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Comparative analysis of ZigBee, LoRa, and NB-IoT in a smart building: advantages, limitations, and integration possibilities

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ABSTRACT

This paper compares the performance of various wireless technologies: ZigBee, long range (LoRa), and narrowband internet of things (NB-IoT), which support smart building applications. The highlight of this work is that we focus on wireless communication between the floors of the building by analyzing the performance metrics using the received signal strength indicator (RSSI) and packet loss ratio (PLR). First, the ZigBee tests confirmed reliable packet delivery without any loss over distances up to 40 meters on the same floor, with RSSI results ranging from -65.5 to -87.5 dBm. ZigBee also maintained signal transmission through one cross-floor level, with RSSI values between -60 and -119 dBm. The second set of tests, with LoRa, indicated signal transmission over several floors with slightly improved RSSI values for the 2 dBi antenna compared to those for the -4 dBi antenna, despite increased packet loss with distance. Finally, NB-IoT showed the most consistent long-range connectivity, achieving a stable signal up to 458 meters from the base station with RSSI levels varying from -55.6 to -74.6 dBm, without packet loss in all tests. This study demonstrates how such technologies could be used in smart buildings and provides suggestions on how to determine the most suitable systems and configure them to ensure reliable communication networks within the building.

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1. INTRODUCTION

Wireless communication technology is recognized as a significant catalyst for the implementation of smart buildings, enhancing data transport and connectivity among various devices and systems within the building structure [1]. This technology integrates short-range and long-range wireless networks to accommodate both limited interior spaces and expansive areas [2]. A smart building network combines short-range technologies such as wireless fidelity (Wi-Fi), Bluetooth, and ZigBee with long-range communications like long range (LoRa), narrowband internet of things (NB-IoT), and long term evolution for machines (LTE-M) [3]. This paper presents an in-depth analysis of these wireless technologies. The integration of these wireless systems enables a thorough assessment of individual capabilities, leading to enhanced automation, energy efficiency, and comprehensive facility management [4]. The wireless sensor network (WSN) is described as a connection between sensing and networking components for physical data measurement, offering affordability and extensive coverage across all installation points [5]. In addition, wireless connectivity enables both short-range and long-range communication within smart homes and building environments. WSNs are selected based on bit rate, distance, and power consumption. ZigBee is best suited for low bit rate and energy-efficient data transmission, while Bluetooth and Wi-Fi are more suitable for high bit rates with elevated power consumption [6]. Therefore, WSNs have multiple adaptable features, making them effective solutions in many innovative applications [7].

Previous studies [8] focused primarily on text-based data transmission and used the appropriate platform for small data payloads in ZigBee devices. However, communication systems like LoRa and NB-IoT can transfer data over kilometers [9]. The functionalities inside the building should also be examined by looking at the received signal strength indicator (RSSI), which is particularly meaningful for indoor objects such as buildings, walls, and office paraphernalia that influence wireless communication quality [10]. The packet loss ratio (PLR) is also an essential indicator [11]. Precise signal strength determination under such conditions is crucial for ensuring quality and successful indoor installation of wireless devices. The building monitoring application had a unique networking setup that used mixed protocols like ZigBee, LoRa, and NB-IoT, along with wireless networking elements and application sections [12]. The sensing section uses smart devices to collect information regarding environmental parameters and electrical current values [13]. The building was equipped with various strategically placed sensors that gathered instantaneous information about temperature, humidity, light, energy usage, and many other factors [14]. The gateway (GW) converts data sets from one or several communication protocols to different ones [15]. This support for systems' interoperability promotes efficient data management. Wireless communication made it possible to extend the network connection from short-range to long-range, spreading throughout the entire building [16], [17]. Figure 1 shows the network expansion through the application of wireless technologies. The GW converted ZigBee's data into LoRa and NB-IoT data, respectively.

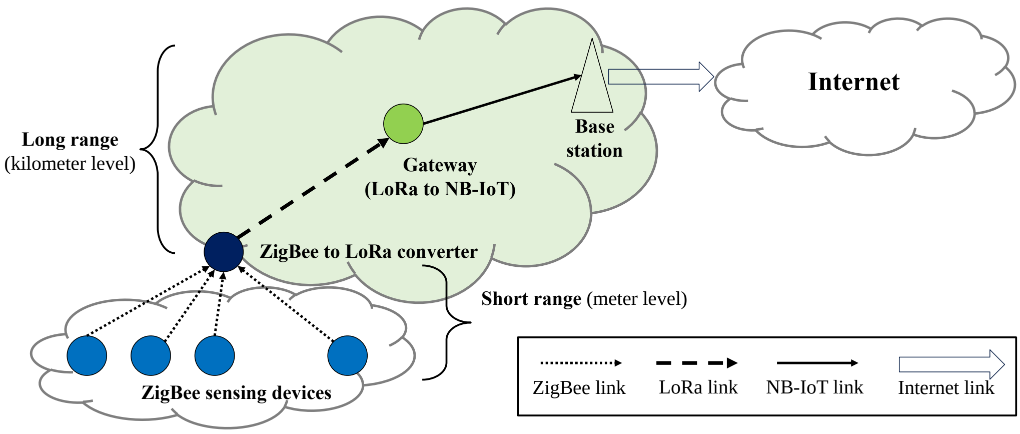


Figure 1. Range comparison of ZigBee, LoRa, and NB-IoT wireless technologies

This paper compares ZigBee, LoRa, and NB-IoT technologies in testbed environments for indoor applications, providing their RSSI and PLR metrics. Therefore, this study evaluates the presumed operational boundaries and strengths of each indoor internet of things (IoT) technology by methodically testing these metrics. Figure 2 illustrates the testbed building used for wireless communication trials. Figure 2(a) shows the exterior view of the faculty of engineering building, which houses the testing facilities. Figure 2(b) depicts the interior corridor where the wireless communication experiments were conducted, providing a controlled environment for the trials. The insights into selecting the best indoor wireless technology for IoT applications, as explained in this study, will expedite the implementation of these technologies into proper smart buildings. Additionally, our experiments were conducted in real-world scenarios that included the presence of potential signal-interfering devices, such as Wi-Fi access points distributed across various floors of the building. It is essential to note that these devices were not under our control during the experimentation. This fact underscores the importance of considering such environmental variables in future research. Studies that have the capability to control these access point devices should certainly include an evaluation of their impact on wireless communication, thereby enriching our understanding of how IoT technologies perform in practical, real-world smart building environments.


(a)


(b)

Figure 2. Testbed building for wireless communication trials of (a) exterior and (b) corridor

2. METHOD

In the methods section, we elaborate on our experimental setup for evaluating the RSSI and PLR in smart buildings using ZigBee, LoRa, and NB-IoT technologies. Our focus is on determining how well these wireless technologies perform in terms of signal quality and reliability within indoor environments. We employed different types of modules for each technology ZigBee, LoRa, and NB-IoT at both the transmitter and receiver ends to measure RSSI and PLR, thereby assessing their suitability for smart building networks. Figure 3 presents a diagram of the wireless and portable devices used in the experiment.

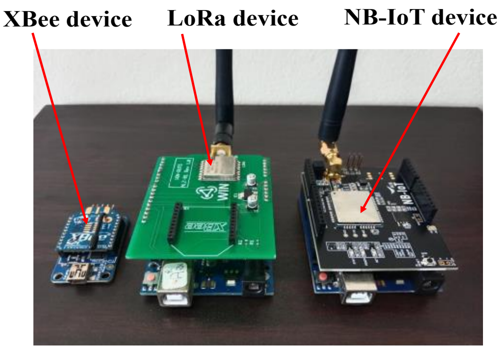


Figure 3. Comparative setup of ZigBee, LoRa, and NB-IoT modules for wireless communication testing

Table 1 compares ZigBee, LoRa, and NB-IoT technologies, highlighting differences in power, data rates, and frequencies. ZigBee operates at 2.4 GHz, LoRa at 433 MHz with variable antenna gains, and NB-IoT features the highest power transmission at 900 MHz. For ZigBee, we used XBee modules with a power transmission of 2 milliwatts (mW), which are typically used in short-range building applications. LoRa measurements utilized the RA-01 module, chosen for its long-range capabilities, while the NB-IoT evaluation was conducted using the Quectel BC95 module, known for its efficient power usage and effective penetration in complex environments. Our testing took place in an actual multi-floor building to simulate real-world conditions and assess each technology's performance under typical operating scenarios.

Table 1. Comparative specifications of ZigBee, LoRa, and NB-IoT technologies [9], [18], [19]

Parameter	ZigBee	LoRa	NB-IoT
Communication module	XBee series 2	RA-01	Quectel BC95
Protocol	ZigBee/IEEE802.15.4	User-defined protocols	UDP/CoAP
Power transmitter	2 mW (3.01 dBm)	158 mW (22 dBm)	199.5 mW (23 dBm)
Antenna type	Wire	Omni-directional	Omni-directional
Antenna gain	N/A	-4 dBi and 2 dBi	2.65 dBi
Frequency band	2.4 GHz	433 MHz	900 MHz
Data transmission rate	250 kbps	Up to 300 kbps	25.2 kbps (downlink) and 15.625 kbps (uplink)
MCU connected	Standalone	Arduino	Arduino
Power input	3.3 V	3.3 V	3.3 V
User interface (UI)	XCTU	Arduino monitor	Magellan platform

We adopted a point-to-point topology for the subsystems across all three technologies, enabling a comprehensive assessment of their performance within the context of an indoor wireless communication network. This assessment specifically focuses on the PLR and RSSI metrics, which are calculated according to (1) and (2), respectively, as detailed in [20], [21]:

$$PLR = \frac{n_L}{n_T} \times 100\% \tag{1}$$

$$\overline{RSSI} = \frac{1}{n_T} \sum RSSI \tag{2}$$

where PLR is packet loss ratio, n_L is number of packets lost, n_T is number of total packets transmitted, $\overline{RSSI}$ is RSSI average, and $RSSI$ is RSSI measurement value per time instance.

2.1. ZigBee experimental setup

In Figure 4, the XCTU software demonstrates device testing, where the ZigBee network consists of a local radio node serving as a coordinator and a remote radio node operating as a receiver. The interface displays a graph that reveals the RSSI levels over a certain period for both remote and local devices, indicating an existing communication signal due to continuous RSSI readings. This software records the number of data packets transmitted and received, along with the RSSI readings, providing a measurable criterion for analysis. Below the RSSI plot, additional bar graphs show the signal strength in dBm for both local and remote modules and the packet success rate during ZigBee range testing, which demonstrates the efficiency of the link between the two nodes.

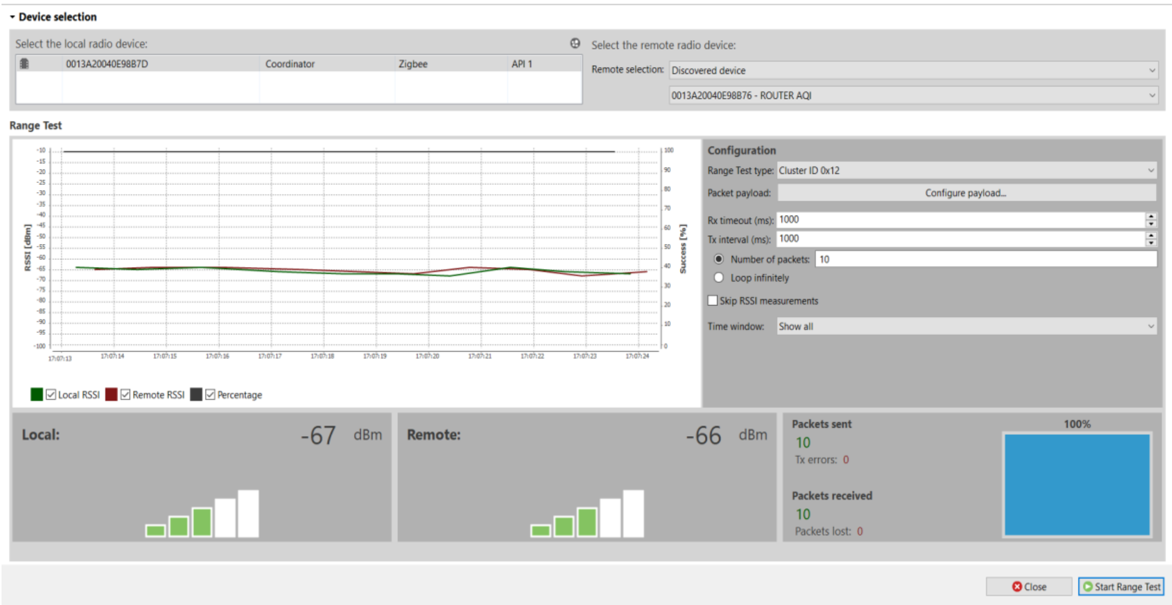


Figure 4. XCTU software interface for ZigBee range testing

The model tested, as depicted in Figure 5, evaluates the RSSI for a ZigBee network in an indoor environment. This experiment specifically focuses on inter-floor communication within designated test areas. It involves a signal reception point with an XBee coordinator located on the 10th floor and an XBee end device acting as a transmitter. The transmitter's position varies, with interpolated tests extending from the 10th floor down to the 9th and 8th floors, respectively. The objective is to ascertain the effective transmission range of the system. For this purpose, ZigBee end device nodes were strategically placed throughout the building, including in central areas and the most remote corners, creating a total of eight distinct test points. The RSSI values were meticulously measured and recorded at these reference sensor nodes. Additionally, for the LoRa testing, the experimental setup was adjusted to include longer distances between floors compared to the ZigBee test, communicating from the 10th floor down to the 7th and 4th floors. The LoRa test diagram is shown in Figure 6.

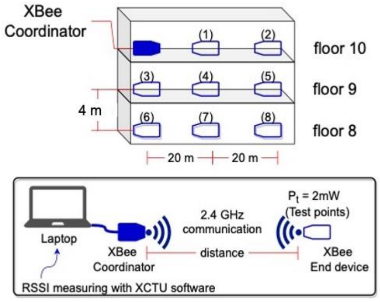


Figure 5. Schematic diagram of ZigBee test setup with RSSI measurement using XCTU software

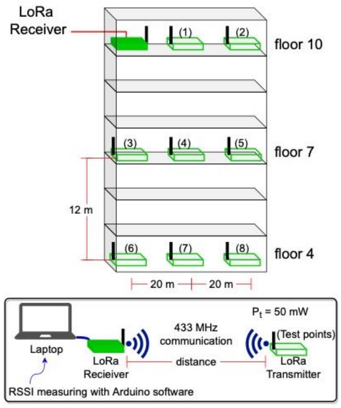
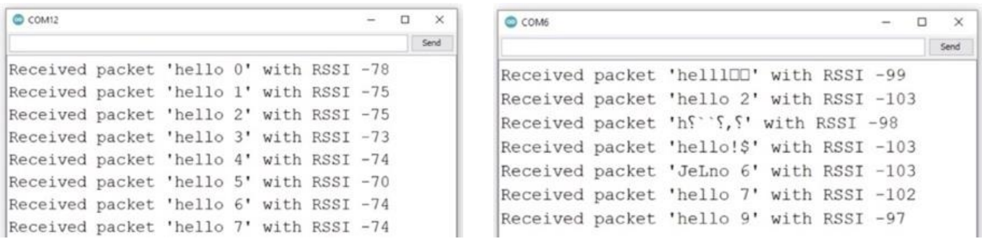


Figure 6. Schematic diagram of LoRa test setup with RSSI measurement using Arduino software

2.2. Long range experimental setup

The receiver is set to a frequency of 433 MHz. Data packets with time-counting details are formed at the transmitter. The transmitter module sends packets every second to maintain a consistent data flow. Arduino monitoring software on a laptop collects real-time data. This software assists in collecting RSSI and packet reception data. Data collection during experiments is facilitated by its UI. The software logs RSSI and packet reception status for post-experiment analysis. Figure 7 shows the software monitoring setup for both normal and error-and-loss cases. Figure 7(a) shows successful packet reception with stable RSSI, while Figure 7(b) displays packet errors and data loss.



(a) (b)

Figure 7. Serial monitor outputs of (a) successful packet reception with stable RSSI readings and (b) packet reception with errors indicative of data loss, using Arduino monitoring software

2.3. Narrowband internet of thing experimental setup

Our experiment aims to rigorously assess the performance of NB-IoT technology in urban building environments. We strategically placed NB-IoT devices at nine different points within a building, distributed across three levels: base (1st floor), middle (5th floor), and top (10th floor). This setup is designed to gather extensive data across various elevations, providing a comprehensive understanding of NB-IoT's effectiveness in urban contexts. Central to our study is measuring two key parameters: RSSI and PLR within the NB-IoT network. We used the Magellan website interface for NB-IoT range testing, as shown in Figure 8, which features a “Graph History” section for tracking and graphically representing RSSI and packet loss over time.

Figure 9 illustrates our methodology, which involved tools like Google Maps and the cell tower application to evaluate the impact of distance from the base station and building floor levels on NB-IoT performance. Consistently using the same mobile service provider for the NB-IoT device, operating in the 900 MHz band, allowed for accurate base station coordinate scanning at our test points. With the nearest telecom base station approximately 458 meters away, this distance acted as a benchmark for our analysis. However, the minimal variance in distance between test points (±20 meters) suggests that these small differences are unlikely to significantly affect our results. This approach contrasts with that of ZigBee technology, highlighting the unique aspects of NB-IoT deployment in urban structures. The consistency in our data collection was further ensured by using the same location for both scanning the base station's coordinates and testing the NB-IoT signal performance.

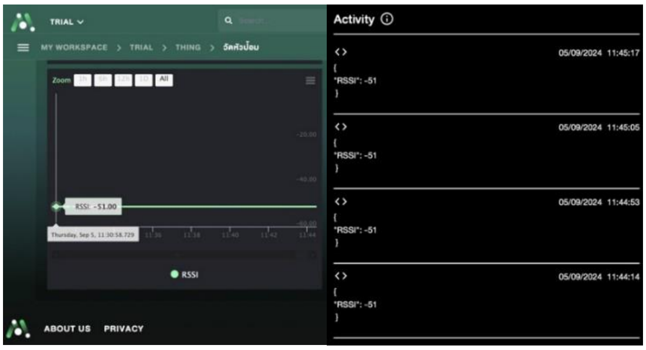


Figure 8. Magellan website interface for NB-IoT range testing

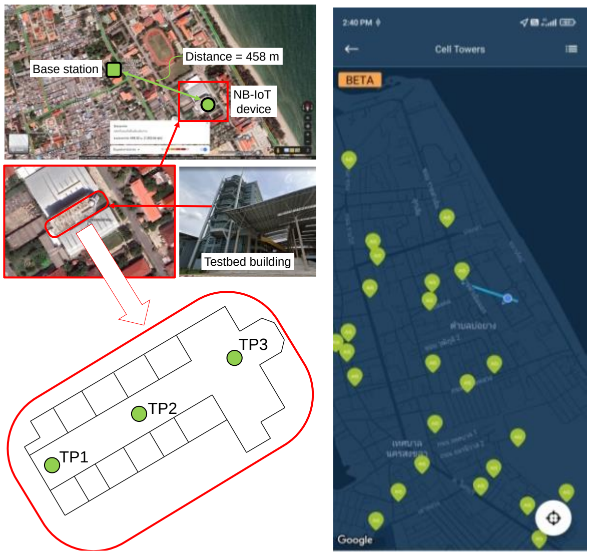


Figure 9. Diagram of NB-IoT transmission testing and cell tower link scan application [source of maps: Google map and cell tower application]

3. RESULTS AND DISCUSSION

In this section, we provide a thorough assessment of the wireless performance results from our research. This paper evaluates the RSSI and PLR using ZigBee, LoRa, and NB-IoT across various test points (TPs) in the building.

3.1. Received signal strength indicator measuring of ZigBee cases

Table 2 presents the measurement results of RSSI and packet loss for ZigBee in an indoor scenario. The results show that data transmission was successful from test points on the 9th floor to the 10th floor. These test points were located in the central corridors of the building, with the main barriers being the floors and other ceilings. Therefore, this configuration allowed for successful data transmission from some of the points on the 9th floor. Signal strengths varied from -65.5 to -87.5 dBm at various test points. Nodes nearer to the XBee coordinator exhibited stronger RSSI values than those farther away. This pattern reinforces the basic laws of signal propagation, which indicate that power decreases with increasing distance from the source due to space loss factors.

The study established that the 9th floor had a solid and reliable communication link, with no packet losses despite signal attenuation. In contrast, there were no signals on the 8th floor, and the packet loss rate was 100% at each measurement point. The sudden drop in signal could imply that it was interrupted by various building barriers, which accumulated and ultimately caused attenuation or exceeded a critical distance threshold. This result suggests that although ZigBee can maintain signal integrity across multiple levels in this building structure, its effective distance is limited. The lack of data on the 8th floor demonstrates that there is a need to apply mesh networking by ZigBee to extend the network and repeat signals to cope with these constraints.

Table 2. The datasets of ZigBee range test

Floor (test point)	$RSSI$ (dBm)										$\overline{RSSI}$	PLR (%)
	1	2	3	4	5	6	7	8	9	10	(dBm)	
Floor10 (1)	-65	-64	-64	-65	-66	-67	-67	-66	-65	-66	-65.5	0
Floor10 (2)	-73	-75	-75	-73	-76	-77	-70	-70	-73	-73	-73.5	0
Floor9 (3)	-85	-84	-84	-85	-84	-84	-84	-84	-84	-84	-84.2	0
Floor9 (4)	-86	-89	-87	-86	-89	-86	-88	-89	-87	-88	-87.5	0
Floor9 (5)	-74	-74	-74	-74	-74	-74	-74	-74	-73	-74	-73.9	0
Floor8 (6)	N/A										N/A	100
Floor8 (7)	N/A										N/A	100
Floor8 (8)	N/A										N/A	100

3.2. Received signal strength indicator measuring of long range cases

This experiment aimed to assess the indoor wireless transmission capabilities of LoRa technology in a seven-story building (4th to 10th floors), considering signal penetration through structural obstacles such as walls and ceilings. We added two-gain antennas (-4 and 2 dBi) to compare performance. This setup was similar to the ZigBee experiment, but the test involved a modified floor plan.

Tables 3 and 4 present the RSSI measurements and packet loss percentages at different test points within the building, using two different antenna gains from element14 site [22]. To determine the performance of LoRa in cases of power attenuation and interference, it is essential to compare LoRa's performance with different antenna gains. With an antenna gain of -4 dBi, LoRa could transmit through up to 6 floors, with RSSI values between -72 and -102.5 dBm, which demonstrates extensive coverage. Nevertheless, when the antenna gain was set to -4 dBi, a high level of packet loss was observed, especially as the signal moved over greater distances or through thicker objects. On the contrary, when the antenna gain was changed to 2 dBi, LoRa showed good performance in terms of strength and signaling reliability, with RSSI values between -62.1 and -103.6 dBm. Such emphasis highlights the importance of antenna arrangements in improving signal permeability and overall communication dependability in complex environments.

Table 3. The datasets of LoRa range test (antenna gain=-4 dBi)

Floor (test point)	$RSSI$ (dBm)										$\overline{RSSI}$	PLR (%)
	1	2	3	4	5	6	7	8	9	10	(dBm)	
Floor10 (1)	-72	-69	-73	-75	-72	-72	-73	-73	-72	-75	-72.6	0
Floor10 (2)	-83	-82	-82	-79	-78	-82	-83	-84	-83	-83	-81.9	0
Floor7 (3)	-103	-103	-103	-104	-103	-103	-103	-100	-103	-104	-102.9	0
Floor7 (4)	-106	-103	-107	-106	-106	-106	-106	-107	-106	-106	-105.9	0
Floor7 (5)	-107	-103	-107	N/A	-106	-107	-107	-103	-107	-103	-105.6	10
Floor4 (6)	-103	N/A	N/A	N/A	-101	-107	-107	-107	N/A	N/A	-105.0	50
Floor4 (7)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100
Floor4 (8)	N/A	N/A	N/A	N/A	-101	-101	N/A	N/A	-102	-106	-102.5	60

Table 4. The datasets of LoRa range test (antenna gain=2 dBi)

Floor (test point)	$RSSI$ (dBm)										$\overline{RSSI}$	PLR (%)
	1	2	3	4	5	6	7	8	9	10	(dBm)	
Floor10 (1)	-63	-63	-62	-63	-62	-62	-59	-63	-62	-62	-62.1	0
Floor10 (2)	-77	-79	-79	-82	-78	-80	-80	-80	-80	-80	-79.5	0
Floor7 (3)	-95	-94	-95	-95	-95	-91	-95	-96	-95	-95	-94.6	0
Floor7 (4)	-102	-102	-102	-99	-102	-103	-102	-99	-102	-101	-101.4	0
Floor7 (5)	-103	-101	-102	-102	-102	-103	-103	-103	-97	-103	-101.9	0
Floor4 (6)	-102	-102	-102	-102	-101	-101	-102	-102	-102	-102	-101.8	0
Floor4 (7)	N/A	N/A	N/A	N/A	N/A	-99	-104	N/A	-104	N/A	-102.3	70
Floor4 (8)	-104	-104	-104	-104	-104	-104	-104	-104	-100	-104	-103.6	0

3.3. Received signal strength indicator measuring of narrowband internet of things cases

In this part, we cover NB-IoT range testing, demonstrating the full potential of the technology to transmit data across all the major floors of the testbed building (1st, 5th, and 10th floors). On the 1st floor, as can be seen from Table 5, despite the low RSSI value caused by obstructions in the building structure, NB-IoT experienced no packet loss and the transmission was not interrupted. This proves its great reliability in the indoor environment. The ability to continue receiving RSSI signal data across different floors and the absence of reported packet loss demonstrate NB-IoT as a robust technology that can overcome physical obstacles in building areas with reliability and effectiveness in operation. The weak signal on the 1st floor is probably due to signal attenuation close to the building's structural elements. The technology's performance was not compromised, indicating that the signals had a well-penetrating character and that the technology can be applied in complex urban settings.

Table 5. The datasets of NB-IoT range test

Floor (test point)	$RSSI$ (dBm) 1	2	3	4	5	6	7	8	9	10	$\overline{RSSI}$ (dBm)	PLR (%)
Floor10 (1)	-61	-63	-63	-63	-63	-63	-61	-61	-61	-63	-62.2	0
Floor10 (2)	-55	-57	-55	-55	-57	-55	-57	-55	-55	-55	-55.6	0
Floor10 (3)	-65	-63	-65	-63	-65	-65	-65	-65	-65	-67	-64.8	0
Floor5 (4)	-65	-65	-65	-67	-67	-65	-63	-65	-65	-65	-65.2	0
Floor5 (5)	-65	-65	-65	-65	-65	-65	-65	-65	-65	-67	-65.2	0
Floor5 (6)	-59	-61	-67	-69	-61	-61	-61	-61	-61	-63	-62.4	0
Floor1 (7)	-73	-77	-73	-73	-75	-75	-73	-73	-73	-73	-73.8	0
Floor1 (8)	-73	-75	-75	-73	-75	-75	-75	-75	-75	-75	-74.6	0
Floor1 (9)	-71	-71	-71	-71	-67	-69	-69	-69	-69	-69	-69.6	0

3.4. Wireless technologies comparison

This section presents a conclusive comparison of various wireless protocol performances within a multi-story office building environment, integrating data from sections 3.1 to 3.3. Our analysis thoroughly explores the capabilities of different wireless technologies, such as ZigBee and LoRa, to overcome power losses, obstacles, and interference typical in urban settings. In (3) defines *d* as:

$$d = \sqrt{x^2 + y^2} \tag{3}$$

where d is the distance between the wireless transmitter and receiver, x represents the horizontal distance across the building, and y represents the vertical distance between the floors within the building. The exposition in Table 6 demonstrates the effectiveness of ZigBee in scenarios where range is tested. It confirms that ZigBee can maintain high data transmission even with physical obstacles such as walls and floors. According to the data in this table, there is no packet loss over various distances and environmental conditions, indicating consistent and robust signal strength.

Table 7 also does a thorough analysis of the range test outcomes, proving the functionality of the LoRa technology in long distance communication and in multi-story buildings. The analysis delves deeply into a signal strength transmission studying using antennas having gain -4 and 2 dBi. The outcomes indicate that at higher distances and passing more floors fores using the -4 dBi antenna, the rate of packet loss increases, while the 2 dBi antenna configuration yields significantly better performance.

Table 8 highlights NB-IoT's ability to deliver strong signals across distances up to 458 meters without any data loss, showcasing its reliable coverage in dense urban environments and effective signal penetration in multi-story buildings, even amidst the complexities of urban infrastructure. Figure 10 shows that comparing ZigBee, LoRa, and NB-IoT technologies leads to fundamental conclusions about their capabilities and limitations in a multi-storied building scenario. In Figure 10(a), ZigBee exhibits a strong and stable signal for indoor applications, with only a slight decrease in strength over distance. However, it is suitable for short- to medium-range communication between two floors. As illustrated in Figure 10(b), the adjustable antenna gains of LoRa allow more signal penetration and dependability in such complex urban environments. The resultant RSSI values also indicate the effect of differential impact on signal quality owing to various antenna gains that support prior findings by Artur *et al.* [23]. In Figure 10(c), we see NB-IoT, characterized by a stable signal and no packet loss. This result agrees with [24], [25], which state that NB-IoT enables the maintenance of highly resilient communications within vast metropolitan areas. It is essential for the reliability of applications where comprehensive coverage and deep propagation into dense structures are required.

Table 6. The result summary of ZigBee range test

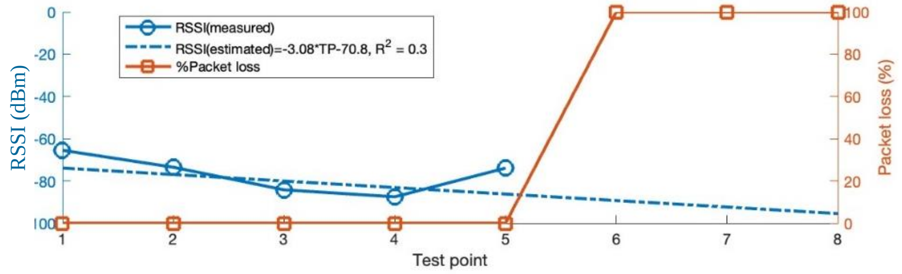
Floor (test point)	No. cross-floor	Distance (m)	$\overline{RSSI}$ (dBm)	PLR (%)
Floor10 (1)	0	20.0	-65.5	0
Floor10 (2)	0	40.0	-73.5	0
Floor9 (3)	1	4.0	-84.2	0
Floor9 (4)	1	20.4	-87.5	0
Floor9 (5)	1	40.2	-73.9	0

Table 7. The result summary of LoRa range test

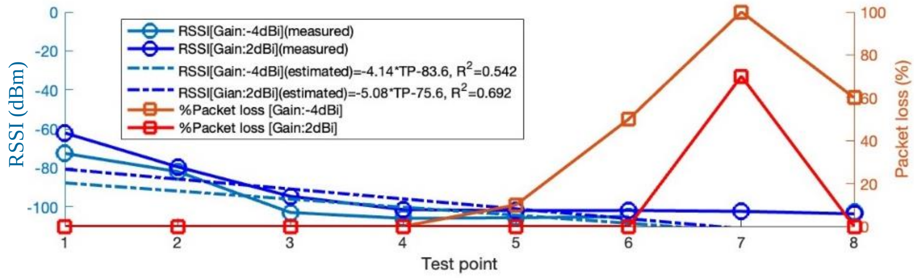
Floor (test point)	No. cross-floor	Distance (m)	-4dBi		2dBi	
			$\overline{RSSI}$ (dBm)	PLR (%)	$\overline{RSSI}$ (dBm)	PLR (%)
Floor10 (1)	0	20.0	-72.6	0	-62.1	0
Floor10 (2)	0	40.0	-81.9	0	-79.5	0
Floor7 (3)	3	12.0	-102.9	0	-94.6	0
Floor7 (4)	3	23.3	-105.9	0	-101.4	0
Floor7 (5)	3	41.8	-105.6	10	-101.9	0
Floor4 (6)	6	24.0	-105.0	50	-101.8	0
Floor4 (7)	6	31.2	N/A	100	-102.3	70
Floor4 (8)	6	46.6	-102.5	60	-103.6	0

Table 8. The result summary of NB-IoT range test

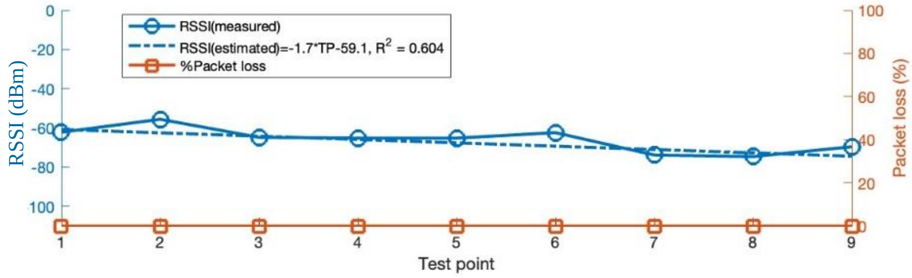
Floor (test point)	No. cross-floor	Distance (m)	$\overline{RSSI}$ (dBm)	PLR (%)
Floor10 (1)	N/A	458 m (Approxmated)	-62.2	0
Floor10 (2)			-55.6	0
Floor10 (3)			-64.8	0
Floor5 (4)			-65.2	0
Floor5 (5)			-65.2	0
Floor5 (6)			-62.4	0
Floor1 (7)			-73.8	0
Floor1 (8)			-74.6	0
Floor1 (9)			-69.6	0



(a)



(b)



(c)

Figure 10. Comparative analysis of RSSI measurements and packet loss percentages across test points for (a) ZigBee, (b) LoRa, and (c) NB-IoT technologies

4. CONCLUSION

This paper evaluates ZigBee, LoRa, and NB-IoT for smart buildings in multi-story office-residential spaces. ZigBee ensures reliable communication over moderate distances, ideal for dense sensor networks. LoRa, with its adjustable antenna gains, adapts to complex environments, ensuring signal penetration across multiple floors. NB-IoT offers broad coverage and robust signal strength, suitable for urban settings with dense structures. In practical tests, ZigBee adapts to sensor-dense environments, LoRa overcomes structural barriers in multi-floor scenarios, and NB-IoT maintains connectivity in urban spaces with high material density. Our analysis uses RSSI and packet loss metrics to highlight the necessity of choosing the right technology based on the environment for efficient smart building network design. The findings demonstrate scalability potential from ZigBee's short-range proficiency to LoRa's extensive reach and NB-IoT's urban connectivity guiding IoT integration in urban infrastructures. This is crucial for smart city advancements, suggesting future research to enhance multi-floor communications by combining these technologies for improved wireless link performance.

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