchronization at the beginning of the communications between the gateway and the end nodes. In this case, the number of users varies to determine the collision probability. The IoT WAN is also investigated in [41] for narrowband IoT (NB-IoT). A power-domain non-orthogonal multiple access (NOMA) is proposed to evaluate the performance of the IoT system under different data rates. The LoRaWAN is also investigated in [42] to measure SNR, RSSI with different transmission distances from the gateway and in [43] to measure packet delivery ratio with a different number of users.

Given the related works, two main shortcomings are identified. First, local-range approaches mainly tend to focus on LR-WPAN connectivity. However, the key problems with the LR-WPAN are very slow data access and short coverage range which limits and fails the requirements of high-demand IoT applications. This shows that new connectivity approaches are required to fulfill the corresponding requirements. Second, no work has been done to take advantage of the newly developed IoT-oriented features of 11ax and implement 11ax-based IoT systems as a promising solution for local-range IoT systems. To address the gaps, this work proposes two new 11ax-based connectivity architectures for the entire IoT system as well as for the backhaul links.

3 Proposed IoT architectures and decision model

The timely, continuous, and consistent access to the data generated by IoT sensors as well as gaining the right information at the right time is critical for the reliability of every IoT system. This can further expand and improve the support for the delivery of IoT services across a wide variety of applications such as crucial healthcare and industrial solutions. Given the 802.11ax newly developed IoT-orientated features, easy integration into the existing infrastructures, and also simple and low-cost installation/maintenance [18] motivate us to leverage the standard for more efficient connectivity towards distributed IoT systems. In this regard, we propose two new IoT connectivity architectures to connect sensors and devices to the cloud for further processing and analysis. On the basis of IoT requirements, we further propose a decision model to evaluate the performance of the two proposed IoT connectivity architectures. This section presents the steps and details for the design and implementation of the proposed architectures and the decision model using the network simulator.

3.1 LoHELR and LoHE

Our modeling of 11ax in the IoT systems comprises different elements illustrated in Fig. 1.

The first proposed IoT connectivity architecture is called 6LoWPAN over high-efficiency and low rate wireless personal area networks (LoHELR) (A in Fig. 1). The LoHELR includes two different integrated interfaces to communicate with two different networks. The first interface is configured for 11ax connections and the second for LR-WPAN connections. This allows two-way communications between LR-WPAN

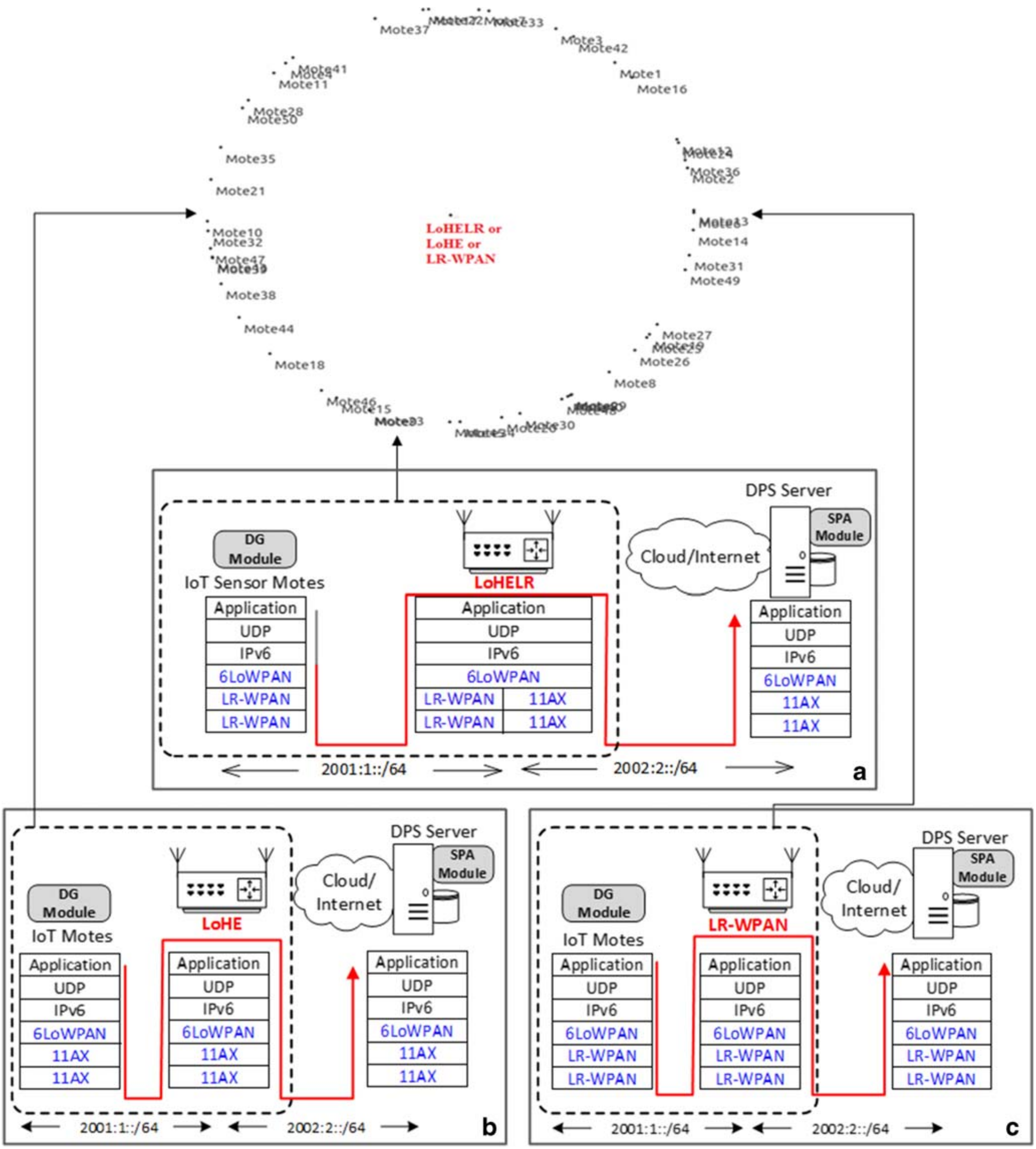


Fig. 1 Overview of the (**a**) LoHELR, (**b**) LoHE, and (**c**) LR-WPAN with 50 sensor motes

and 802.11ax networks. Both interfaces are in different domain areas with different IPv6 addresses. The LoHELR protocol stack provides the same upper layers (transport and network layers) for both interfaces while they are different in the last two layers (PHY and MAC). The transport and network layers provided for both interfaces are UDP and IPv6, respectively, allowing IPv6-only communications. While the 6LoWPAN is currently used only with 802.15.4 for efficient IPv6 transmissions, we attempt to use its advantages and adapt it to work with 11ax as well. Hence, the 6LoWPAN adaptation layer is integrated in both interfaces for fragmentation/reassembly and compression/decompression purposes in the LoHELR. The common parts of the two interfaces terminate here when it comes to MAC and PHY layers. The first interface includes 11ax-MAC and 11ax-PHY layers to connect sensor motes to the cloud and deliver the sensed data to 11ax-based IoT systems. On the other hand, the second interface is utilized to connect to LR-WPAN networks in order to collect and aggregate the data generated by the LR-WPAN sensor motes.

As a result, the whole IoT system using LoHELR includes three functional parts. In the first part, the sensor motes are developed with the LR-WPAN protocol stack and the 6LoWPAN adaptation layer. These sensor motes model the interaction with the environment and generate data with a variety of different aspects based on the proposed decision model as will be explained later. All the sensor motes are positioned randomly within a circular disc and the LoHELR coordinator is placed at the center, to which the sensor motes are connected. While the disc has an adjustable radius to reflect per distance requirements, it changes equally for all the sensor motes. For example, if radius changes to n meter, the distance of all the sensor motes from the LoHELR coordinator equally will be n meter. The reason for such an arrangement in the sensor motes domain is to avoid any unfair extra performance gain or loss caused by unequal distances and also to overcome the problem of uneven energy [44]. There is a direct relationship between the energy consumption of the sensors and the transmission range so that more energy is consumed for longer distances. This eliminates the equality of transmission opportunity and provides unfair conditions for characterizing the performance of the IoT system. Therefore, to bring fairness to the transmission conditions, all the sensor motes are treated similarly.

The generated data then passes through all the layers from the application to the PHY to be delivered to the second part where the data is received by the LR-WPAN-enabled interface. Here, the data is prepared for conversion from LR-WPAN format based on the characteristics and requirements of 11ax format, and then, it is transmitted over the 11ax-enabled interface to the cloud as the third part. At the cloud, the data is received by a remote management unit called data processing and storage (DPS) server. Here is where all the required processing, calculations, and analysis, as well as the measurements to evaluate the performance of the LoHELR, are taken placed based on the decision model as will be explained later.

Further, we propose the second IoT connectivity architecture called 6LoWPAN-enabled high efficiency (LoHE) (B in Fig. 1) to allow the 6LoWPAN adaptation layer in 802.11ax. The key idea is that, unlike LoHELR in which the 802.11ax is used as the backhaul portion of the IoT systems, the LoHE is pure 802.11ax standard so that the entire IoT system from the sensor motes to the remote DPS server all have 11ax-PHY layer and 11ax-MAC layer with 6LoWPAN on top. As explained earlier, the 6LoWPAN was initially adapted for LR-WPAN for efficient IPv6 communication. Moreover, the 6LoWPAN is essentially independent of the lower layers of the protocol stack [45]. Therefore, the LoHE is proposed with the 6LoWPAN adaptation layer above the 11ax-MAC layer. The resulting protocol stack is used to evaluate the performance and determine whether 6LoWPAN functionalities can also bring any benefits to the 11ax-based IoT systems. Furthermore, since the LR-WPAN network utilizes the 6LoWPAN, the LoHE equipped with this adaptation layer will assure more fairness consideration to the corresponding aspects of the comparative analysis. The 11ax sensor motes generate data based on the decision model and then transmit it to the LoHE coordinator. The LoHE is developed with two 11ax interfaces splitting the sensors and the DPS server into two different domains. All the sensed data is sent to the LoHE coordinator which forwards the data to the DPS server for IoT services and further analysis based on the decision model. The arrangement of the sensor motes and remote DPS server, as well as the decision model, are all developed with similar characteristics as the LoHELR otherwise a straight and reliable comparison cannot be provided.

We additionally develop a third IoT connectivity system as the original LR-WPAN network (C in Fig. 1). This system is designed so that the three parts, including the sensor motes, coordinator, and remote DPS server, are equipped with only LR-WPAN protocol stack and 6LoWPAN. This network is utilized as the baseline IoT system and the reference point for further performance assessment of the LoHELR and LoHE connectivity architectures. Without baseline data, it is not possible to evaluate the service delivery performance of the proposed LoHELR and LoHE in IoT systems.

3.2 Decision model

The key to success for every IoT system deployment is proper planning by considering the factors that affect the system performance. The IoT with a large number of use cases, technologies, and standards has extended in many different areas, each with a diverse mix of applications and services with different needs. Depending on the area, there are a variety of factors that influence the performance of the IoT systems where the ultimate goal is to enhance the success rate of the entire service delivery process. In order to characterize the benefits of incorporating the LoHELR and LoHE in IoT systems and determine their contribution to the performance enhancement of the IoT systems, we propose a decision model. The model consists of a wide-ranging IoT use cases to demonstrate the capabilities of the proposed LoHELR and LoHE on the basis of IoT requirement factors. The decision model includes two modules called data generating (DG) module and IoT system performance assessment (SPA) module (shown in Fig. 1) integrated into the sensor motes and remote DPS server, respectively. Using these modules, the model is able to generate, collect, and analyze data in IoT systems. Moreover, the arrangement of separate modules in the model is beneficial for using the same assessment measurements for the given protocol stacks. The modules' details are as follows.

3.2.1 DG module

The data generating (DG) module is developed and integrated into all the sensor motes. It is adapted to the IoT system requirements representing a structure for data generation and management by the sensor motes. The DG module includes the IoT requirement factors that directly contribute to the IoT system efficiency. Moreover, the values of the factors can be alternatively changed to correspond with the real-life applications as well as providing a deep level of evaluation for diverse needs. The factors are organized into four groups, including connection density, data transfer rate, protocol overhead, and effective link distance as follows.

A) Connection density

The connection density represents the number of active sensor motes placed in the IoT systems. As noted earlier, IoT systems are deployed in various areas to cover different needs. Considering the rapid growth in the number of IoT devices, one of these needs is the ability to allow connecting new devices to the IoT system without affecting the performance. Therefore, it is an absolute necessity to analyze the scalability and stability of the IoT system to determine whether the system can handle a growing amount of work and provide a reliable connection. Based on the Cisco definition, a network is classified as high-density if more than 30 nodes are simultaneously connected to the same access point [24]. In this regard, for the stability-related use cases where the number of sensor motes is the prime concern, the DG module considers three types of connection density as low, medium, and high to determine the growth rate influencing the performance of the LoHELR and LoHE. For the low connection density, the number of sensor motes varies between 5, 10, and 15, for the moderate density it varies between 20, 25, and 30, and for the high connection density, the number of sensor motes varies between 35, 40, 45, and 50. Moreover, for the use cases that are not density-related, the number of sensor motes is set to 20 representing an IoT system with medium connection density.

B) Data transfer rate

The data transfer rate (DTR) is the next IoT requirement factor indicating the speed with which the sensed data can be transmitted from the sensor motes to the DPS server. The higher data rates increase the data load in the IoT systems resulting in more collisions and errors. On the other hand, the reliable performance of the high-bandwidth IoT services relies on the establishment of high data rate backhaul links. Accordingly, the DG module provides both low and high DTRs to further validate supporting the requirements of low- and high-bandwidth IoT services by the LoHE and LoHELR. The low data rates specified in the DG module are 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 Kbps and the high data rates include 100, 150, 200, and 250 Kbps. The reason is that 250Kbps is the maximum allowable data rate in the LR-WPAN networks. For the use cases with a fixed DTR, it is set to 20Kbps.

C) Protocol overhead

From sensing and generating data by the sensor motes to forwarding it toward the remote server, different protocol overheads are imposed on the data in the path. While some overheads are necessarily used for the communication reliability and interoperability, the other extra overheads can be minimized by proper parameter configurations to enhance the system performance. In this regard, the DG module takes into account two types of communication overheads related to the compression methods and the size of packets. Due to the low latency requirement of the IoT services, communication is usually based on the shorter size packets. Therefore, following the limited packet size in LR-WPAN (54B in the application layer), the DG module supports varying the size in the range of 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 bytes. This size variation allows evaluation of the performance with and without fragmentation/reassembly overheads. Furthermore, the module is able to separately apply the IPHC and HC1 compression methods over the packets. In this context, to determine the efficiency of the two compression methods, the IPv6 packets are also transmitted without using any compression (NoComp). As a result, using this combination, different protocol overheads, including no-fragmentation, fragmentation and reassembly, compression, and no-compression will occur in the IoT system for thorough evaluation of the LoHELR and LoHE. For the use cases with a fixed protocol overhead, the default payload size and compression method are set to 40B and IPHC, respectively.

D) Effective link distance

One fundamental requirement for deployment of the IoT systems is to completely cover the given communication area. The whole sensing, transmitting, and receiving process should be done in a reliable way over the given access link. In order to determine how the proposed architectures can meet this requirement, the DG module represents the link distance as the distance of the sensor motes from their coordinator. It characterizes eleven distinct distances in the range of 1, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 meters. This wide range will position the sensor motes very close, far, and very far from their coordinator to determine the performance of the LoHELR and LoHE compared to LR-WPAN, as well as identifying the effective transmission range, at which the sensors are able to transmit data efficiently. For the use cases with a fixed link distance, it is set to 20 m.

It is worth noting that, in addition to the mentioned values for the IoT requirement factors, the DG module allows manipulating the values within any arbitrary ranges to extend the examination and testing more use cases. The DG module also takes into account communication parameters. The channel bandwidth in the proposed architectures and LR-WPAN is 20 MHz and 2 MHz, respectively while working in the same 2.4 GHz band. Due to operating at the same 2.4 GHz spectrum, the LR-WPAN devices are subject to interference caused by 11ax devices [46, 47]. To avoid interference, the proposed architectures are set on channel 1 representing frequency center of 2.412 GHz and LR-WPAN is set on channel 11, which is 2.405 GHz. Moreover, the QPSK modulation method is used in both proposed architectures compared to the OQPSK in the LR-WPAN. This represents the index 1 for modulation coding scheme (MCS). The transmission power and sensitivity level parameters are set as default in the real world. The transmission power for the LR-WPAN and the proposed architectures is 0dBm (1 mW) and 16.0206 dBm (40 mW), respectively [25, 48, 49].

3.2.2 SPA module

The IoT system performance assessment (SPA) module is developed and integrated into the DPS remote server, as shown in Fig. 1. When the DPS receives the sensing data from the sensor motes, the data is used as input to the SPA module where all the corresponding processing and calculations are taken placed for performance assessment of the LoHELR and LoHE on the basis of the IoT requirement factors provided by the DG module. This is a critical task to ensure that all the calculations, analyses, and decisions are based on accurate and precise measurements to further assist in selecting the most suitable connectivity method among the alternatives. With this in mind, the SPA module incorporates both the link performance metrics including throughput, end-to-end delay (ETE), packet loss ratio, and jitter as well as link reliability metrics including signal to noise ratio (SNR) and bit error rate (BER), as well as packet error rate (PER). These metrics can determine the optimization level achieved by the LoHELR and LoHE IoT systems which in turn assist in encompassing a wider range of IoT services and applications. In order to measure these metrics, some notations are used which are shown in Table 1.

An important key parameter to measure the quality of the signal is SNR. The SNR plays a critical role in wireless measurements as a good indication of the quality of the connection link. To measure the SNR, the SPA module measures the linear SNR (SNR_L) based on the power of signal and noise shown in Eq. (1):

$$SNR_L = \frac{PS_{mW}}{PN_{mW}} \tag{1}$$

Then, the SNR of the connection link in dB is calculated as shown in Eq. (2):

$$SNR_{dB} = 10 \times \log_{10}(SNR_L) = 10 \times \log_{10}\left(\frac{PS_{mW}}{PN_{mW}}\right), \tag{2}$$

where PS_{mW} and PN_{mW} are the power of signal and noise in milliwatt, respectively.

Moreover, reliability is one of the most important characteristics of an IoT system which should be satisfied with high consideration. In this regard, the SPA module measures BER which represents the ratio of the number of erroneous bits to the number of transmitted bits from the sensor motes to the

Table 1 Notations and descriptions

Notation	Description
BER	Bit error rate
BW_{Hz}	Bandwidth (Hertz)
DTR_{bps}	Data transfer rate (bits per second)
Eb	Energy of signal per bit (Joules)
$erfc$	Complementary error function
No	Noise power density per 1 Hz
PER	Packet error rate
PN_{mW}	Power of noise (milliwatt)
PS_{mW}	Power of signal (milliwatt)
SNR_b	Per bit signal to noise ratio
SNR_{dB}	Signal to noise ratio (dB)
SNR_L	Linear signal to noise ratio

remote server. The BER measurement is performed based on several parameters shown in Eq. (3):

$$Power = \frac{Energy}{Time} \Rightarrow \begin{cases} PS_{mW} = \frac{Eb}{Time} \Rightarrow Eb = \frac{PS_{mw}}{DTR_{bps}}, \\ No = \frac{PN_{mw}}{BW_{Hz}} \end{cases} \quad (3)$$

where Eb is the energy of signal per bit, DTR_{bps} is data transfer rate in bps, No is noise power density, and BW_{Hz} is the channel bandwidth which as noted earlier is 20 MHz for the proposed architectures and 2 MHz for the LR-WPAN. Using the above equation, per bit SNR (SNR_b) is defined as the ratio of Eb and No as shown in Eq. (4):

$$SNR_b = \frac{Eb}{No} = \frac{PS_{mw} \times BW_{Hz}}{PN_{mw} \times DTR_{bps}} \quad (4)$$

Thereby, based on the Eq. (3) and Eq. (4), the SPA module measures the per bit SNR (SNR_b) using the measured SNR_L from Eq. (1) as follow:

$$SNR_b = \frac{SNR_L \times BW_{Hz}}{DTR_{bps}} \quad (5)$$

The SNR_b is used to measure BER. The Eq. (6) shows the relationship between the SNR_b and BER using the Q function:

$$BER = Q\left(\sqrt{SNR_b}\right) \text{ where } Q(Z) = \frac{1}{2} \times erfc\left(\frac{Z}{\sqrt{2}}\right) \quad (6)$$

Finally, the BER is measured in the SPA module using the complementary error function ($erfc$) as shown in Eq. (7) as follow:

$$BER = \frac{1}{2} \times erfc\left(\sqrt{SNR_b}\right) \quad (7)$$

Given the BER and also the number of bits in data payload (n), we measure the packet error rate (PER) as follow:

$$PER = 1-(1-BER)^n \quad (8)$$

Given all these together, the assessment model provides 1188 distinct IoT experiments that are organized into four main classes correspond to the four main IoT requirements factors. This extensive number of experiments allows in-depth performance evaluation of the proposed LoHELR and LoHE connectivity architectures with respect to the IoT requirements.

4 Results and discussion

This section presents the results from the implementation of the proposed architectures along with the corresponding analysis. The findings are used to, first, determine the performance of the LoHELR and LoHE for different IoT services, second, identify the optimal values of the IoT requirement factors that contribute to the performance enhancement of the LoHELR and LoHE in diverse use cases.

4.1 Connection density

The performance of the LoHELR and LoHE connectivity architectures is evaluated with respect to the influence of the connection density as the number of connected sensor motes creates three conditions, including low, moderate, and high density. The findings lead to identifying the scalability aspects of the architectures and further address the density-related challenges for the long-term IoT deployments. The link performance results of varying the connection density are provided in Fig. 2.

The throughput results show that as the number of sensor motes increases from low to moderate and high, the LoHE can effectively manage the bandwidth and retain the connection stability without noticeable changes. In contrast, the LoHELR and LR-WPAN results show that throughput is inversely proportional to the number of transmitting sensors. In LoHELR, a complete performance match with LoHE is achieved only when the least number of motes exist in the IoT system (5 motes). Afterward, the throughput starts to decline so that beyond 30 sensor motes, the network is not practically able to respond to the current communication conditions. Moreover, the LR-WPAN results imply the least throughput performance compared to the LoHE and LoHELR under all the three density conditions of low, moderate, and high.

The delay results further confirm the same findings as better performance of the LoHE and LoHELR compared to the LR-WPAN. By growing the density of the active motes, the corresponding congestions and the resulting longer intervals between the transmission opportunities are more effective on the LR-WPAN compared to the LoHE and LoHELR in terms of increasing delay. This is due to the fact that in lower density conditions, the channel is often idle and few or no collisions happen, which leads to lower delay. In this regard, the LoHE achieves a delay close to zero and thus, meets the requirement of the time-sensitive IoT applications. Regarding the jitter, the LR-WPAN shows slightly lower values than the LoHELR. Jitter is important as it shows how the access link can cause the time difference between the packets that are transmitted with evenly distributed time intervals. In terms of loss packets, the differences are significant when LoHE is the connectivity architecture for the IoT systems. The loss rate is zero for low and moderate density conditions. Even when the density is in high condition, the loss rate is significantly lower than the other two connectivity architectures.

Therefore, based on the results, while both LoHE and LoHELR provide better performance than LR-WPAN, the LoHE outperforms the LoHELR in IoT systems. The reason is related to using the OFDMA by the sensor motes in the

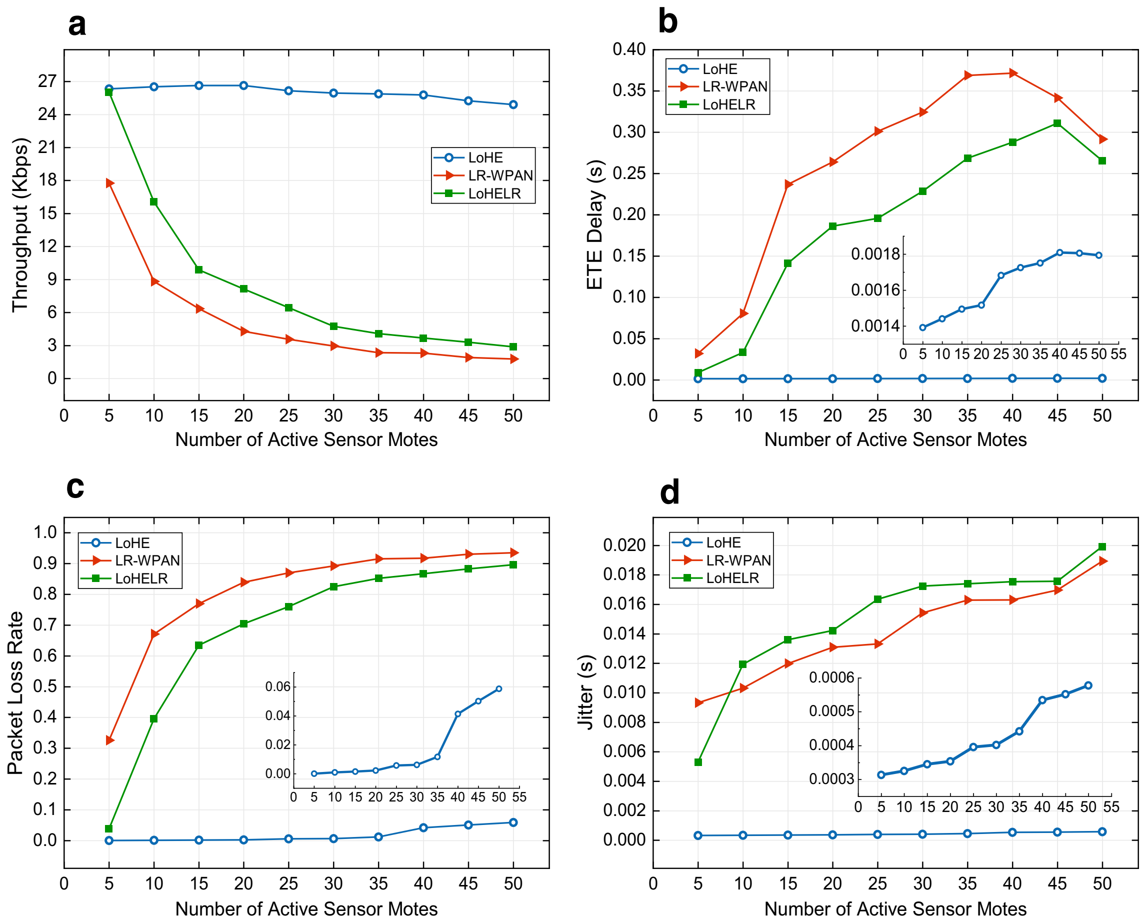


Fig. 2 Link performance as a function of connection density in terms of (**a**) throughput, (**b**) end-to-end delay, (**c**) loss rate, (**d**) jitter

LoHE architecture. As mentioned earlier, the OFDMA allows multi-user access by dividing the channel into multiple sub-channels as resource units (RUs) and then assigning them to different devices. This allows simultaneous transmission of multiple sensors which in turn results in the reduction in collisions and contention time and thereby improving the overall performance. In contrast, since the sensor motes in the LoHELR architecture are not using OFDMA, they cannot benefit the RUs and simultaneous transmission. Hence, lower performance is achieved in the LoHELR compared to the LoHE.

Further to this, maintaining reliability without losing the link operation by growing the number of connected sensor motes leads to the success of service delivery in IoT systems. For this reason, we measure and assess the link reliability of the connectivity architectures in accordance with the SNR and BER parameters. The results are provided in Fig. 3.

In wireless communication, there is a minimum BER and SNR required by the receiver. Typically, a BER less than 1% is acceptable, as well as a -2.2dB and 12dB as the minimum SNR required for LR-WPAN OQPSK and 802.11 QPSK with 20 MHz channel width, respectively [49]. Thereby, the LoHE SNR results show a good quality of the signal. Although by increasing the density of the connection the SNR reduces alongside, even for the highest level of density, the minimum SNR requirement is satisfied. Moreover, the LoHELR achieves the SNR values smaller than the LR-WPAN, while the difference is not significant. The SNR values characterize the quality of the reception of radio signals. As SNR decreases the quality of the signal decreases (due to higher noise level) and as a result, the BER will increase in the whole IoT system. Looking at the BER results proves the efficiency of the LoHE in which a considerable low error rate is imposed on the data communication even when the network is highly congested with the highest number of active sensors. In this case, both LoHELR and LR-WPAN achieve similar and constant BER.

4.2 Data transfer rate

The insufficient data rates can have distinct negative impacts on different IoT applications. In this regard, the main concern is that the IoT system can adapt automatically to any rate variations. In this context, we attempt to determine how efficiently the connectivity architectures can handle the growing amount of data generated by the sensor motes. Therefore, while keeping the data size constant, the sensor motes transmit

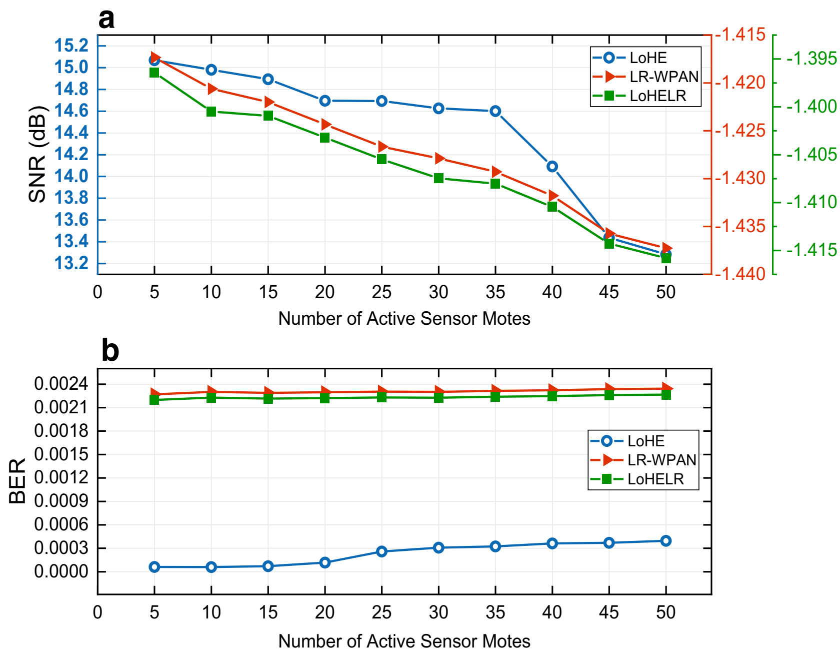


Fig. 3 Link reliability as a function of connection density in terms of (**a**) SNR, (**b**) BER

the sensed data to the coordinator in low and high rates, which in this work are referred to as the rates below and above 100Kbps, respectively. The low data rates are 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 Kbps and the high data rates include 100, 150, 200, and 250 Kbps. The link performance results are provided in Fig. 4.

From the LoHE results, we observe that the throughput increases with an increase in data rate, and accordingly, the bandwidth is utilized optimally. However, in the LoHELR and LR-WPAN, although the throughput gradually increases along with the data rate, it quickly reaches the saturation point after which no throughput changes is observed even at the highest data rate. In this case, the LoHELR utilizes the bandwidth slightly more efficient than the LR-WPAN. With regard to the latency results, we observe that increasing data rate has a negative impact on the LoHELR and LR-WPAN. As the data rate increases, the resulting congestion highly affects the LoHELR and LR-WPAN and causes higher delay and jitter compared to the LoHE. The reason is the fact that higher data rates lead to significant growth in the traffic load. As a result, the competition to access the transmission channel increases, inducing more backoffs and retransmissions. The apparent limitation of LR-WPAN devices in higher data rates also is observed in the high loss rate for delivery of the packets containing the sensed data. For the DTR of 50 and above, the loss rate for LoHELR and LR-WPAN is close to one which practically means no data delivery. This is explained by the fact that higher data rates mean heavier traffic load, which increases the probability of packet collision. This is in contrast to the very low loss rate in IoT systems utilizing the LoHE connectivity architecture.

Therefore, the LoHE architecture manages the growing amount of data generated by the sensor motes in the IoT systems more efficient than the LoHELR and LR-WPAN. The RUs' collision occurrence in uplink direction is reduced by OFDMA in the LoHE. This consequently improves the spectrum efficiency and channel capacity, the result of which is the performance improvement of the LoHE-based IoT systems. This improvement can particularly fulfill the demands of high-bandwidth and time-sensitive IoT applications such as e-health care with large amounts of medical data to manage or surveillance videos.

Moreover, the higher data rates and the subsequent congestion can cause erroneous data which in turn results in incorrect entry to the IoT applications making the reliability of the whole system vulnerable to failure. In this regard, we further extend the evaluation of the connectivity architectures to analyze the link reliability for different configurations of the data transfer rate. The results in terms of SNR and BER are provided in Fig. 5.

From the LoHE results, the SNR increases with a simultaneous increase in the data rate until 50Kbps, after which the SNR is maintained at a constant value irrespective of the data rate. Although the lower data rates can enhance the SNR values in the LoHE to some extent, the LoHELR and LR-WPAN equally achieve a constant level of SNR for both low and high data rates. Moreover, the results confirm the inverse relation between SNR and BER. The BER results of the LoHE show slight error reduction as the data rates increases. However, again for the 50Kbps data rate and above, the BER remains constant at a very low value which indicates significant reliability of the LoHE for service delivery in IoT

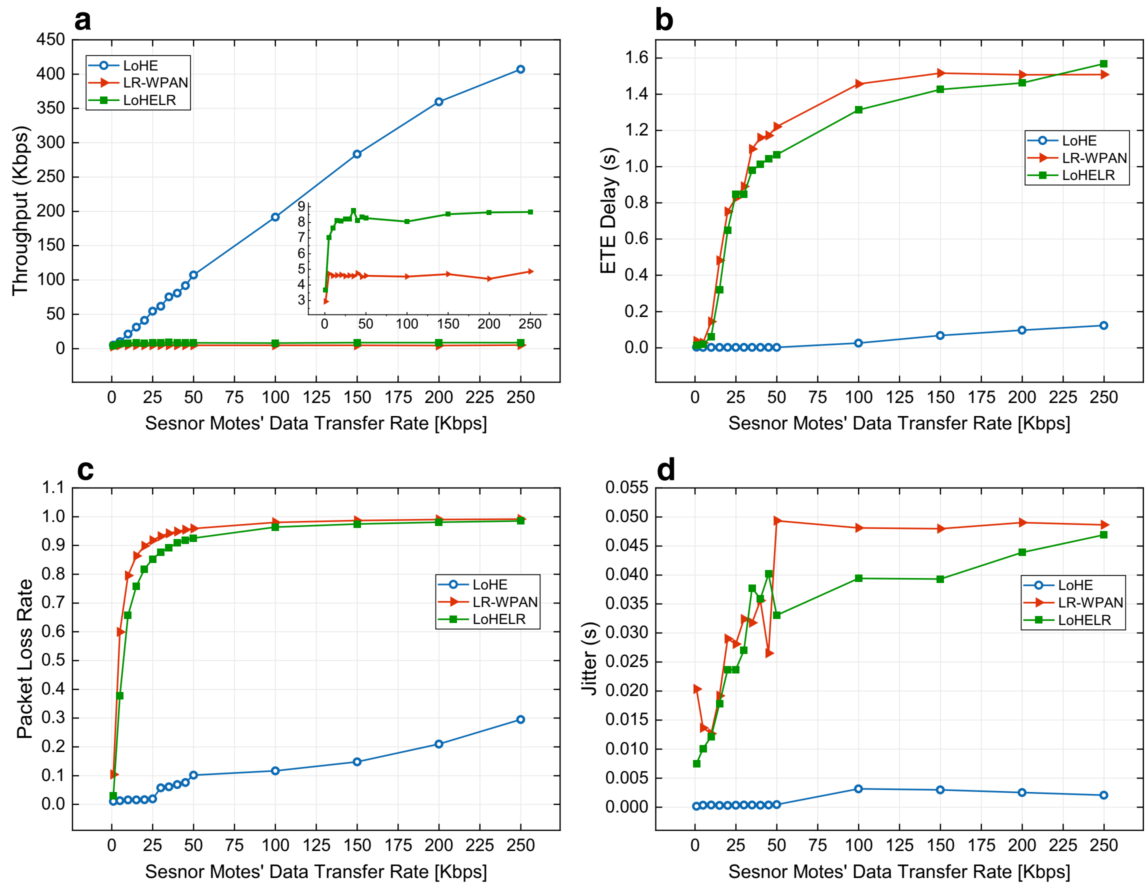


Fig. 4 Link performance as a function of DTR in terms of (**a**) throughput, (**b**) end-to-end delay, (**c**) loss rate, (**d**) jitter

systems. In contrast, the LoHELR and LR-WPAN achieve equal BER values, which are considerably higher than the LoHE. Errors are caused by noise. However, as the results show, an increase in data rate increases SNR which means noise reduction. This is the reason for decreasing BER as the data rate increases in the LoHE. Hence, increasing the data

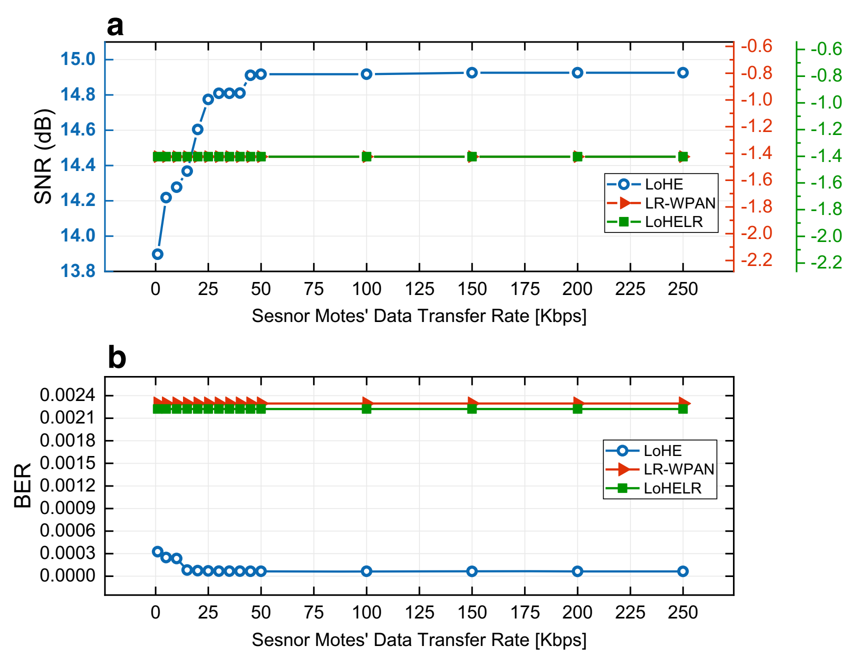


Fig. 5 Link reliability as a function of DTR in terms of (**a**) SNR, (**b**) BER

rate does not show any influence on the SNR and BER values in IoT systems utilizing LoHELR and LR-WPAN.

4.3 Protocol overheads

Due to the limited resources available in IoT devices, it is essential to capture the performance of the connectivity architectures regarding different protocol overheads imposed on data. In this context, the packet size of the sensed data varies in the range of 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 bytes. Then, each data is separately compressed with the IPHC and HC1, as well as no-compression, and transmitted. This combination allows us to evaluate different protocol overheads, including fragmentation, reassembly, no-fragmentation, compression, and no-compression. The link performance results are provided in Figs. 6, 7, 8 and 9.

The throughput results show that the IPHC and HC1 compression methods have no considerable influence on the performance of the LoHE and LoHELR. In this regard, the same throughput values are achieved compared to when no compression is applied over the sensed data. In contrast, the LR-WPAN provides higher throughput values using IPHC and HC1 compared to no compression. Moreover, the results present a better performance of the LoHE in the presence of smaller packets in terms of higher throughput. Increasing the payload size decreases the achieved throughput values in LoHE so that the optimum size is 10B for achieving the highest throughput among the given sizes. It is well-known that for every data payload, some overheads are attached to it before transmission. Consequently, the combined overheads of different protocols can be significant, especially for smaller payloads which leads to the reduction of effective performance. However, the OFDMA solves the issue by sharing some of the overheads between N devices instead of replicating them N times and thereby reduces the overall overhead. This is also more advantageous for shorter data payloads where the amount of overhead is significant compared to the larger payloads with less overheads [23]. The above LoHE results clearly confirm this as a better performance is achieved in the presence of the smaller packets and imply that the LoHE can meet the small packet size requirement of the IoT applications.

On the contrary, increasing the payload size up to 60B shows positive effects on the LoHELR and LR-WPAN by enhancing the throughput values. In this regard, excessive overheads with respect to the data in the smaller packets overwhelm the systems so that the optimum payload size is 60B by providing the maximum throughput. Concerning the delay and jitter of the data delivery process, the same behavior is observed in LoHE, LoHELR, and LR-WPAN in terms of no significant impact of compression methods. In this regard, the most suitable connectivity architecture for time-critical IoT applications is LoHE with the least amount of delay and jitter compared to LoHELR and LR-WPAN. From the loss rate results, the significant impact of compression methods to reduces losing the data packets in LoHE is observed. In this case, IPHC is completely tolerant of losing packets with a size less than 80B. However, increasing the size of payloads to 90 and 100B slightly leads to losing packets which is negligible. For the HC1, losing packets starts with smaller packets compared to IPHC. For the payloads up to 40B, HC1 does not cause any packet losing, however after that, losing packets increases and then remains constant. In contrast to these LoHE results, no significant difference regarding the compression methods is observed in LoHELR and LR-WPAN.

Therefore, IPHC and HC1 perform better in both proposed connectivity architectures while IPHC outperforms HC1. Moreover, given the results, it is concluded that smaller payloads in LoHE and larger payloads under the packet fragmentation threshold (73B) in LoHELR and LR-WPAN, achieve optimal performance. The reason is that packets larger than 73B will be fragmented, resulting in more overhead to the system. Since the OFDMA does not exist in the LoHELR and LR-WPAN, no overhead reduction is available in this regard. Therefore, without OFDMA, the smaller packets impose more overheads on the network, reducing the effective performance. This is why by increasing the size of packets under the fragmentation threshold, the performance increases as well. However, when the payload size increases above the

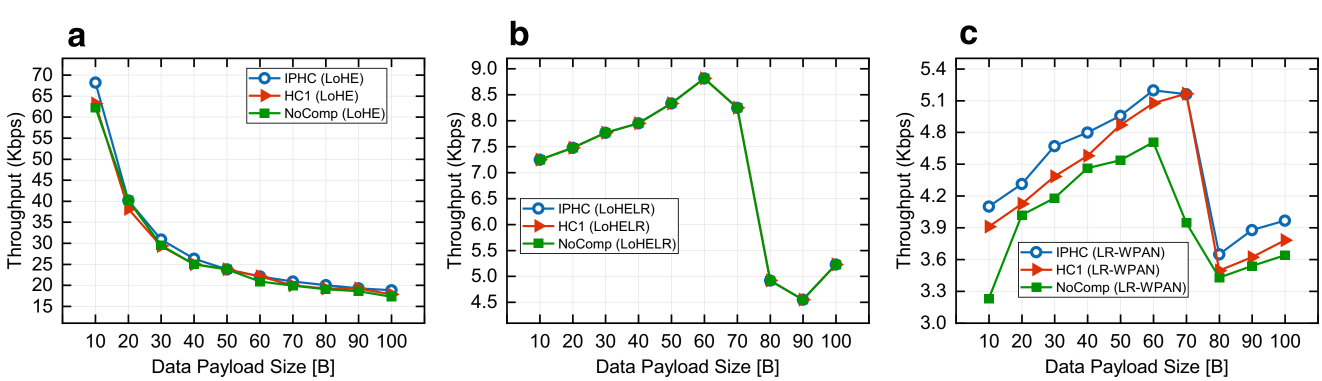


Fig. 6 Throughput as a function of protocol overheads for (**a**) LoHE, (**b**) LoHELR, (**c**) LR-WPAN

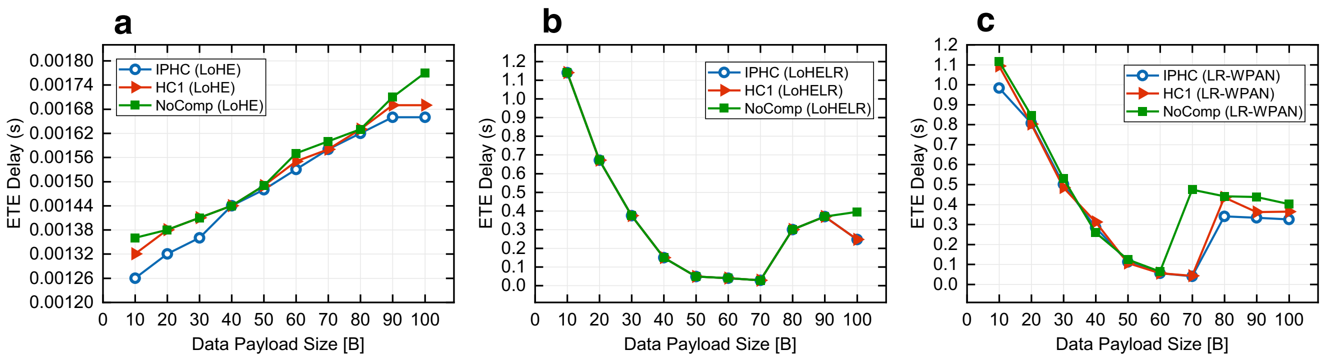


Fig. 7 Delay as a function of protocol overheads for (**a**) LoHE, (**b**) LoHELR, (**c**) LR-WPAN

threshold, the performance reduces because the fragmentation happens and smaller packets are generated.

More experiments are carried out in which the reliability assessment of the IoT connectivity architectures is analyzed in terms of BER and SNR. The results assist in capturing the behavior of the architectures and determine to what extent they are able to provide reliable connectivity for the IoT systems. The link reliability results are provided in Figs. 10 and 11.

From the above results, we observe the probability of success to deliver the sensed data in the LoHE will increase inversely with the size of the payload. In this case, the SNR values are higher for the smaller payloads, particularly when the IPHC is used to compresses the data. In contrast, the size of payloads and the type of compression methods do not influence the SNR in LoHELR and LR-WPAN. Despite the small differences, the LoHELR provides higher SNR values than the LR-WPAN. The PER results also confirm the LoHE findings as the IPHC and HC1 are only effective for larger payloads. As the size of payloads increases up to 80B payloads, the PER also increases similarly for IPHC, HC1, and NoComp. After that, the transmission errors are higher when no compression is applied over the data. The PER results of the LoHELR and LR-WPAN present identical performance regardless of the compression methods and size of payloads. In both LoHELR and LR-WPAN, the larger payloads impose more errors on the sensed data.

4.4 Effective link distance

The effective link distance indicates the range at which the connectivity architectures can guarantee full and uniform coverage to efficiently deliver services in the IoT systems. To identify the effective link distance provided by the connectivity architectures, the distance of the sensor motes from the corresponding coordinator varies between 1, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 meters. The results in the context of link performance are provided in Fig. 12.

From the results, the link distance has a certain influence on throughput performance. The LoHE throughput results show that the distances below 70 m are quite tolerant of performance degradation. However, as the distance goes beyond this point, the throughput slightly decreases until 90 m beyond which no further transmission is taken placed by the sensor motes. On the contrary, the coverage distance by the LoHELR and LR-WPAN is smaller than the LoHE. In this regard, the performance of both the LoHELR and LR-WPAN is quite similar, however, we can notice minor differences. To keep sufficient performance, the distance up to 50 m for them is optimum. The performance reduction in both of them starts from 50 m and continues, however, in the LR-WPAN, the throughput drops to zero at link distances of 80 m and above while at 80 m the LoHELR is still able to preserve the communication. But the further increasing distance to 90 m results in the LoHELR throughput also reaches zero. With regard to the delay and jitter

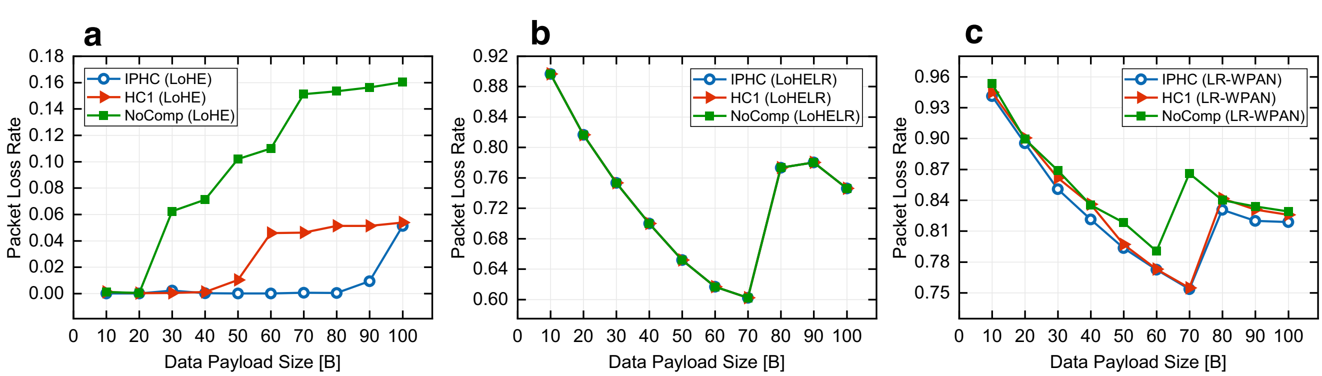


Fig. 8 Packet loss rate as a function of protocol overheads for (**a**) LoHE, (**b**) LoHELR, (**c**) LR-WPAN

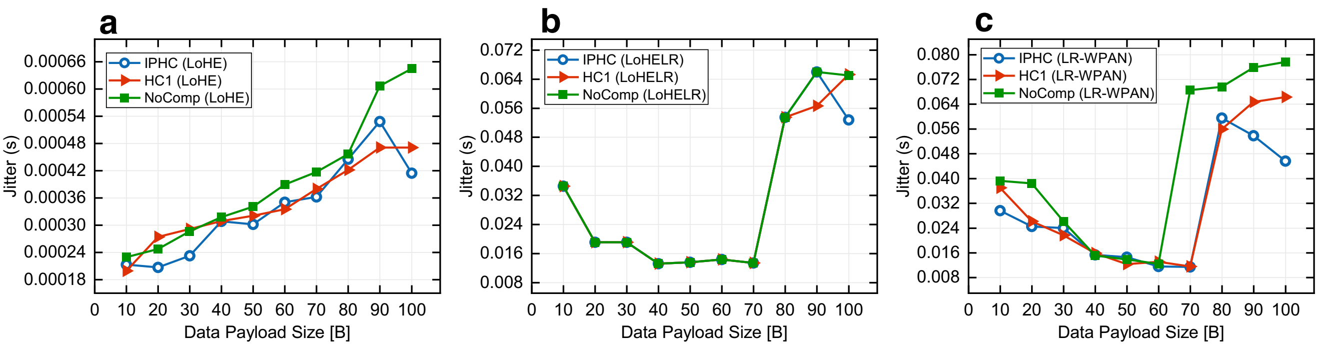
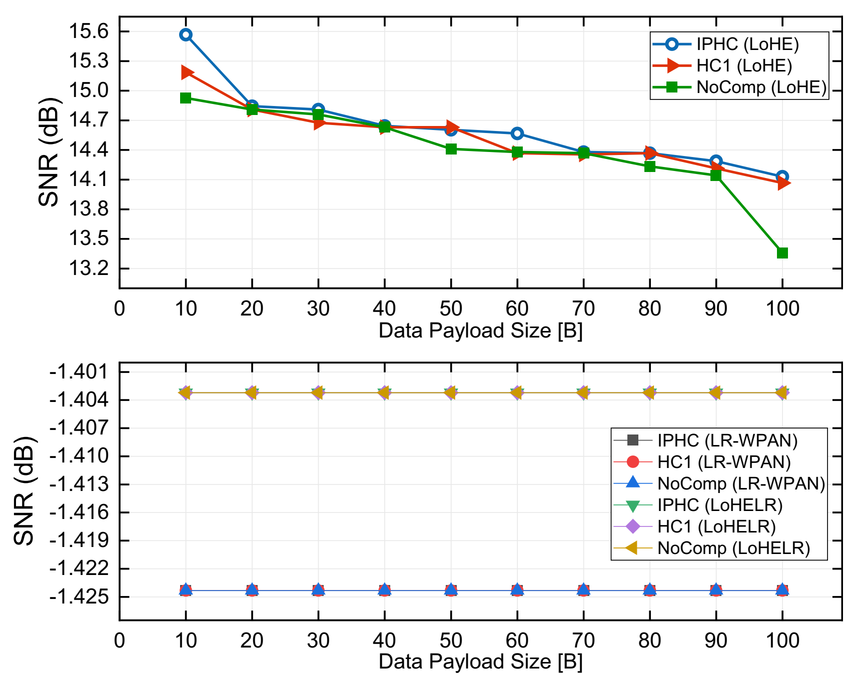


Fig. 9 Jitter as a function of protocol overheads for (**a**) LoHE, (**b**) LoHELR, (**c**) LR-WPAN

results, the findings show no influence of increasing distance on the LoHE. For all the link distances up to 90 m, the IoT system maintains significantly low delay and jitter close to zero. On the contrary, delay and jitter increase by increasing the distance up to 60 and 70 m in the LoHELR and LR-WPAN, respectively. After that delay values decline which is explained by the reduction of the load of the data transmitted. Moreover, the loss rate results also confirm the increase of the distance is more effective on the LoHELR and LR-WPAN than the LoHE. Therefore, on the basis of the results, the effective link distance is longer in the LoHE-based IoT systems compared to the LoHELR and LR-WPAN. The reason is related to the OFDMA ability at a low data rate. The OFDMA is able to extend the coverage and transmit data in greater distances because low data rates address the problem of decoding signals at long ranges [50]. Now, we extend the evaluation to further identify the reliability of the connectivity as the coverage distance of the sensor motes varies. The results of link reliability are provided in Fig. 13.

From the results, it is observed that the SNR level provided by the LoHE can assure the quality of the communication for distances less than 80 m at which the SNR values remain above 12dB representing the acceptable quality. However, by increasing the distance to 90 m, the SNR drops to its lowest value, 11dB, which is under the minimum SNR requirement. With regard to the results of the LoHELR and LR-WPAN, the SNR values constantly decrease in parallel to increasing the distance while both of them achieve similar results with no considerable differences. Concerning the BER results, the LoHE is quite tolerant of transmission errors over the given distances in terms of very low BER values. This guarantees the reliability of the LoHE IoT systems as minimizing transmission errors is critical to IoT applications. Moreover, as the link distance in the LoHELR and LR-WPAN increases, the BER values increase as well significantly higher than the LoHE while still, the rate is lower than 1% representing an acceptable level of transmission errors.

Fig. 10 SNR as a function of protocol overheads



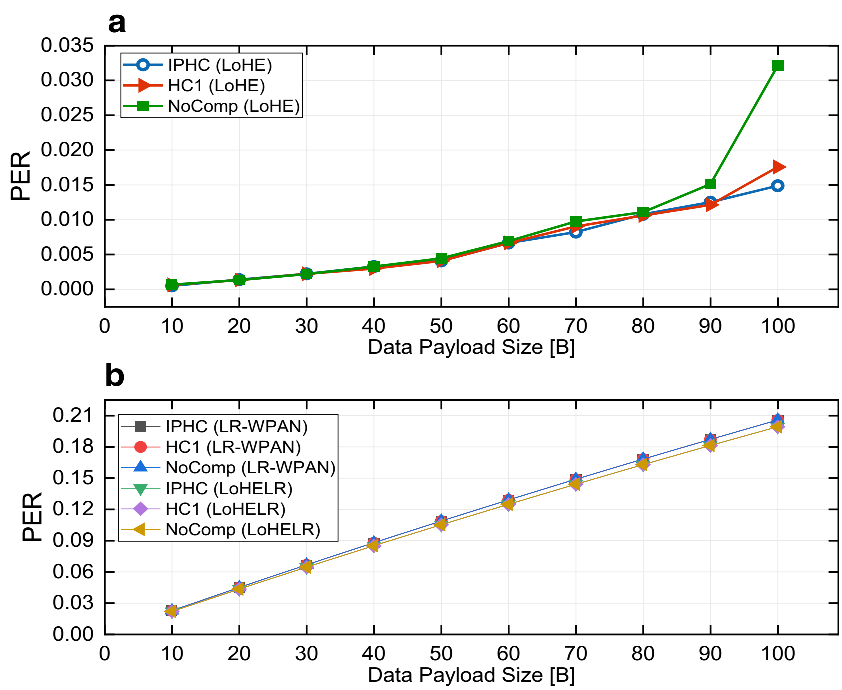


Fig. 11 PER as a function of protocol overheads

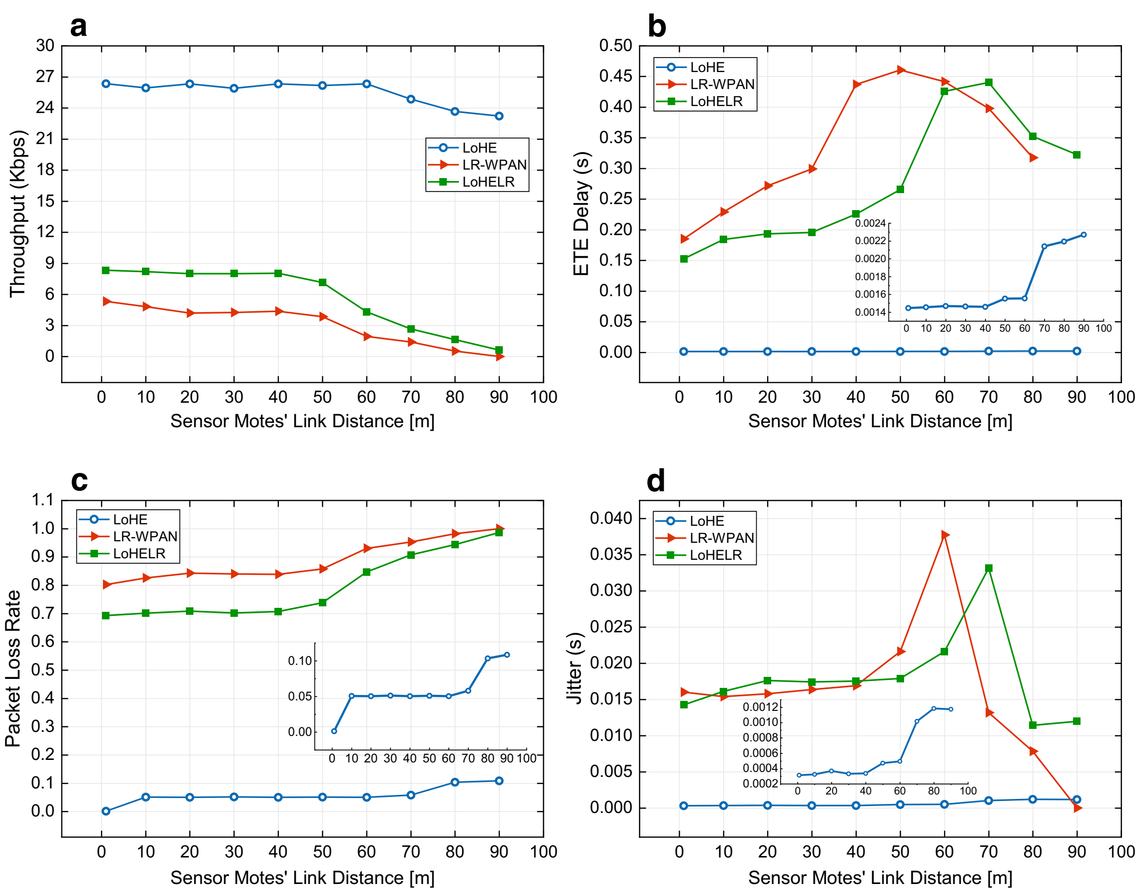


Fig. 12 Link performance as a function of link distance in terms of (**a**) throughput, (**b**) end-to-end delay, (**c**) loss rate, (**d**) jitter

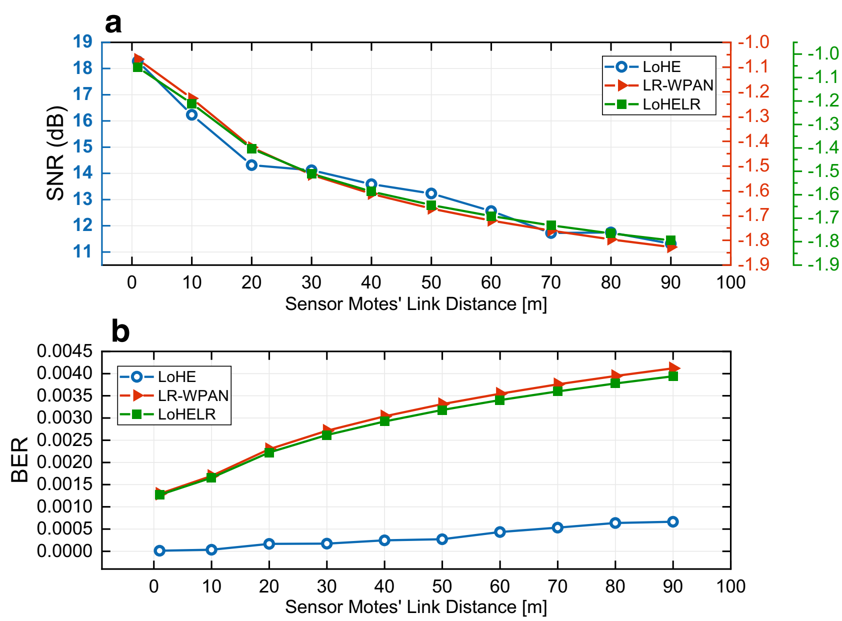


Fig. 13 Link reliability as a function of link distance in terms of (**a**) SNR, (**b**) BER

5 Conclusion

This work leverages the IoT-oriented features of 802.11ax to establish efficient connectivity for indoor local sensing and control IoT systems. Two new IoT connectivity architectures called LoHELR and LoHE are proposed. To determine the level of performance enhancement provided by the LoHELR and LoHE in IoT systems, the original LR-WPAN as the reference point of comparison is also implemented. Furthermore, a decision model with two integrated DG and SPA modules is introduced to evaluate the architectures on the basis of the IoT requirement factors. Due to diverse use cases of the IoT systems and for the aim of being as comprehensive as possible, the model includes 1188 distinct experiments. The implementation results demonstrate both LoHELR and LoHE outperform LR-WPAN with an improved performance level for IoT systems. The connection density results show that while both LoHELR and LoHE perform better than LR-WPAN, the LoHE retains the steady-state in all the given aspects. In this regard, increasing the number of transmitting sensor motes can highly degrade the LR-WPAN compared to the LoHE and LoHELR. However, when it comes to varying the data transfer rate, while LoHE is of great significance in the IoT performance enhancement, the LoHELR does not show substantial differences with the LR-WPAN. In connection with the performance variation due to different payload sizes and corresponding compression methods, while both LoHE and LoHELR outperform LR-WPAN, they show different behavior. The LoHE performs better with the smaller packets while LoHELR is more efficient in the presence of the larger payloads that are under the fragmentation limit (73 bytes). In this regard, the compression methods are more effective on LoHE and LR-WPAN so that IPHC outperforms HC1. Moreover, when the sensor motes move away farther from their coordinator, the resulting performance degradation is more significant on LR-WPAN compared to the LoHE and LoHELR. The LoHE can successfully manage distances up to 90 m, while at this point the LR-WPAN completely fails.

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Data availability All the required data is in the manuscript.

Compliance with ethical standards

Declarations I am submitting you our manuscript entitled “Developing New Connectivity Architectures for Local Sensing and Control IoT Systems”. We would like to have this manuscript considered for publication in “Peer-to-Peer Networking and Applications”.

Conflict of interest This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

Code availability The required code is available in the manuscript itself.

References

1. Adi E, Anwar A, Baig Z, Zeadally S (2020) Machine learning and data analytics for the IoT. Springer Neural Comput Appl 32:16205–16233
2. Ding J, Nemati M, Ranaweera C, Choi J (2020) IoT connectivity technologies and applications: A survey. IEEE Access 8:67646–67673
3. Ray PP (2018) A survey on internet of things architectures. Elsevier J King Saud Univ Comput Inf Sci 30:291–319

4. Al-Kashoash HAA, Kemp AH (2017) Comparison of 6LoWPAN and LPWAN for the Internet of Things. Aust J Electr Electron Eng 13(4):268–274
5. Shafique K, Khawaja BA, Sabir F, Qazi S, Mustaqim M (2020) Internet of Things (IoT) for next-generation smart systems: A review of current challenges, future trends and prospects for emerging 5G-IoT scenarios. IEEE Access 8:23022–23040
6. Ahmadi H, Arji G, Shahmoradi L, Safdari R, Nilashi M, Alizadeh M (2019) The application of internet of things in healthcare: A systematic literature review and classification. Springer Univ Access Inf Soc 18:837–869
7. Kumar G, Tomar P (2018) A survey of IPv6 addressing schemes for Internet of Things. Int J Hyper Connectivity Internet of Things 2(2): 43–57
8. Khadr MH, Salameh HB, Ayyash M, Almajali S, Elgala H (2019) Securing IoT delay-sensitive communications with opportunistic parallel transmission capability. IEEE Global Communications Conference (GLOBECOM), Waikoloa
9. Ayoub W, Mroue M, Nouvel F, Samhat AE, Prévotet JC (2018) Towards IP over LPWANs technologies: LoRaWAN, DASH7, NB-IoT. IEEE Sixth International Conference on Digital Information, Networking, and Communications W (DINWC), Beirut, Lebanon
10. Nikoukar A, Raza S, Poole A, Güne M, Dezfouli B (2018) Low-power wireless for the Internet of Things: Standards and applications. IEEE Access 6:67893–67926
11. Garg R, Sharma S (2016) Comparative study on techniques of IPv6 header compression in 6LoWPAN. Fourth International Conference on Advances in Information Processing and Communication Technology (IPCT)
12. Yang Z, Chang (2019) 6LoWPAN overview and implementations. International Conference on Embedded Wireless Systems and Networks (EWSN), Beijing, China
13. Al-Kashoash HAA, Kharrufa H, Al-Nidawi Y, Kemp AH (2018) Congestion control in wireless sensor and 6LoWPAN networks: Toward the Internet of Things. Springer Wirel Netw 25:4493–4522
14. Olsson J (2014) 6LoWPAN demystified. Texas Instruments, Dallas
15. Tan ZZ, Yap KM, Lim WN (2017) Flow control technique for LR-WPAN network in sensors data transmission. IEEE 13th International Colloquium on Signal Processing & its Applications (CSPA 2017), Penang, Malaysia
16. Gonzalez VB, Afaqui MS, Aguilera EL, Villegas EG (2016) IEEE 802.11ah: A technology to face the IoT challenge. MDPI J Sensors, 16(11)
17. Guo H, Liu J, Qin H (2018) Collaborative mobile edge computation offloading for IoT over fiber-wireless networks. IEEE J Netw 32(1)
18. Afaqui MS, Villegas EG, Aguilera EL (2017) IEEE 802.11ax: Challenges and requirements for future high efficiency Wi-Fi. IEEE Wirel Commun 24(3)
19. Hang Y, Deng DJ, Chen KC (2018) On energy saving in IEEE 802.11ax. IEEE Access 6:47546–47556
20. Selinis I, Katsaros K, Allayioti M, Vahid S, Tafazolli R (2018) The race to 5G Era; LTE and Wi-Fi. IEEE Access 6:56598–56636
21. Ali MZ, Misic J (2019) Misic. Bridging the transition from IEEE 802.11ac to IEEE 802.11ax: Survival of EDCA in a coexistence environment. IEEE J Netw 33(3):102–107
22. Muhammad S, Zhao J, Refai HH (2020) An empirical analysis of IEEE 802.11ax. International Conference on Communications, Signal Processing and their Applications, At Sharjah, UAE
23. Schelstraete S (2018) Optimizing efficiency and throughput in 11ax: OFDMA and MU-MIMO. https://www.quantenna.com/wp-content/uploads/2018/03/WP-Optimizing-efficiency-and-throughput-in-11ax.pdf. Accessed 22 June 2020
24. Cisco Meraki (2019) Wi-Fi 6: The next generation of wireless. Whitepaper. https://meraki.cisco.com/lib/pdf/meraki_whitepaper_wifi6.pdf. Accessed 16 July 2020
25. Ausaf A, Khan MZ, Javed MA, Bashir AK (2020) WLAN Aware cognitive medium access control protocol for IoT applications. MDPI J Future Internet 12(1)
26. Luong P, Nguyen TM, Le LB (2016) Throughput analysis for coexisting IEEE 802.15.4 and 802.11 networks under unsaturated traffic. Springer EURASIP J Wirel Commun Netw 127
27. Ndih EDN, Cherkaoui S (2016) On enhancing technology coexistence in the IoT Era: ZigBee and 802.11 Case. IEEE Access 4: 1835–1844
28. Winter JM, Muller I, Soatti G, Savazzi S, Nicoli M, Becker LB, Netto JC, Pereira CE (2015) Wireless coexistence and spectrum sensing in Industrial Internet of Things: An experimental study. Hindawi Int J Distrib Sensor Netw. https://doi.org/10.1155/2015/627083
29. Winter JM, Muller I, Pereira CE, Savazzi S, Becker LB, Netto JC (2014) Coexistence issues in wireless networks for factory automation. IEEE 12th International Conference on Industrial Informatics (INDIN), Porto Alegre, Brazil
30. Krupanek B, Bogacz R (2016) Cooperation of wireless networks IEEE 802.15.4 and IEEE 802.11b/g – introduction and measurements. Prz Elektrotechniczny 1(11):134–137
31. Zhang J, Hasandka A, Wei J, Alam SMS, Elgindy T, Florita AR, Hodge BM (2018) Hybrid communication architectures for distributed smart grid applications. MDPI J Energ 11(4)
32. Ahmed N, Rahman H, Hussain MI (2016) A comparison of 802.11ah and 802.15.4 for IoT. ScienceDirect ICT Express Vol 2(3):100–102
33. Henna S, Sajeel M, Bashir F, Asfand-e-yar M, Tauqir M (2017) A fair contention access scheme for low-priority traffic in wireless body area networks. MDPI J Sensors 17(9)
34. Abbas N, Yu F (2018) A comprehensive analysis of the end-to-end delay for wireless multimedia sensor networks. Springer J Electr Eng Technol 13(6):2456–2467
35. Peir´o PT, Gallego FV, Mu˜noz J, Watteyne T, Zarate JA, Vilajosana X (2019) Experimental interference robustness evaluation of IEEE 802.15.4–2015 OQPSK-DSSS and SUN-OFDM Physical Layers. MDPI J Electron 8(9)
36. Garg R, Sharma S (2018) Modified and improved IPv6 header compression (MIHC) scheme for 6LoWPAN. Springer Wirel Pers Commun 103:2019–2033
37. Touati F, Mnaouer AB, Ochir OE, Mehmood W, Hassan A, Gaabab B (2016) Feasibility and performance evaluation of a 6LoWPAN-enabled platform for ubiquitous healthcare monitoring. Wiley J Wirel Commun Mob Comput 16(10):1271–1281
38. Gomes T, Salgado F, Pinto S, Cabral J, Tavares A (2018) A 6LoWPAN accelerator for Internet of Things endpoint devices. IEEE Internet of Things J 5(1)
39. Moghanjoughi AA, Sali A, Amazonas JR, Ali BM, Subramaniamc S, Khatun S (2013) Tightly-coupled integrated LR-WPAN/WiMAX network: architecture and performance modelling. ScienceDirect IERI Procedia 4:59–67
40. Rajab H, Cinkler T, Bouguera T (2020) IoT scheduling for higher throughput and lower transmission power. Wirel Netw. https://doi.org/10.1007/s11276-020-02307-1
41. Mostafa AE, Zhou Y, Wong VWS (2019) Connection density maximization of narrowband IoT systems with NOMA. IEEE Trans Wirel Commun 18(10):4708–4722

42. Rahman AMA, Zaman FHK, Abdullah SAC (2018) Performance analysis of LPWAN using LoRa technology for IoT application. Int J Eng Technol 7(4.11):212–216
43. Abeele FVD, Haxhibeqiri J, Moerman I, Hoebeke J (2017) Scalability analysis of large-scale LoRaWAN networks in ns-3. IEEE Internet of Things J 4(6):2186–2198
44. Liu X, Wu J (2019) A method for energy balance and data transmission optimal routing in wireless sensor networks. MDPI J Sensors 19(13)
45. Lenders MS, Schmidt TC, Wählisch M (2019) A lesson in scaling 6LoWPAN – Minimal fragment forwarding in lossy networks. IEEE 44th Conference on Local Computer Networks (LCN), Osnabrueck. https://doi.org/10.1109/LCN44214.2019.8990812
46. Wagh SS, More A, Kharote PR (2015) Performance evaluation of IEEE 802.15.4 protocol under coexistence of WiFi 802.11b. ScienceDirect Procedia Comput Sci 57:745–751
47. Kumar S, Kaltenberger F, Ramirez A, Kloiber B (2019) An SDR implementation of WiFi receiver for mitigating multiple co-channel ZigBee interferers. J Wireless Com Network. https://doi.org/10.1186/s13638-019-1512-3
48. Nurchis M, Bellalta B (2019) Target wake time: scheduled access in IEEE 802.11ax WLANs. IEEE J Wirel Commun 26(2):142–150. https://doi.org/10.1109/MWC.2019.1800163
49. Henna S, Sarwar MA (2018) An adaptive backoff mechanism for IEEE 802.15.4 beacon-enabled wireless body area networks. Wirel Commun Mob Comput. https://doi.org/10.1155/2018/9782605
50. Cisco White Paper (2020) IEEE 802.11ax: The sixth generation of Wi-Fi. https://www.cisco.com/c/en/us/products/collateral/wireless/white-paper-c11-740788.html. Accessed 3 April 2020

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