Clustered WSN for Building Energy Management Applications

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Abstract. Wireless sensor networks are usually deployed in mesh topologies using radio communication links. The mesh selforganizes to route data packets from sensors to the sink. However, if not carefully designed, this may create holes of uncovered areas and energy holes when many networks paths traverse a limited number of sensors. This paper presents the design and performance evaluation of a low-cost clustered wireless sensor network for Building Energy Management (BEM) applications using Bluetooth Low Energy (BLE) and Better Approach to Mobile Ad-hoc Networking (BATMAN). The latter is used to interconnect gateways and cluster headers that have enough power to forward packets and make computations without compromising their battery lifetime, while the former is used to connect sensors to a cluster header. A prototype of a BEM application has been developed and the performance of the network was tested. Results show that the throughput and latency achieved are adequate for BEM applications.

Keywords: Internet of Things (IoT) · Better Approach to Mobile Ad-hoc Networking (BATMAN) · Bluetooth Low Energy (BLE) · Building Energy Management · Wireless Sensor Network (WSN) · Clustered-topology

1 Introduction

The Internet of Things (IoT) has gain tremendous momentum due to the large number of smart devices connected to the Internet. It connects everyday objects (lights, televisions, etc.) as well as more sophisticated objects (motors, agricultural systems, etc.) with the Internet in order to collect data and control cyber-physical objects [1,2]. The application domains of IoT include Smart Cities [3], Health Care [4] and the Industrial Internet of Things (IIoT) [5].

Wireless sensor networks (WSNs) are increasingly used in Building Energy Management (BEM) applications due to the large number of sensors and the distance between them. These sensors are usually powered with batteries that

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work over long periods of time without recharging or changing [11]. Energy harvesting is also used to power sensors or increase their battery lifetime [33]. The latter can also be achieved using clustering techniques [12], as energy efficiency in devices is improved. IoT applications such as condition monitoring of electric motors [7,8], agricultural IoT services [9] and BEM applications [10] take advantage of these techniques.

One of the main challenges of WSNs are coverage holes, also known as uncovered areas, which are the result of correlated node failures, sensor movements and obstacles that hinder communications [13,14]. This leads to a loss of part of the network nodes and therefore to a loss of quality of service, or even to permanent damage to the network [15].

In WSNs the traffic is sent following a many-to-one pattern, from the nodes to the sink or gateway. Energy holes are created around the sink due to the higher battery consumption of surrounding nodes, which receive and forward large numbers of packets through the network. When this happens, no more packets can be sent to the sink, causing a reduction of the network lifetime [16]. In addition, many IoT applications deal with a large number of devices producing enormous amounts of data that must be filtered, processed and stored in the cloud. In order to cope with the challenges this entails, the fog computing paradigm proposes using edge devices to reduce the use of cloud resources [6]. This further increases the energy consumption of nodes in the WSN.

In this paper, we propose a low-cost dual-layer WSN designed for BEM applications. The WSN avoids uncovered areas by including redundant cluster headers and reduces the number of energy holes as cluster headers are connected to the power grid. It also enables the use of fog computing to reduce cloud costs by applying data processing and filtering on edge devices. The main contribution of this work is the combination of low cost, fog-computing capacity and performance of the proposed WSN in a real BEM scenario. The rest of the paper is organized as follows. Previous work in the research context is outlined in Sect. 2. The dual-layer WSN is presented in Sect. 3.1, while the dimensioning of the WSN and its performance analysis can be seen in Sect. 3.2 and Sect. 3.3 respectively. Section 4.1 shows a case of study in a BEM system. The experiments and results are discussed in Sect. 4.2. Finally, Sect. 5 presents the conclusions.

2 Background

In BEM applications multiple low-power wireless communication protocols are used to communicate multisensor modules and gateways or cluster headers. Bluetooth, Bluetooth Low Energy (BLE), Near Field Connection (NFC), Z-Wave and ZigBee are the most commonly used short-range low-power protocols. Table 1 shows the maximum data rate, coverage range, battery consumption and cost of devices for each of these protocols. As can be seen, NFC offers the shortest range and a maximum data rate of 848 kbps. In the case of Bluetooth, the maximum range is 100 m, offering a maximum data rate of 2 Mbps but a higher battery consumption than the other protocols. Z-Wave and ZigBee also have a coverage area

Table 1. Low-power communication protocols

	Characteristics			
	Maximum bitrate	Coverage area	Battery consumption	Cost
Bluetooth	2 Mbps	100 m	Medium	Low
BLE	1 Mbps	100 m	Very low	Low
NFC	848 kbps	10 cm	Low	Low
Z-Wave	100 kbps	100 m	Low	Medium
ZigBee	250 kbps	100 m	Low	Medium

of 100 m [18], with maximum data rates of 100 kbps and 250 kbps respectively. Finally, the Bluetooth Low Energy protocol has a maximum data rate of 1 Mbps, a theoretical maximum range of 100 m, the lowest battery consumption [35] and is supported by most low-cost devices [17].

In order to build a WSN connecting gateways and cluster headers, there are three types of routing protocols: proactive, which have the route available at all times; reactive, which compute the optimal route on demand; and hybrid, which are a combination of the two and are used in large networks [19]. The main difference between them is that proactive protocols have lower latency than reactive protocols, while reactive protocols have higher throughput [20] and need lower bandwidth and lower energy [21]. Having low latency and high throughput are the most important factors in real-time and time-sensitive IoT applications [22].

In the work by Jornet-Monteverde et al. [23], a heating, ventilation and air conditioning (HVAC) system is developed using a WSN based on the Raspberry Pi computer and the CC3200 device provided by Texas Instruments. It is a low-cost, low-power IoT application that uses WiFi and MQTT protocols to establish communications. A monitoring and ventilation control platform was proposed by Lachhab et al. [24], using a WSN composed of sensors to measure air quality and an Arduino Uno, which communicates using an NRF24 module with a Raspberry Pi 3 acting as a gateway. The use of these devices reduces cost and power consumption. Finally, Nigam et al. [25] developed a structural health monitoring (SHM) system that uses three different types of sensors connected to an Arduino Nano to measure the temperature, humidity, physical strength and electrical charge of an area. It communicates with the corresponding gateway using ZigBee. As in the previous cases, a low-cost, low-power WSN is deployed.

Luca Davoli et al. [31] carried out an analysis of the performance of a Better Approach To Mobile Ad-Hoc Networking (BATMAN) mesh using Raspberry Pi's as nodes. Their results show that communications between the nodes forming the mesh is reliable and throughput, latency and jitter are influenced by the number of hops between nodes. Another performance analysis of the BATMAN protocol is done by Edmundo Chissungo et al. [32] in an indoor mesh potato testbed. They prove that communications between nodes are reliable for VoIP applications.

The main issue of most of these low-cost BEM approaches is the high battery consumption. They commonly use WiFi rather than other low-power communication protocols such as ZigBee or BLE [26]. Also, the use of ZigBee as the main communication protocol leads to a lack of control of the network topology. This make it difficult to implement optimal fog architectures for time-sensitive applications to reduce the resources of storage and communication in the cloud [27]. Most of them do not deal appropriately with uncovered areas and energy holes when many paths traverse a limited number of sensors.

3 Network Architecture

The following subsections present the developed WSN, the dimensioning of the network and the performance analysis carried out.

3.1 Topology

The WSN developed follows a clustered approach in which the first layer is composed of multisensor modules and the second layer is composed of heterogeneous gateways and cluster headers. The first layer follows a star topology, where the central node is a gateway or cluster header, which manages a set of heterogeneous multisensor modules using BLE. The second layer follows a meshed topology using the BATMAN protocol. All nodes in this layer have access to the cloud and use WiFi to improve throughput. Some resilience is achieved by using redundant gateways.

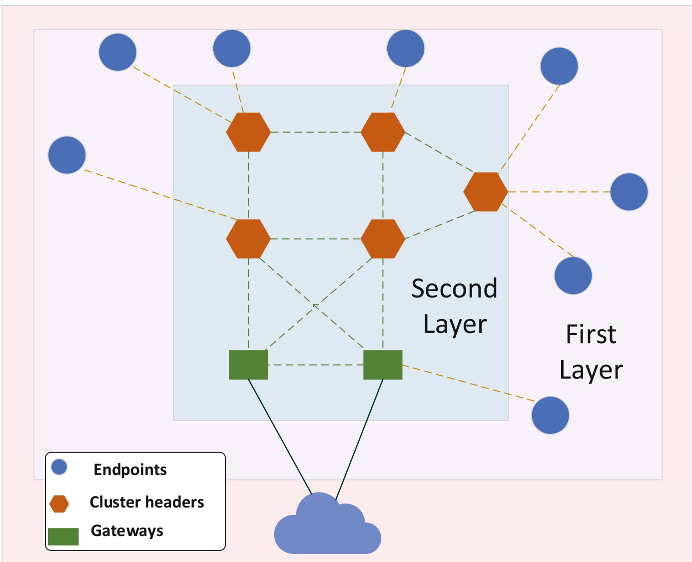


Fig. 1. Dual-layer topology

Figure 1 shows the organization of the entities that compose the WSN:

- Cluster headers: they are connected to other cluster headers and gateways using WiFi. They forward messages through the mesh network until they reach a gateway in order to communicate with the cloud. These devices control a set of endpoints and perform the necessary transformations and operations on the data received, so fog computing approaches can be implemented. Raspberry Pi's 3 Model B+ and Raspberry Pi's 4 are used as cluster headers.
- Gateways: they are connected to the Internet and forward the data collected by sensors and processed at the cluster headers to the cloud. They can also manage a group of endpoints, collecting the data gathered by sensors and processing it before sending it to the cloud. Raspberry Pi's 4 are used as gateways.
- Endpoints: they are heterogeneous multisensor modules collecting data from the environment. These devices are connected to a cluster header or gateway following a star topology. Some low-cost multisensor modules used as endpoints are SensorTag CC2650, SmartBond DA14585 IoT, Sensortile.box and BlueTile.

Due to the low cost of the multisensor modules used, the number of protocols supported for communicating with the cluster headers or gateways is limited. The Sensortag CC2650 supports ZigBee and BLE, but a CC2531 dongle is necessary for using ZigBee. In the case of the Sensortile.box, BlueTile and SmartBond DA14585 IoT, only BLE is supported. BLE has been selected as the low-power communication protocol used to communicate multisensor modules with cluster headers and gateways not only for its compatibility with more manufacturers but also for its higher noise immunity and higher bandwidth [17,34].

In order to connect cluster headers and gateways the protocol selected to build and manage the mesh network is BATMAN. BATMAN is a decentralized, proactive protocol used in multi-hop ad-hoc mesh networks [28]. Knowledge about the best route between two nodes through the network is distributed among all the nodes composing the route: each node only stores information related to its neighbouring nodes. This reduces the overhead on the network and the amount of information stored with other proactive routing protocols [29].

3.2 Dimensioning

Before deploying the WSN, it is necessary to determine the maximum distance between devices. Firstly, the maximum distance between gateways and cluster headers, and secondly, the maximum distance between the multisensor modules and the gateway or cluster header that manage them must be studied.

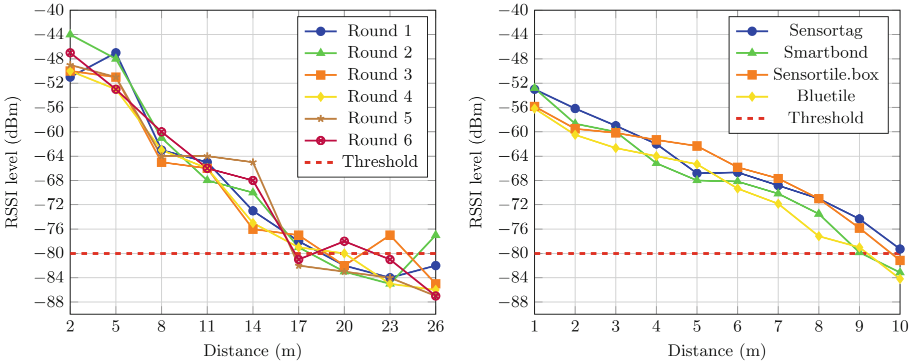
To determine the maximum distance between gateways and cluster headers, a gateway was positioned at a fixed point and a cluster header was moved to different distances from the gateway with no obstacles, taking the RSSI level between the devices for each position. Table 2 lists the signal strength values, the associated state of the network [30], and a description of the consequences of each RSSI level. As seen in this table, any value greater than −80 dBm can be used in BEM applications.

This experiment was carried out six times per distance. The results are shown in Fig. 2(a). As can be seen, the RSSI values are above −80 dBm up to approximately 17 m, although sometimes at this distance the RSSI is below the threshold value (rounds 5 and 6). Therefore, the maximum distance between gateways and cluster headers has been set at 14 m, a distance at which the average RSSI obtained in this experiment is close to −72 dBm. This is suitable for use in BEM applications.

The process followed to calculate the maximum distance between gateways or cluster headers and multisensor modules was similar. A gateway was positioned at a fixed point and the multisensor modules were moved to different distances. For each of the multisensor modules, the fluctuation of the RSSI as the distance varies was studied by performing six tests and then calculating the average at each of these distances.

Table 2. Received signal strength indicator (RSSI)

RSSI	State	Description
-30 dBm	Excellent	Maximum possible signal
-67 dBm	Very good	Minimum RSSI level for applications that need a reliable delivery and reception of packages
-70 dBm	Good	Minimum RSSI level for reliable package forwarding
-80 dBm	Bad	Minimum RSSI level for basic connectivity Package forwarding is somewhat unreliable
-90 dBm	Inoperable	Unlikely to carry out any functionality



(a) Gateway and cluster headers (b) Gateway and multisensor modules

Fig. 2. RSSI-distance between gateway, cluster headers and multisensor modules

Fig. 3. Scenario used for the performance analysis

Based on the results, shown in Fig. 2(b), the maximum distance for the Sensortag CC2650 and Sensortile.box was set at 9 m, since at this distance the RSSI is above the established threshold, −74.34 dBm and −75.83 dBm respectively. However, in the case of the Smartbond DA14585 IoT and BlueTile, the mean RSSI is very close to the threshold value at a distance of 9 m (−79.84 dBm and −79 dBm respectively), sometimes dropping below it. Thus, 8 m was selected as the maximum distance for all devices.

3.3 Performance Analysis

After establishing the maximum distance between the devices that compose the WSN, an analysis of the network performance was carried out, studying the throughput, latency and jitter between gateways and cluster headers according to the number of hops between them (single hop, two hops or three hops). For this performance analysis, the tests were performed on the scenario shown in Fig. 3, which consists of a router, a gateway and three cluster headers connected in a chain. The gateway is connected to the router through an Ethernet link and through the BATMAN protocol with cluster header 1. This in turn is connected to cluster header 2 also with BATMAN. Finally, cluster header 3 also uses BATMAN to connect to cluster header 2. All cluster headers are 14 m apart, which was determined as the maximum distance between gateways and cluster headers in Sect. 3.2.

Firstly, a throughput analysis was performed using the **batctl throughput-meter** command, which consists of the transfer of 14 MB of data between two nodes: between gateway and cluster header 1 (single hop), gateway and cluster header 2 (two hops) and gateway and cluster header 3 (three hops). The purpose of this test is to evaluate the throughput obtained according to the number of hops using BATMAN. It was tested 30 times per round, each round separated by a period of 5 min, with a total of 6 rounds. Figure 4(a) shows the average throughput obtained per round. For the one-hop case, the throughput is in the range between 2512.7 kB/s and 3008.33 kB/s, for two hops, between 522.18 kB/s and 620 kB/s, and for three hops, between 76.53 kB/s and 98.55 kB/s.

Secondly, a study of latency and jitter was carried out, using the **batctl ping** command, which executes a layer 2 ping command. The latency was approximated as the round-trip time (RTT) divided by 2. This test was done in the same way as the throughput test, performing 6 rounds separated by 5 min, each round consisting of 30 executions of the command. Figure 4(b) shows the average latency obtained per round. In the case of one hop the latency is between 0.99 ms and 1.34 ms, between 2.7 ms and 3.33 ms for two hops and between 3.07 ms and 3.91 ms when there are three hops. The average jitter for each round is shown in Fig. 4(c). For one hop the jitter ranges from 0.44 ms to 1.77 ms, for two hops between 1.53 ms and 5.30 ms, and for three hops the average jitter varies between 1.54 ms and 4.52 ms.

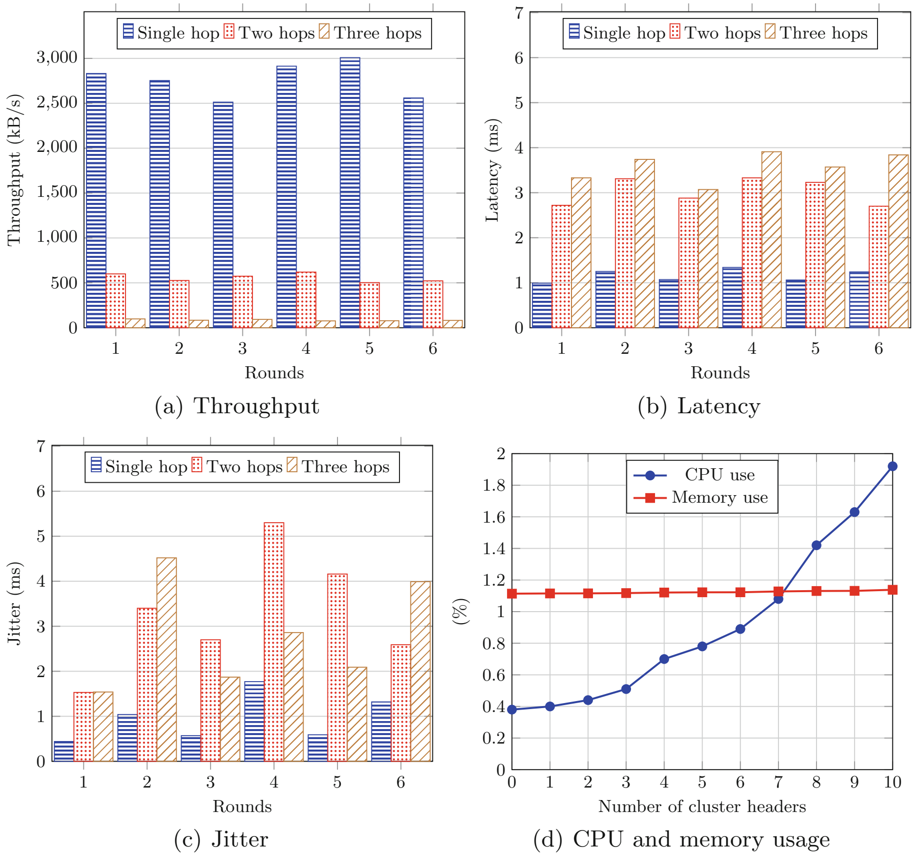


Fig. 4. Performance analysis results

From the results of these tests, it can be seen that an increase in the number of hops leads to a decrease of throughput. Latency increases with the number of hops. However, the results obtained with respect to jitter do not show any pattern: the jitter obtained with three hops is not always higher than with two.

Finally, a analysis of the CPU and memory use on the gateway while using the BATMAN protocol was carried out using the command **sar -u -r 1**, which returns the percentage of both CPU and memory use. Figure 4(d) shows the CPU and memory use as the number of cluster headers in the network increases from 0 to 10, each of them sending 108 bytes/s through the network. The CPU use is extremely low, although it seems to increase exponentially as the number of cluster headers in the mesh increases, reaching 1.92% when there are 10 cluster headers. Memory use increases gradually as the number of cluster headers increases, varying from 1.1137% with no cluster headers to 1.1382% with 10.

4 Case Study: Building Energy Management System

The following subsections present the implementation of a BEM system following the dual-layer WSN previously defined. It also describes the experiments carried out to analyze the communications between the different devices that form the BEM system with the cloud.

4.1 Prototype Deployment

A BEM prototype has been deployed to monitor light level, temperature, humidity and barometric pressure in the Computer Science Department building at the University of Oviedo. This information is displayed to the user using the dashboard shown in Fig. 5. For this prototype 3 Raspberry Pi's 4 were used, one of them acting as a gateway and the other 2 as cluster headers in the mesh network. A Raspberry Pi 3 Model B+ was used as another cluster header. A total of 16 multisensor modules were used: 5 Sensortag CC2650 and 4 Smartbond DA14585 IoT to monitor rooms, and 2 Sensortile.box and 5 BlueTile to monitor building halls and corridors.

The distribution of the devices in the building is shown in Fig. 6. The gateway is located on the ground floor, connected to the router via an Ethernet link and managing 5 multisensor modules. The Raspberry Pi 3 Model B+ is on the first floor acting as a cluster header that manages 3 multisensor modules. On the second floor there is another cluster header with 5 multisensor modules. Finally, another cluster header was installed in the basement, managing other 4 multisensor modules. The ground, first and second floors are connected by an interior courtyard, while the ground floor and the basement are separated by a concrete floor.

There is usually one hop between cluster headers and the gateway, although sometimes there are two between the second floor cluster header and the gateway. This depends on the best route computation based on the network performance. Each of the cluster headers and the gateway collect data from the multisensor modules on the same floor using BLE and perform the necessary operations to send them to the cloud using the MQTT protocol.

4.2 Experiments and Results

On this prototype, a study similar to the one performed in Sect. 3.3 was carried out: first, an analysis of the RSSI level between the cluster headers and the gateway, and then between the multisensor modules and the gateway or the cluster

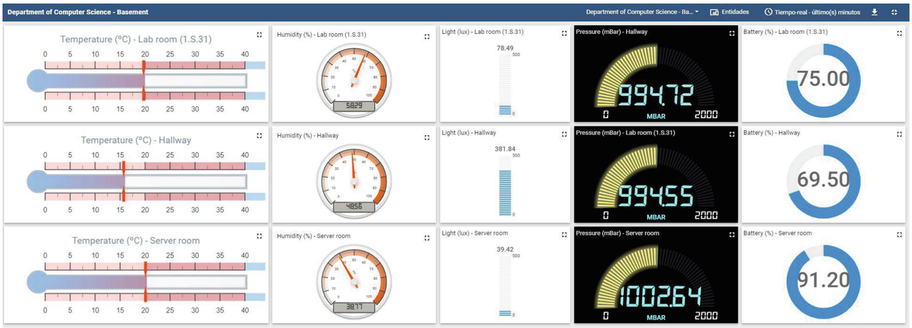


Fig. 5. BEM dashboard application

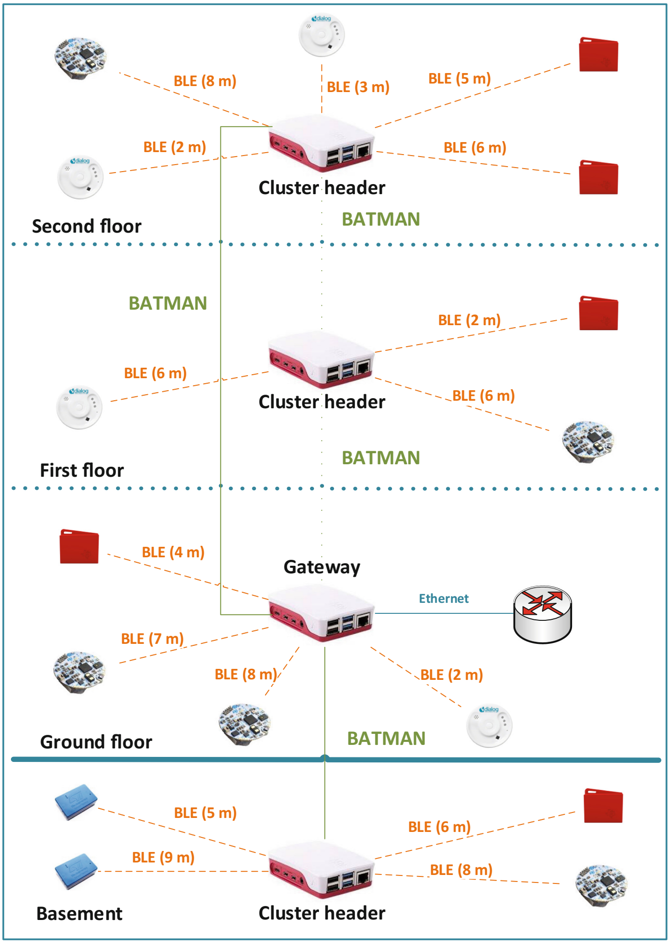


Fig. 6. WSN of the BEM system

headers controlling them. Finally, the throughput, latency and jitter between the cluster headers and the gateway was analysed.

The average RSSI levels between the cluster headers and the gateway are shown in Table 3. As can be seen, in all of the cluster headers the RSSI level is over the threshold of −80 dBm, so their distance is not an issue when forwarding packets.

Table 3. RSSI level between Cluster headers and Gateway

Cluster head	Basement	First floor	Second floor
RSSI level	−76 dBm	−62.5 dBm	−64.67 dBm

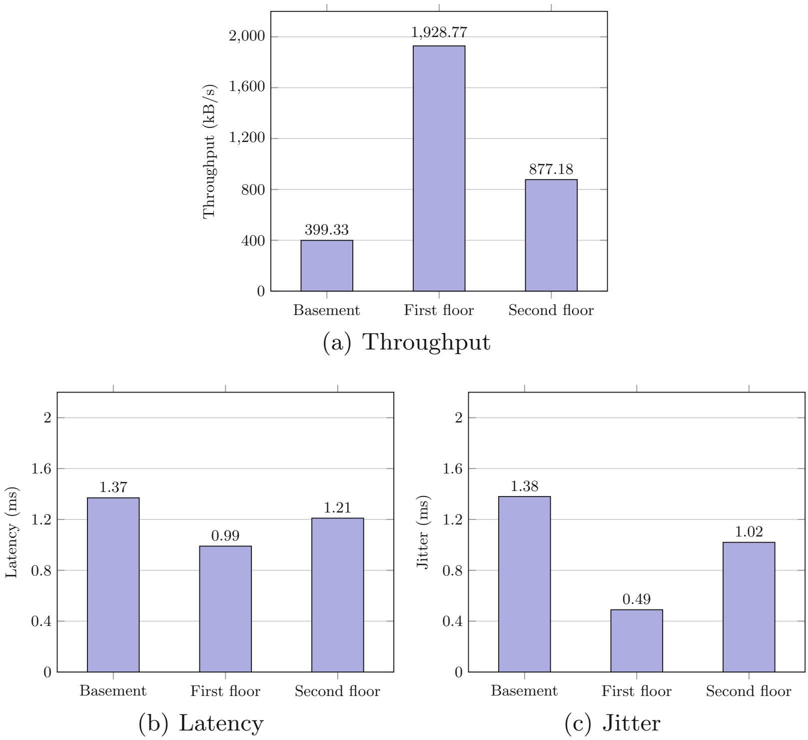


Fig. 7. Building energy management prototype analysis

The same occurs with the RSSI level between the multisensor modules and the cluster header or gateway. Depending on the type of multisensor module, the maximum RSSI level obtained may be closer to the threshold. The maximum RSSI level of the Sensortag CC2650 is −74 dBm, −65 dBm for Smartbond

DA14585 IoT, −79 dBm for Sensortile.box, and −79 dBm for BlueTile. All of these are over −80 dBm, so the communication between multisensor modules and the gateway or cluster header is not an issue.

The throughput analysis has been carried out between each of the cluster headers and the gateway. Figure 7(a) shows that the throughput obtained between the cluster header located in the basement and the gateway is 399.33 kB/s. The throughput measured between the cluster header on the first floor and the gateway is 1928.77 kB/s. Finally, the cluster header on the second floor gives a throughput of 877.18 kB/s. Therefore, the throughput obtained for all of the cluster headers is enough to carry out BEM communications.

Figure 7(b) shows the latency measured. The latency obtained is 1.37 ms, 0.99 ms and 1.21 ms for the cluster headers located in the basement, first floor and second floor respectively. These results are similar to those obtained in Sect. 3.3, as the cluster header located in the basement, which is the one with the lowest throughput, has the highest latency. The same happens with the cluster header located on the first floor, which has the highest throughput and the lowest latency.

The analysis of the jitter in this case is conclusive, as it is exactly the same as in the case of latency (see Fig. 7(c)). The cluster header located in the basement has a jitter of 1.38 ms, the one on the first floor has a jitter of 0.49 ms, and the one on the second floor has a jitter of 1.02 ms.

All these analyses show that the cluster header located in the basement has worse results than the rest. This is mainly due to the fact that the ground floor, first floor and second floor are connected by an open inner courtyard, while the basement is separated by a concrete floor. Even so, the results obtained for the three cluster headers indicate that communication can be carried out with no problem.

5 Conclusions

In this paper, a clustered WSN using BLE and BATMAN has been presented. The WSN uses BLE to carry out the communications between low-cost multisensor modules with gateways and cluster headers, using the BATMAN protocol to create a mesh network between gateways and cluster headers. This WSN avoids uncovered areas due to the use of redundant gateways and cluster headers. It also prevents energy holes by taking advantage of cluster headers connected to the power grid. This facilitates the integration of fog architectures in order to reduce cloud costs by applying data processing in cluster headers and edge devices.

The WSN was dimensioned by analyzing the RSSI level between devices. Maximum distances between gateways and cluster headers, and between sensors and the gateway were established.

Once the WSN was deployed, a performance analysis was carried out studying the variation in throughput, latency and jitter as the number of hops between gateways and cluster headers increases. Latency increases and throughput decreases as the number of hops increases. In addition, an analysis of CPU and memory use was performed in the gateway. The results show very low CPU use with a possible exponential increase, while memory use gradually increases as more cluster headers are added to the network. Thus, the number of cluster headers must be thoroughly studied in WSN deployments.

Finally, this WSN was implemented as a case study, creating a BEM application. This application collects data such as light level, temperature, humidity and barometric pressure for cloud storage. A performance analysis was carried out to ensure that communications are performed correctly, studying the RSSI level between devices, latency, throughput and jitter. The results obtained confirm that the communication in the clustered WSN can be performed with no problem even in the presence of concrete floors.

Future work will be focused on using the WSN in more challenging scenarios such as condition monitoring in industrial environments. Applications can take advantages of fog deployments, so vibration or current signals are filtered and processed at the cluster headers to save cloud resources.

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