**Journal of Engineering and Applied Research (JEAR)**

**National University of Skills**

**Winter & Spring 2025, Vol. 2, No. 1, p. 121-138**

**Journal Homepage: [https://jear.tvu.ac.ir](https://jear.tvu.ac.ir)**
doi:10.48301/jear.2025.506258.1091

# Performance Evaluation and Optimization of ZigBee in Different Applications in Smart Grid

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## ARTICLE INFO

**Article Type:**
Original Research

**Received:** 02.14.2025
**Revised:** 04.25.2025
**Accepted:** 10.20.2025

**Keyword:**
Smart Grid
Performance Evaluation
Wireless Sensor Network
ZigBee Protocol

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## ABSTRACT

The development of Smart Grids has introduced a wide array of applications and challenges, particularly in terms of data transmission across various components. To address these challenges, researchers have increasingly turned to wireless sensor networks (WSNs), which offer innovative solutions for enhancing communication and overcoming the limitations of traditional grid systems. Among the many protocols available for WSNs, ZigBee has emerged as a widely adopted standard due to its low power consumption, cost-effectiveness, and suitability for low-data-rate applications. This paper focuses on the performance evaluation and optimization of the ZigBee protocol in diverse Smart Grid environments, including power stations and substations. Special attention is given to critical network performance metrics such as battery life, packet loss, network throughput, end-to-end delay, and energy consumption. Using the NS-2 simulator, we conducted extensive simulations to analyze the protocol's behavior under different conditions. The results show that ZigBee achieves an 85% packet delivery rate in main control rooms but fails in 500 kV outdoor substations due to interference and path loss (0% delivery), demonstrating its suitability for low-bandwidth scenarios and its limitations in harsh environments. These insights contribute to a deeper understanding of ZigBee's role in modernizing energy infrastructure.

**E-ISSN:** 3060-6357

## Introduction

The smart grid has been designed to integrate advanced communication technologies in electric power networks and to make these networks smarter. If there are tools and technologies with faster and better communications for the electric network, the current situation indicates that blackouts and voltage drops in the network are preventable [1], [2].

In this area, there are many challenges for smart grid communications such as generalizability, scalability, flexibility, portability, security, and efficiency [1]. In the past decade, several small-range wireless technologies have been developed in response to the increasing demand for portable and flexible communications.

On the one hand, with the development of the IEEE 802.11 standard based on wide-area wireless networks, technologies with low power consumption and low cost, including the IEEE 802.15.4 standard, have established their place in the market and have appeared under the name of wireless sensor networks.

Recently, the ZigBee smart energy standard, which is an application of the standard IEEE 802.15.4 has been developed as a powerful way to establish communication based on energy information such as cost and consumed energy [3], [4], [5], [6], [7], [8], [9], [10].

These factors make ZigBee ideal for monitoring operations, data collection, and analysis in various smart grid applications [11], [12], [13], [14], [15], [16], [17], [18]. On the other hand, ZigBee also has disadvantages, including the fact that the ZigBee standard supports a low data rate, which makes it unsuitable for high-bandwidth applications. ZigBee was chosen because:

- It offers low power consumption, making it suitable for long-term deployment in remote areas.
- Its cost-effectiveness aligns with the budget constraints of many smart grid projects.
- It supports low-data-rate applications, which are common in smart grid monitoring and control systems.

Therefore, in order to realistically evaluate the reliability of the network in smart grid systems based on ZigBee, a wide evaluation of ZigBee's performance in different smart grid environments is needed [19]. While ZigBee is widely used in smart grids, its performance under diverse environmental conditions—particularly in high-interference settings—has been less explored. This study addresses this gap by simulating ZigBee in three distinct smart grid environments.

There are articles on packet error rate calculation in sources [20], [21], [22]. In [23] and [24], the behavior of the ZigBee network in wireless wide-area network devices has been investigated. In the articles [25], [26], [27] and [28], many efforts have been made in the field of energy efficiency calculation and stack protocol optimization for wireless sensor networks. Also, in the articles [15] , [16], [29] and [30] some estimates have been made for link quality. In this article, first of all, several existing communication technologies for the realization of a smart network, IEEE802.15.4 standard and ZigBee will be mentioned then, network efficiency in smart power distribution systems based on ZigBee will be evaluated in terms of network performance, packet delivery ratio, energy consumption, battery life, and End-to-end delay.

As novelties in this article, these things have been done:

- Comprehensive evaluation of ZigBee performance in different smart grid environments, including power stations and substations.
- Analysis of critical performance metrics such as battery life, packet loss, network throughput, end-to-end delay, and energy consumption.
- Use of the NS-2 simulator to conduct extensive simulations under varying conditions.
- Identification of optimal configurations (e.g., Beacon Order and Superframe Order) for energy efficiency and communication reliability.
- Insights into the limitations of ZigBee in harsh environments and recommendations for hybrid solutions.

## Communication Technologies for Smart Grids

Two main communication technologies can be used in smart grids:

### A. Wired

- **Power Line Communication (PLC)**: generally operated by transmitting a modulated carrier signal on the wiring system [31]. The PLC itself has low-speed shortcomings for data communication. So to make the Smart Grid data transmission reliable and robust, we have to either improve the transmission media or use certain technologies [1].

### B. Wireless

- **IEEE 802.15.4 (ZigBee)**: is a standard that specifies the Physical layer (Phy) and Media Access Control (MAC) layer for low-data rate wireless personal area networks. ZigBee is a popular, low-power wireless communication technology developed based on the physical layer and MAC Layer of the IEEE 802.15.4 standard [32].
- **IEEE 802.11 (Wi-Fi):** is the most dominant wireless technology for the high-speed Internet in indoor and outdoor environments and for

entertainment purposes. Wi-Fi is a standard that specifies the Physical layer and the MAC layer based on the IEEE 802.11 standard [33].

- **IEEE 802.16 (WiMAX)**: WiMAX is a wireless communication technology developed under the IEEE 802.16 standards and provides reliable, high data rate and automatic network connectivity along with low overall installation costs and large coverage area for the smart grid application [34], [35].
- **GSM** and **GPRS**: GSM is the most popular cellular network deployed all over the world. In Smart Grid applications mostly it is used for remote monitoring purposes [36], [37], [38]. Home Monitoring and Load Control can be easily done via GSM–GPRS technology.
- **DASH 7**: is a new wireless sensor network technology using the ISO/IEC 18000-7 standard. It is developed for active Radio Frequency Identification Devices operating [39].

## IEEE 802.15.4 standard and ZigBee

The 802.15.4 is a part of the IEEE family of standards for physical and link layers and is suitable for low-rate wireless personal area networks. Three types of basic network topologies are defined in this standard: star topology, mesh topology, and cluster tree topology, as shown in Figure 1 [16]. The IEEE 802.15.4 standard has two types of devices, Full Function Devices (FFD) and Reduced Function Devices (RFD). FFDs are advanced nodes capable of all network functions, including acting as coordinators (PAN coordinators), routers, or end devices. They support full protocol stacks, can communicate with any other device (FFD or RFD), and are essential for forming mesh networks. In contrast, RFDs are lightweight, low-cost devices designed for simple tasks—they can only communicate with FFDs (not other RFDs), have minimal memory/processing power, and operate as end devices (e.g., sensors or actuators). This hierarchy optimizes energy and resource usage: FFDs handle complex routing and network management, while RFDs serve as battery-efficient edge nodes for data collection (e.g., smart meters or environmental sensors in smart grids).

ZigBee strikes a unique balance between energy efficiency, low cost, and adequate performance for smart grid monitoring. Unlike Wi-Fi/WiMAX, which are over-engineered (and overpriced) for simple telemetry tasks, ZigBee's lean architecture aligns perfectly with the needs of distributed sensor networks. Its ability to support thousands of nodes with minimal power and infrastructure makes it the go-to technology for scalable, long-term smart grid deployments.

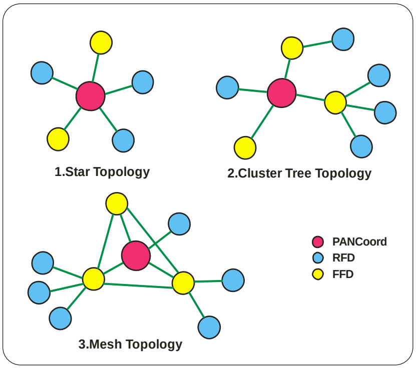

**Figure 1.** Network Topologies

The IEEE 802.15.4-based devices can utilize one of three frequency bands, as shown in Table 1 [16], [17], [18]. In this paper, we use a 2.4 GHz frequency bandwide.

**Table1.** : IEEE 802.15.4 Operating Conditions

| | **Frequency Band** | | |
|---|---|---|---|
| | **2.4 GHZ** | **915 MHZ** | **868 MHZ** |
| **No. of Channels** | 16 | 10 | 1 |
| **Data Rate(kbps)** | 250 | 40 | 20 |
| **Applicability** | World Wide | USA | Europe |
| **Restriction** | Unlicense | Licensed | Licensed |

The ZigBee protocol stack is composed of four main layers: the application layer, the network layer, the medium access control layer, and the physical layer as shown in Figure 2 [40], [41].

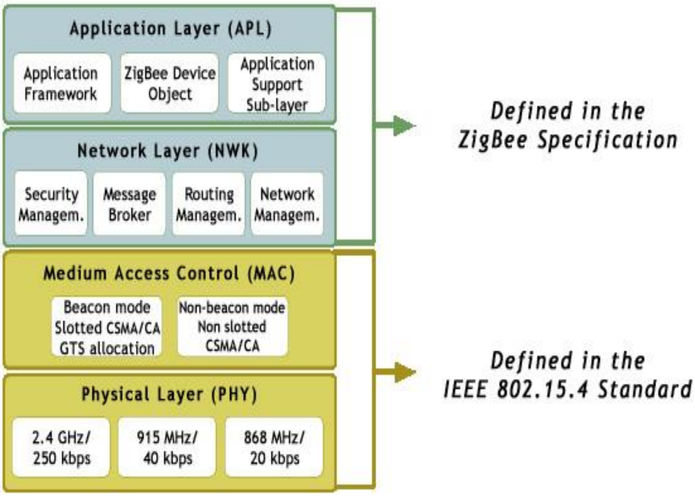

**Figure 2.** ZigBee protocol stack

## Wireless Sensor Network-based Smart Grid Application

Control systems and online monitoring systems have become cost-effective with the recent advances in wireless sensor networks. In these systems important parameters, including voltage, current, temperature, and other related data are monitored and then either transmitted to a centralized station or processed locally in a data processing system by the nodes. In this regard, WSNs play an important role in creating a highly reliable smart electric power grid. The major smart grid applications based on WSNs, from power generation systems to end-users can be summarized as follows:

- Real-time pricing [42]
- Outage detection [42]
- Wireless automatic meter reading [42]
- Line fault and power theft detection [2]
- Energy saving [2]
- Node Clustering [43]

## Performance Results and Simulation

In this section, the performance evaluations of IEEE 802.15.4 with 20 sensor nodes in a star topology and different environments are shown. The simulations were carried out with ns-2 simulator. The Shadowing reflection model has been used for the Radio Propagation model. This model gives a more accurate prediction at a long distance than the free space and two-ray ground model. The received power at distance d is predicted by:

$$\left[\frac{p_r(\mathrm{d})}{p_r(d_0)}\right] = -10\beta\log(\frac{d}{d_0}) + \mathrm{X}_{dB} \qquad (1)$$

Where $d_0$ is a reference distance, $\beta$ is called the path loss exponent and is usually empirically determined by field measurement. $\mathrm{X}_{dB}$ is a Gaussian random variable with zero mean and standard deviation $\sigma_{\mathrm{dB}}$. $\sigma_{\mathrm{dB}}$ is called the shadowing deviation and is also obtained by measurement. On the other hand in (2) the main formula is

$$P_r(d)=P_t+G_t+Gr-L_0-10\cdot\beta\cdot\log_{10} \qquad (2)$$
$$(d)-X_{dB}$$

Where:

- $P_r(d)$: Received power at distance $d$ (in dBm).
- $P_t$: Transmitted power (in dBm).
- $G_t,G_r$: Gains of the transmitting and receiving antennas (in dB).
- $L_0$: Path loss at reference distance $d_0$ (typically 1 meter).
- $\beta$: Path loss exponent (empirically determined).
- $X_{dB}$: Shadowing effect (a Gaussian random variable with zero mean and standard deviation $\sigma_{dB}$).

Another parameter is energy consumption, to quantify energy consumption in ZigBee nodes, we should introduce a formula that models the energy usage based on transmission power, data rate, and other parameters.

$$E_{total}=E_{tx}+E_{rx}+E_{idle} \qquad (3)$$

Where $E_{tx}=P_{tx}\cdot T_{tx}$, $E_{rx}=P_{rx}\cdot T_{rx}$, $E_{idle}=P_{idle}\cdot T_{idle}$ and

- $E_{total}$: Total energy consumed by a node.
- $E_{tx},E_{rx},E_{idle}$: Energy consumed during transmission, reception, and idle states, respectively.
- $P_{tx},P_{rx},P_{idle}$: Power consumption in transmission, reception, and idle modes (in watts).
- $T_{tx},T_{rx},T_{idle}$: Time spent in transmission, reception, and idle states (in seconds).

Although, to mathematically define the packet delivery ratio, we use (4) as a standard formula.

$$PDR = \frac{N_{sent}}{N_{received}} \times 100 \qquad (4)$$

Where

- $PDR$: Packet Delivery Ratio (in percentage).
- $N_{received}$: Number of packets successfully received at the destination.
- $N_{sent}$: Total number of packets sent by the source.

To analyze the delay performance, we can use a formula for calculating the average end-to-end delay.

$$D_{avg} = \frac{1}{N} \sum_{i=1}^{N} \left( T_{arrival,i} - T_{transmit,i} \right) \qquad (5)$$

where

- $D_{avg}$: Average end-to-end delay (in seconds).
- $N$: Total number of packets transmitted.
- $T_{arrival,i}$ : Arrival time of the $i^{th}$ packet at the destination.
- $T_{transmit,i}$ : Transmission time of the $i^{th}$ packet from the source.

To calculate network throughput, we use the following formula.

$$T = \frac{N_{successful} \times L_{packet}}{T_{total}} \qquad (6)$$

*Where*

- $T$: Network throughput (in bits per second).
- $N_{successful}$: Number of successfully delivered packets.
- $L_{packet}$: Length of each packet (in bits).
- $T_{total}$: Total simulation time (in seconds).

Another main parameter is battery life. To estimate the battery life of ZigBee nodes, we use the following formula.

$$L_{battery} = \frac{E_{initial}}{E_{avg\_consumption}} \qquad (7)$$

*Where*

- $L_{battery}$: Estimated battery life (in seconds).
- $E_{initial}$: Initial energy of the battery (in joules).
- $E_{avg\_consumption}$: Average energy consumption rate (in joules per second).

And finally, to evaluate link quality, we introduce the Signal-to-Noise Ratio (SNR) formula like (8).

$$SNR = \frac{P_{signal}}{P_{noise}} \qquad (8)$$

*where:*

- $SNR$: Signal-to-Noise Ratio (dimensionless or in dB).
- $P_{signal}$: Power of the received signal (in watts).
- $P_{noise}$: Power of the noise (in watts).

We can find shadowing parameters used in our simulation for three different environments in Table 2.

**Table 2.** Shadowing Channel Parameters

| Propagation environments | Path Loss | Shadowing deviation |
|---|---|---|
| **500 kV outdoor substation** | 2.42 | 3.12 |
| **Underground transformer vaults** | 1.45 | 2.45 |
| **Main power room** | 1.64 | 3.29 |

The shadowing parameters (path loss exponent and shadowing deviation) reveal the challenges posed by each environment. For example:

- The 500 kV outdoor substation has a high path loss exponent (2.42) and shadowing deviation (3.12), indicating significant signal degradation.
- The main power room and underground transformer vaults have lower path loss exponents but still face challenges due to confined spaces and interference.

These environments were selected due to their varying signal propagation characteristics and unique challenges, providing a comprehensive understanding of ZigBee's performance.

The other parameters used in our performance evaluations are listed in Table 3.

**Table3.** Required Parameters for Simulation

| | | | |
|---|---|---|---|
| **No. of Nodes** | 20 | **Propagation Model** | Shadowing |
| **Area** | 50 x 50 | **Routing Protocol** | AODV |
| **MAC protocol** | 802.15.4 | **Traffic Flow** | 5 |
| **Traffic Type** | CBR | **Packet length** | 70 Bytes |
| **Queue Type** | Drop Tail | **TX Range** | 5 m |
| **Initial Energy** | 9720 J | **Antenna Height** | 1.5 m |

We have four frame types in IEEE 802.15.4 standard, namely beacon frames, data frames, acknowledgment frames, and MAC control frames. Beacon frames are used by the coordinator to describe the channel access mechanism to other nodes. Each beacon frames have two fields, the beacon order (BO) subfield specifies the transmission interval of the beacon, and the superframe order (SO) subfield specifies the length of time during [44].

In the simulation, first, we study the effect of changing BO and SO ratio in Energy Consumption and choose best ratio. Then we investigate the following performance metrics:

- **Battery Life**: represents the average time each node can work.

- **Energy Consumption**: represents the average percentage of the consumed energy by nodes.
- **Network Throughput**: represents the amount of data transmitted between transceivers in a specific time period.
- **End-to-End Delay**: represents the average time to receive all data on the destination side.
- **Packet Loss Rate**: represents the amount of data drops between transceivers.
- **Delivery ratio**: represents the ratio between the number of successful packets and the total number of transmitted packets.

Based on these performance metrics and simulation parameters we present the performance results in Figure 3 to Figure 10. Figures 3 and 4 show the average delivery ratio and average battery life of nodes with changes in Beacon Order and Superframe Order. For these simulations, we elaborated on the challenges:

- Ensuring accurate modeling of shadowing effects in different environments.
- Balancing energy efficiency and communication reliability through BO/SO optimization.

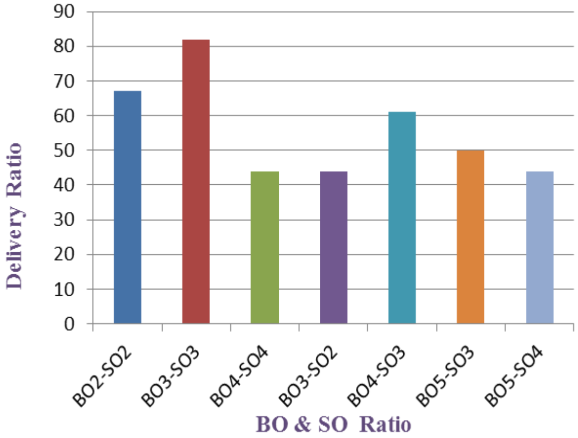

**Figure 3.** Average Delivery Ratio of Nodes with different Bo and So Ratio

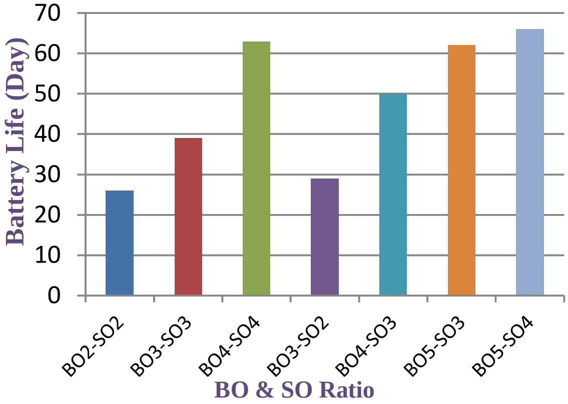

**Figure 4.** Average Battery Life of Nodes with different Bo and So Ratio

Figure 3 shows the general trend of the Delivery Ratio decreasing as BO is increased. There is the same result for the SO ratio. Figure 4 shows that increasing in BO results in an increase in Battery Life, and the same result for SO. Based on the current results, we choose BO = 4 and SO = 3 to continue the simulation. Figures 3 and 4 demonstrate that increasing BO and SO improves battery life but reduces the delivery ratio. The authors select BO = 4 and SO = 3 as the optimal configuration for their simulations, balancing energy efficiency and communication reliability.

Figure 5 shows the average energy consumption in different smart grid environments. Figure 6 shows the average battery life, based on this performance metric, generally, when the data rate increase, the average battery life decrease, so we have maximum battery life at a lower data rate.

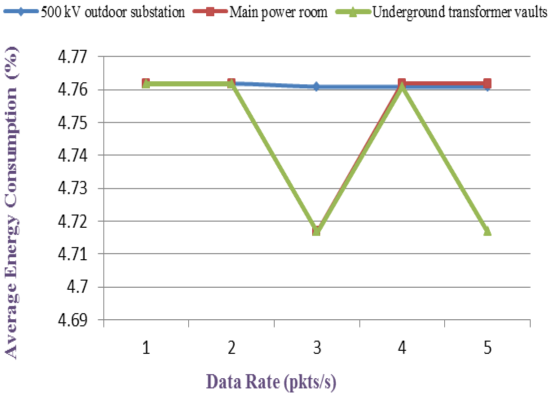

**Figure 5.** Average Energy Consumption

The results show that energy consumption varies significantly across environments. Underground transformer vaults exhibit the highest energy consumption due to signal attenuation and interference caused by metallic structures and confined spaces. In contrast, the 500 kV outdoor substation shows the lowest energy consumption, but this is likely due to failed communication attempts rather than efficient operation.

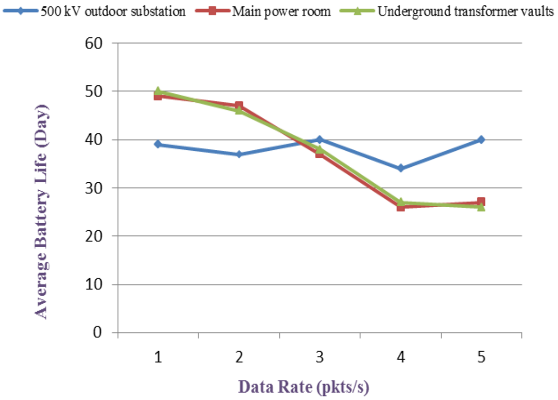

**Figure 6.** Average Battery Life

Figure 6 shows battery life decreases as the data rate increases. Lower data rates result in longer battery life, making ZigBee more suitable for low-bandwidth applications.

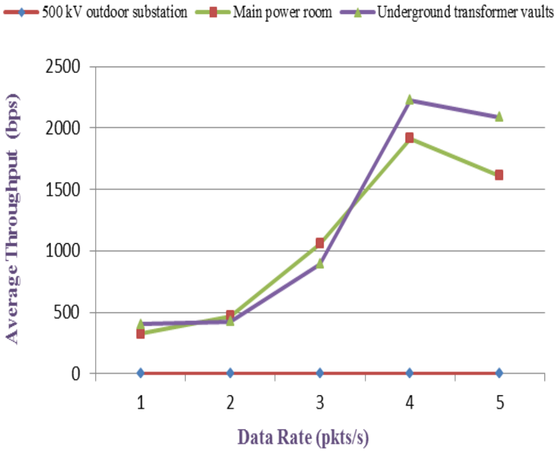

**Figure 7.** Average Throughput

Figure 7 shows throughput generally increases with higher data rates, except in the 500 kV outdoor substation, where no throughput is achieved. This highlights the unsuitability of ZigBee for harsh environments with significant interference and path loss.

In Figure 7 generally average throughput increases when the data rate increases, except in the 500kV outdoor substation we have no throughput, and no delivery in this environment (Figure 8). This shows ZigBee is not suitable for harsh environments. Figure 9 shows the minimum delay in lower data rate.

Figure 10 shows the amount of sent packets and dropped packets. All the packets dropped in the 500kV outdoor substation.

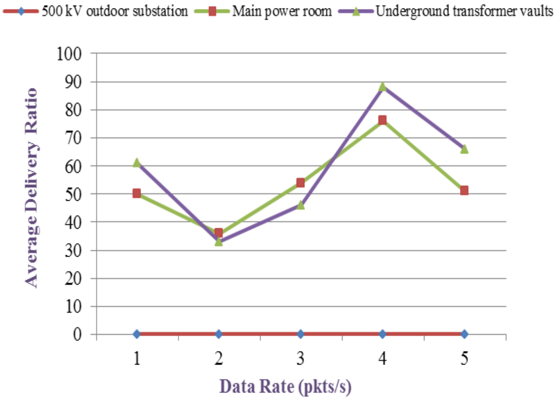

**Figure 8.** Average Delivery Ratio

In Figure 8, no packets are delivered in the 500 kV outdoor substation, indicating that ZigBee struggles in environments with high shadowing and path loss.

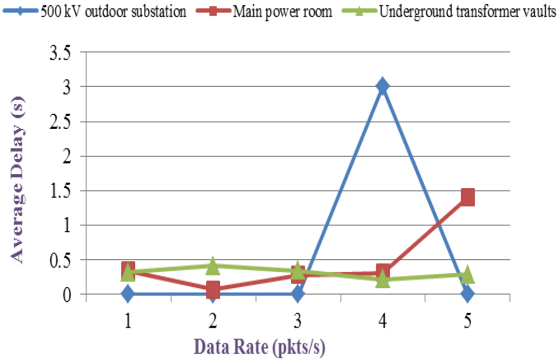

**Figure 9.** Average Delay

Figure 9 shows lower data rates result in minimal delays, which is beneficial for applications requiring timely communication. However, in harsh environments like the outdoor substation, delays are irrelevant due to complete communication failure.

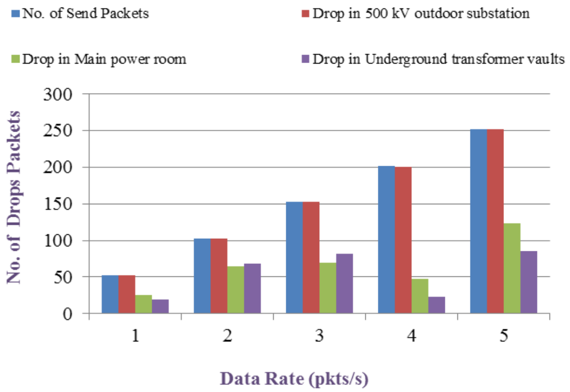

**Figure 10.** Number of Send and Drop Packets

Figure 10 illustrates all packets that are dropped in the 500 kV outdoor substation, further emphasizing the limitations of ZigBee in such environments.

ZigBee is well-suited for low-data-rate applications in controlled environments like the main power room, where communication reliability and energy efficiency are achievable. However, ZigBee is not suitable for harsh environments such as outdoor substations, where high interference, path loss, and shadowing lead to communication failures. This limitation underscores the need for alternative technologies or hybrid solutions in such scenarios.

The study highlights the importance of selecting appropriate communication technologies based on environmental conditions. While ZigBee offers cost-effective and energy-efficient solutions for certain applications, its limitations in harsh environments necessitate further research into adaptive protocols and robust alternatives. The findings also emphasize the need for optimization techniques, such as adaptive transmission power control and routing protocols, to enhance ZigBee's performance in challenging smart grid environments.

## Conclusion

Recently, ZigBee technology based on the IEEE 802.15.4 standard has been developed and offers an affordable way for communicating energy-related information. These make ZigBee ideal in various smart grid applications. In This paper, we study the performance evaluation and optimization of ZigBee protocol in Different Smart Grid environments, e.g. 500kV outdoor substation, main power control room, and underground network transformer vaults, with a special focus on its essential network performance parameters such as battery life, packet loss, network throughput, end-to-end delay, energy consumption, and other critical factors. The performance evaluation shows that the ZigBee can only be used for low data rates and is not suitable for harsh environments and real-time deadlines. The authors suggest exploring hybrid communication systems that combine

ZigBee with other technologies (e.g., Wi-Fi or WiMAX) to address its limitations in high-interference environments. Potential advancements and roles for ZigBee in future smart grids are incorporation of advanced AI-driven algorithms for real-time optimization of network parameters, adoption of energy harvesting techniques to mitigate high energy consumption in challenging environments and development of hybrid communication systems combining ZigBee with other technologies (e.g., Wi-Fi or WiMAX) for improved performance. into energy harvesting techniques could mitigate the impact of high energy consumption in underground transformer vaults and similar environments. Investigating advanced AI-driven algorithms for real-time optimization of network parameters could improve ZigBee's adaptability and reliability in dynamic smart grid applications. Also, further research in investigating adaptive algorithms for power optimization in underground environments.

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