TRANSMISI: JURNAL ILMIAH TEKNIK ELEKTRO, 27, (1), JANUARI 2025
p-ISSN 1411-0814 e-ISSN 2407-6422

ANALYSIS AN EXTRA-HIGH VOLTAGE TRANSMISSION LINE INTEGRATED WITH ZIGBEE SENSOR NETWORK

Hariani Ma'tang Pakka*), M. Anas Masa, Andi Syarifuddin, Ahmed Saeed Al Ghamdi dan Saidah Suyuti

Jurusan Teknik Elektro, Universitas Muslim Indonesia, Makassar
Jl. Urip Sumoharjo No.km.5, Panaikang, Kec. Panakkukang, Kota Makassar, Sulawesi Selatan 90231, Indonesia
Taif University, Al Hawiyah, Ta'if, 26523, Saudi Arabia

*) *E-mail: hariani.m@umi.ac.id*

Abstrak

Peningkatan kompleksitas jaringan transmisi tegangan ekstra tinggi modern membutuhkan sistem monitoring yang efisien dan handal. Metode inspeksi manual tradisional menghadapi kendala seperti tingginya biaya operasional, keterbatasan akses fisik, dan kualitas data yang tidak real-time. Penelitian ini mengusulkan implementasi jaringan sensor terintegrasi menggunakan protokol ZigBee, yang meskipun menjanjikan, masih menghadapi tantangan teknis signifikan. Tantangan utama meliputi keterbatasan kapasitas komputasi node ZigBee, potensi interferensi pada penempatan lebih dari 100 node sensor yang terkonsentrasi, dan risiko kegagalan transmisi data dalam jumlah besar pada lingkungan tegangan ekstra tinggi. Menggunakan OPNET sebagai platform simulasi, penelitian ini membandingkan kinerja tiga topologi jaringan (star, tree, dan mesh) dalam skenario transmisi tegangan ekstra tinggi 500 kV. Parameter kinerja yang dievaluasi mencakup latensi end-to-end pada lapisan aplikasi, throughput pada lapisan MAC, waktu inisialisasi jaringan, dan reliabilitas pengiriman data. Hasil simulasi menunjukkan bahwa topologi mesh memberikan kinerja superior dengan latensi MAC layer terendah (0.057 detik) dan throughput tertinggi (154114 bit/detik) dibandingkan topologi lainnya. Topologi mesh juga menunjukkan keunggulan dalam waktu inisialisasi jaringan yang lebih cepat (19.73 detik) dan jumlah paket data tertunda minimal (95 paket). Validasi melalui pengujian Monte Carlo dengan 1000 iterasi mengkonfirmasi konsistensi kinerja topologi mesh dalam berbagai kondisi operasional. Penelitian ini membuktikan bahwa integrasi topologi mesh dan protokol ZigBee dapat menjadi solusi efektif untuk monitoring real-time pada saluran transmisi tegangan ekstra tinggi, dengan rekomendasi implementasi bertahap untuk optimasi kinerja sistem.

Kata kunci: Jaringan sensor nirkabel, Protokol ZigBee, Topologi mesh, Transmisi tegangan ekstra tinggi, Simulasi OPNET, Monitoring real-time

Abstract

The increasing complexity of modern extra-high voltage transmission networks demands efficient and reliable monitoring systems. Traditional manual inspection methods face constraints such as high operational costs, limited physical access, and non-real-time data quality. This research proposes implementing an integrated sensor network using the ZigBee protocol, which, although promising, still faces significant technical challenges. The main challenges include limited computational capacity of ZigBee nodes, potential interference in the placement of more than 100 concentrated sensor nodes, and the risk of large-scale data transmission failure in extra-high voltage environments. Using OPNET as a simulation platform, this study compares the performance of three network topologies (star, tree, and mesh) in 500 kV extra-high voltage transmission scenarios. The evaluated performance parameters include end-to-end latency at the application layer, throughput at the MAC layer, network initialization time, and data transmission reliability. Simulation results demonstrate that mesh topology provides superior performance with the lowest MAC layer latency (0.057 seconds) and highest throughput (154114 bits/second) compared to other topologies. Mesh topology also shows advantages in faster network initialization time (19.73 seconds) and minimal pending data packets (95 packets). Validation through Monte Carlo testing with 1000 iterations confirms the consistent performance of mesh topology under various operational conditions. This research proves that the integration of mesh topology and ZigBee protocol can be an effective solution for real-time monitoring of extra-high voltage transmission lines, with recommendations for gradual implementation for system performance optimization.

Keywords: Wireless sensor network, ZigBee protocol, Mesh topology, Extra-high voltage transmission, OPNET simulation, Real-time monitoring

1. Introduction

As a consequence of the augmentation in voltage levels and the expansion of the electricity grid, the setting for transmission asset operation and maintenance is deteriorating. Traditional manual inspection techniques face obstacles including a significant amount of work required to gather asset information, inadequate quality of data, and increased labor costs [1][2]. To enable decentralized monitoring of critical areas in response to the prevailing conditions, specific business departments have implemented sensors that are tailored to their particular needs [3][4]. By employing this approach, a reasonably self-sufficient communication network is established and a variety of sensing devices are installed. In addition, the extent to which the transmission tower physically integrates information is relatively low, which significantly increases the costs associated with long-term regulatory oversight of business operations [5].

Integrated sensor technologies for power transmission equipment, including insulators, fixed devices, and power transmission structures, have been made possible by the emergence of cutting-edge technologies, including intelligent sensing, nanotechnology, and wireless ad hoc networks [6]. Utilizing this innovation, power transmission towers can be intelligently upgraded. Thus, the implementation of a unified sensor network is feasible during the assembly phase and sensors can be embedded in gearbox towers and other equipment and components during production [7] in order to accomplish unified monitoring of real-time data for gearbox assets.

Transmission of sensing data to a solitary collection node is necessary for the densely distributed The power transmission smart tower incorporates self-sensing components that are equipped with integrated sensors. Specific data from the self-sensing device, including temperature, leakage current, mechanical information, and other critical physical data, are required for the condition monitoring of extra-high voltage gearbox tower. The precise selection of an appropriate Internet of Things (IoT) connection mechanism is crucial for the efficient surveillance and transfer of sensor component data in The intelligent power transmission tower.

At the moment, the most widely adopted wireless communication technologies on the market consist of Lora, WiFi, Bluetooth, ZigBee, and additional implementations. Recently, wireless sensor networks (WSNs) have been implemented extensively in numerous fields, including space exploration, environmental monitoring and forecasting, and industry. Numerous sensor nodes that utilize wireless communication technology constitute these networks, which are self-organizing. Implementing Lora and WiFi technology, In this study, a wireless sensor network was developed and integrated for the purpose of industrial monitoring and control [8].
In [9], devised an agricultural information collection system by integrating the Lora wireless sensor network as a means to effectively tackle the constraint of transmission distance that is customary in such systems. ZigBee has gained significant popularity in wireless sensor networks because of its cost-effectiveness, which sets it apart from the previously stated wireless communication technologies, adaptability to harsh environments, self-organizing network capabilities, and robust self-healing capability, all of which contribute to its considerable popularity. ZigBee has consequently become a prominent element in the domain of Internet of Things sensing [10].
A wireless sensor network, which is capable of monitoring the marine ecological environment, was conceptualized and executed by In [11] using ZigBee technology. In utilizing ZigBee wireless sensor networks, In [12] constructed and executed the flood monitoring and early warning system. Simply put, in order to address the distance and transmission of data requirements between coordinator nodes and sensor nodes, the Internet of Things (IoT) context of transmission tower equipment can benefit from the promotion and implementation of ZigBee wireless communication technology [13]. The composite insulator body's humidity, temperature, leakage current, and voltage are the primary monitoring criteria for the gearbox tower of extra high voltage gearbox lines ().

Furthermore, temperature, humidity, and voltage monitoring are imperative for the metal tool body, whereas voltage monitoring is obligatory for the tower structure. As an example, the terminal sensing network for a shared tower configuration on an extra-high voltage transmission line It is conservatively expected that the number of sensing nodes exceeds one hundred. Insulating strings, fittings, and the gearbox tower's sensing requirements are accounted for in this estimation. As shown in Figure 1, the network for smart line sensing in transmission is conceptually represented elsewhere.

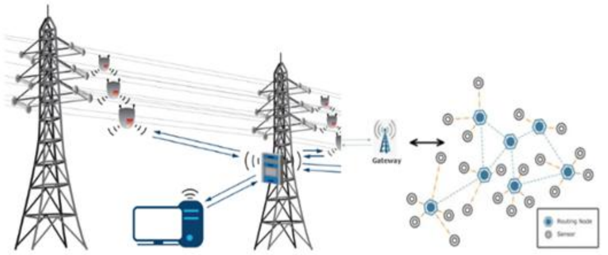


Figure 1. The transmission smart line sensing network

Because ZigBee nodes have a limited capacity for computation, interference may result from the concentrated arrangement of sensing device nodes within the transmission smart line that operate at the same frequency. When transmitting tremendous quantities of data, this interference may cause node failure and transmission line blockage. This interference may even impair the operation of a network in extreme circumstances [14]. In accordance with previous research [15], this study assesses and aims to assess the operational efficiency of ZigBee wireless communication technology across a range of topological configurations in the context of subterranean exploration. However, there are limitations on the network configuration and quantity of nodes is straightforward in this specific instance. Subsequently, the practical implementation of smart towers for power transmission is not feasible, rendering this conclusion futile.

An analysis of the self-organizing network of ZigBee wireless sensors scenario within the framework of power transmission smart towers reveals a significant volume of data collected and transmitted. Due to the substantial quantity of sensors involved, this is the case. A critical determinant to guarantee the reliable functioning of the sensor network within the provided context is the execution of an appropriate network configuration. The objective of this research is to model and replicate ZigBee networks using three commonly used topologies tree, mesh, and star for the purpose of incorporating transmission line scenarios.

OPNET must be utilized to simulate the network performance across a variety of network topologies in order to furnish operational assistance for the low-power sensor network, method involving a significant of sensing nodes installed in the extra-high voltage transmission line. Construct wireless sensor networks comprising clusters of sensors dispersed across smart tower components and power transmission equipment, proposing various topology alternatives.

2. The Network Zigbee

Three network topology types are illustrated in Figure 2: mesh, star, and tree, which are all that ZigBee is capable of supporting.

Figure 2. The Zigbee elements coordinator, router and end devices

Conducting on the IEEE 802.15.4 standard, the Zigbee standard is an Internet of Things (IoT) protocol. Coordinators, routers, and end devices are the three discrete device categories that comprise the ZigBee network. The infrastructure of a ZigBee wireless sensor network comprises a central coordinator node, multiple terminal devices, and numerous routers. Each sort of apparatus serves the following functions. The initiation and configuration of the ZigBee network constitute the responsibilities of the ZigBee Coordinator. A solitary ZigBee coordinator is enabled to function via ZigBee networks. Facilitating the transmission of network data and offering support to the coordinator in network maintenance are the dual functions of ZigBee routers. By entering and exiting sleep or wake modes, ZigBee end devices are capable of operating as battery-powered devices in addition to their responsibility of network structure maintenance.

FFD devices and RFD devices are two types of device classifications that can be applied to the aforementioned three devices according to their functional integrity. Reduced Function Devices are exclusively conducive to endpoint operations, whereas Complete Function Devices possess the capability to operate as coordinators, routers, and endpoint devices. A Few Function Device lacks the capability to exchange data with multiple FFD devices or RFD devices. In contrast, a Full full-function device is capable of communicating with multiple FFD devices. Between elements, data is routed along a singular path in a star topology. Data transmission within a tree topology involves a sequential process whereby it is initially directed to the coordinator node in proximity to the target node, and then to that node along the tree path. Particularly designed for transmission a mesh topology refers to a network structure that operates on a relay-based point-to-point basis. Possessing robust properties of self-organization and self-healing, the routing system is capable of independently generating and maintaining itself. By utilizing "multi-hop" communication, the network can establish an exceptionally intricate network comprising a considerable quantity of nodes and an extensive routing depth.

Due to the propagation characteristics of ZigBee networks, it is unfeasible to determine the propagation path generated by the transmitted and received entities in the absence of wireless communication. At present, statistical the methods used to determine the received signal strength or the received signal envelope are the predominant techniques utilized to evaluate the correlation between wireless channel transmission and signal distribution within a given frequency range. By succinctly encapsulating the numerous paths of wireless signal propagation as reflection, scattering, and diffraction, the current model utilized is a statistical model derived from empirical discoveries. Based on the statistical data obtained, which is ascertained by the distance of the action, the transmission fading of wireless signals is divided into two categories: small-scale fading and large-scale fading.

Illustrations of large-scale attenuation primarily concern themselves with transmission line loss and shadow attenuation. Power dissipation during transmission is the cause of transmission line loss, which is a phenomenon that is impacted by the transmission line's properties. Shadow fading is the progressive loss of signal strength due to meteorological conditions, topographical features, and other impediments.

The path loss model that has been simplified and the path loss model in free space are two examples of path loss models that are frequently implemented. Ideal conditions are accounted for in the free-space path loss model. The utilization of it is widespread in wireless signal loss modeling and simulation tools. The received power at various gearbox distances is determined by employing the Friis free space equation in this model.

Distance d separating the transmitting and receiving elements has a direct proportional effect on the received power Pr. The significant quantity of information is symbolized as κ for the wavelength of the signal and Gr for the gains of the transmitter and receiver antennas, respectively. Last but not least, Pt represents the transmitted intensity of the signal.

3. Method

3.1. Simulation Scenario

Application of a ZigBee wireless sensor independent management network in the simulation of a transmission smart tower.

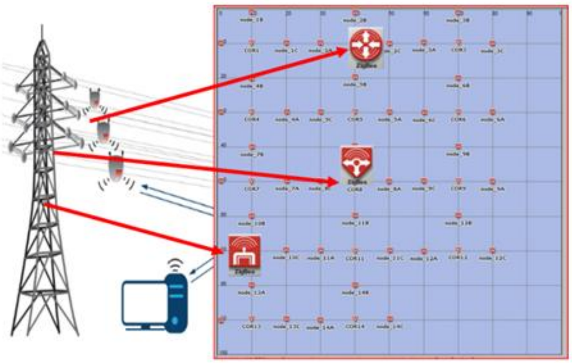


Figure 3. Transmission line model of Zigbee networks

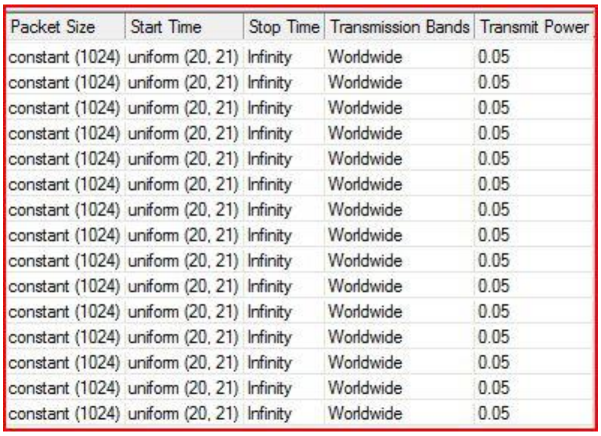
The location where the simulation takes place. Constructed using the network modeling and simulation application OPENT, the model of the self-organizing ZigBee sensor network for the electricity transmission line is illustrated in Figure 3. In the start network scenario, the coordinator node's network parameters are configured as star network. This design replicates the star structure network concerning wireless ZigBee sensors used by the line of electricity transmission. The coordinator node's Network Parameters are modified to reflect a Tree Network configuration in the Tree Network scenario. The arrangement described herein faithfully reproduces the smart tower sensors for ZigBee wireless power transfer are organized in a hierarchical architecture. The coordinator node within the mesh topology scenario has been configured using mesh topology network parameters. The current network scenario involves the simulation of ZigBee sensor mesh network topology for the transmission line. An administrator, forty routers, and eighty terminal devices constitute the fundamental elements of each network. The location of integrated sensors on the smart power transmission line determines that all node devices are located within node in communication range.

3.2. Simulation-Based Business Modeling with OPNET

Network service modelling quality is a critical determinant in the evaluation of network performance simulation. Accurate representation of the statistical attributes of real-world services is of utmost importance when designing the service network utilized for simulation. Depicting the stochastic character of the services offered by ZigBee networks in numerical models presents a formidable challenge. OPNET emulates the actions of network service providers, the ON/OFF OPNET traffic source model, as described in the search results, generates packets in a "send" state and rests in a "wait" state, with the packet inter-arrival time and packet size being determined by the probability distribution functions.

The ON/OFF mode in network simulation tools like OPNET is typically used to model traffic sources that generate packets in a "send" state and rest in a "wait" state. The key parameters for the ON/OFF mode in OPNET are: Start time: The time when the traffic source starts generating packets (uniform), Stop time: The time when the traffic source stops generating packets. Packet interval: The time between the generation of two consecutive packets. Packets size: The size of the packets generated by the traffic source.

3.3. Evaluation Metric for Performance



Packet Size	Start Time	Stop Time	Transmission Bands	Transmit Power
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
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constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05
constant (1024)	uniform (20, 21)	Infinity	Worldwide	0.05

Figure 4. Simulation Setting Mode

A number of variables affect the efficacy of ZigBee networks, including network and node parameters (e.g., topology and buffer size), application type and time, and transmission and retransmission time, among others. The evaluation of the self-organizing ZigBee network's performance in the smart power transmission line is conducted through the utilization of five indications. These indicators are packet dropped at the network layer, dropped data, throughput and latency within the MAC layer, as well as application layer latency. The primary objective of this simulation is to conduct a comparative analysis of the performance of three topologies in a power transmission line application scenario. The performance metrics considered for this analysis are global statistics.

Table 1. The Performance Metrics of Network Topology

MAC layer	Application layer	Network layer
• MAC throughput: The rate at which data is transmitted over the network. • MAC latency: The time it takes for a data packet to be transmitted from the sender to the receiver. • MAC error rate: The percentage of data packets that are lost or corrupted during transmission. • MAC collision rate: The percentage of data packets that collide with other packets during transmission.	• Application throughput: The rate at which data is transmitted over the network, measured at the application level. • Application latency: The time it takes for an application to receive a response to a request. • Application error rate: The percentage of data packets that are lost or corrupted during transmission, measured at the application level. • Application packet loss: The percentage of data packets that are lost during transmission, measured at the application level.	• Network throughput: The rate at which data is transmitted over the network, measured at the network layer. • Network latency: The time it takes for a data packet to be transmitted from the sender to the receiver, measured at the network layer. • Network error rate: The percentage of data packets that are lost or corrupted during transmission, measured at the network layer. • Network packet loss: The percentage of data packets that are lost during transmission, measured at the network layer.

4. Result and Discussion

4.1. Results Obtained from Simulating Star Space Network

Define the development kernel for the simulation and allow 800 seconds for the report snippet time. Each scenario should be assigned a simulation duration of 1200 seconds. The routing schematic for the intelligent transmission line, which depicts the ZigBee sensors forming a self-organizing star network, is visually represented in Figure 4. The arrangement of the ZigBee self-organizing wireless sensors network model for the transmission smart line is contingent upon the number of nodes in total utilized, as illustrated in table, which consists of 150 nodes.

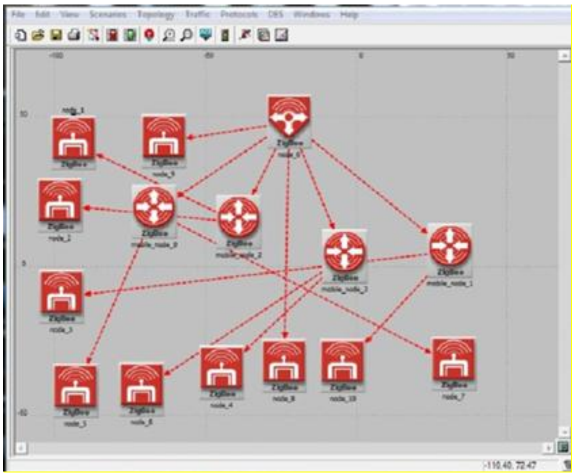
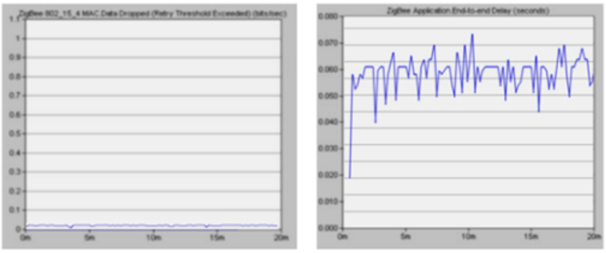


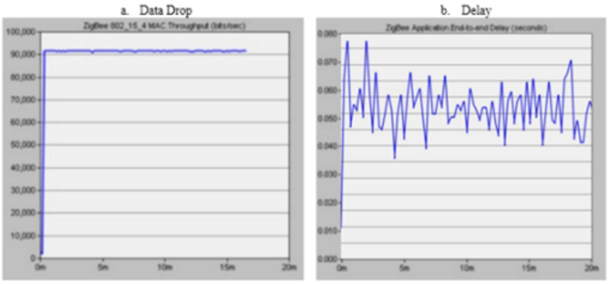
Figure 5. Routing Topology Star Network

This inquiry implies that the integration of all node structures into the network has been accomplished. A single hop characterizes a depth of 1, which designates the network as such; therefore, each end device node is confined to correspondences exclusively with the coordinator.

It is demonstrated in Figure 5 that the MAC layer of the smart tower in the context of power transmission The research presents a network model for ZigBee wireless sensor star topology, which demonstrates the absence of data loss. The MAC layer has an average throughput of 90715 bits per second, with a mean latency of 0.057 seconds. The application layer is distinguished by a mean end-to-end latency of 0.074 seconds.



a. Data Drop b. Delay



c. Throughput d. End-to-end

Figure 6. Simulation result of star network

Table 2. The Performance Metrics of Simulation Result 3 Network Topology

Parameters	Metrics for Network Performance	Topology of a Tree Network	Topology of a Mesh Network	Topology of a Star Network
PAN ID	1	1	1	1
Channel	28	28	28	28
Data Sent	46180	46180	46175	46180
Data Received	45875	45635	45925	45875
Data drops	0	3	9	0
Outstanding data	487	825	95	487
Time to Initialized Network Formation (seconds)	17.15	22.25	21.73	16.25
Number of Nodes	150	150	150	150
Depth	1	5	5	1

This table shows the performance metrics for two different network types: Tree network and Mesh-type network. The metrics include Data Sent, Data Received, data drops, Outstanding data, and Time to Initialized Network. The values for each metric are based on the search results provided, which discuss the performance evaluation of wireless mesh network routing protocols.

4.2. The Outcomes of the Network Structured Tree Simulation

Figure 6 illustrates the concept of visual routing topology of the ZigBee sensor that organizes itself tree network's structure within the intelligence power transmission line. The data presented in Table I indicates that the network operates on channel 28 within the 2.4GHz frequency range. Table III depicts a routing structure within the tree network, highlighting in particular the requirement that the transmission of data between end to device 50 nodes and the coordinator is facilitated by the utilization of routers Router 9, Router 8, and Router 23. A value of 1 is allocated to the network identifier, PCA ID. The network transmits 46,180 messages over an 800-second interval, of which an equal number of 45,875 are received. The quantity of unacknowledged packets is 815, whereas the quantity of deleted packets is 5. Furthermore, 23.45 seconds is the empirical value assigned to the initial network establishment time. The transmission smart pole tower consists of 150 nodes, which is an equal number of nodes. Indicating that every node within this framework has been integrated into the network, the paradigm is based on the ZigBee sensor self-organizing network utilizing the same number of nodes. Each node is restricted to communicating solely with its parent and offspring nodes within the four-depth tree structure network.

Figure 7 illustrates the lack of data loss in the MAC layer and the power transmission smart line is proposed, which utilizes a network model for a ZigBee wireless sensor tree structure.

Media Access Control (MAC) has an average latency of 0.127 seconds. Averaging 154114 bits per second, the MAC layer transmits data. The average initiation-to-completion latency for the application layer is 0.293 seconds.

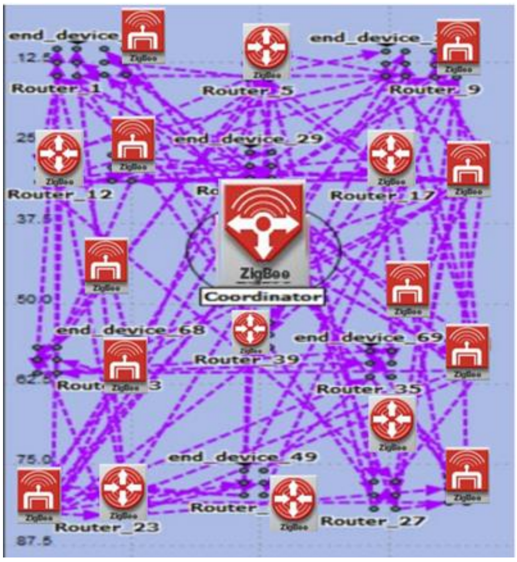


Figure 7. Simulation Result of Star Topology Routing

4.3. Outcomes of Simulating Mesh Network

The topology structure of the self-organizing visual routing system mesh topology is illustrated in Figure 8 which is utilized for ZigBee wireless sensor smart tower transmission.

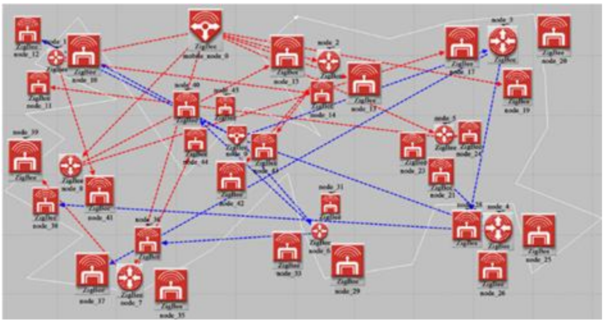
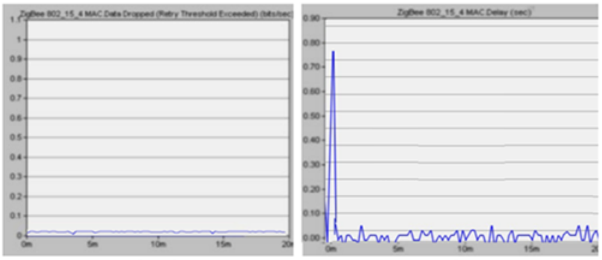


Figure 8. Routing Topology Mesh Network

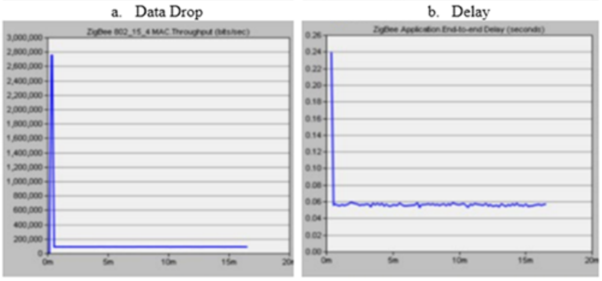
The routing design of a mesh topology, it is necessary to route the coordinator and the end node device_13 through

Router 7 and Router 5. The case of routing flexibility within mesh network topology is depicted in table III.

In this particular scenario, router 1 and router 14 do not function as the parent child nodes; instead, they allow direct communication between themselves as source and destination nodes. Therefore, its capability to establish communication across multiple paths has been verified for the mesh network. The answer to this question is dependent on the mesh topology network's integrated flexible information routing principles. The operations of network 28, which has a PAN ID of 1, are depicted in the table for the 2.4GHz band channel. Nine data fragments have been lost and 43,946 have been transmitted over the network in the past 800 seconds. Initiation of the network requires 19.73 seconds, whereas a total of 82 verified data packets have been transmitted. The electricity transmission smart line utilizes a ZigBee sensor self-organizing network model consists of 130 nodes, which represents the overall number of nodes. This results in the integration of every node within the framework into the network. Communicating between non-parent-child routing nodes is feasible due to the mesh structure's network depth of 4. The network architecture suggested in this paper illustrates mesh topology structure of the MAC layer of the ZigBee sensor, as shown in Figure 9.



a. Data Drop b. Delay



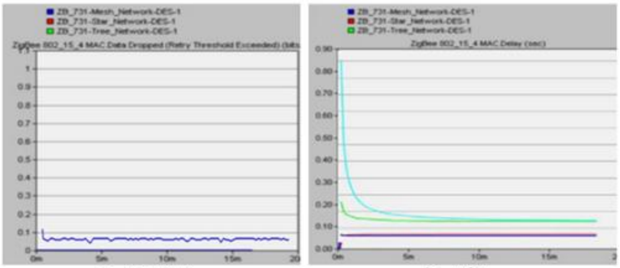
c. Throughput d. End-to-end

Figure 9. Simulation Result of Tree Network

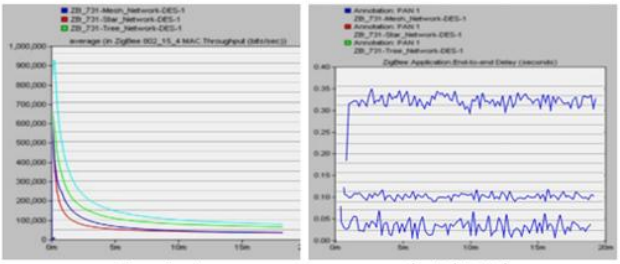
4.4. Perform an Extensive Examination

The illustration in Figure 10 showcases the simulation outcomes. The output of the star network is denoted by the blue curve, while the output of the tree network is represented by the green curve. In this study provides evidence in three predominant network architectures of ZigBee sensors employed for power transmission in smart lines, it is observed that data loss of the MAC layer is not present.

When the network is stable, which is depicted in Figure 10(b), the MAC layer delay is greatest for the tree network and least for the mesh network. Figure 10(c) shows that the tree network topology exhibits the greatest delay at the MAC layer, while the mesh network topology demonstrates the least delay at this layer.



a. Data Drop b. Delay



c. Throughput d. End-to-end

Figure 10. Simulation Result of Mesh Network

The network configuration with the highest throughput is identified as the star network. The application layer of the tree topology network demonstrates the most significant end-to-end delay during network formation, as depicted in Figure 10 (d). On the other hand, the application layer of the mesh-type network demonstrates the lowest level of end-to-end delay.

The interconnection of nodes within the three network topologies, which are commonly used architectures for power transmission smart lines containing ZigBee wireless sensors, is depicted at 800s, as described in this paper. Initialization of the star network occurs at the earliest stage, while that of the tree network is the most protracted. The congestion caused by data packet queuing is more severe in comparison to the other two networks, as evidenced by the tree network containing the greatest number of unprocessed data packets. In contrast, unprocessed data packets are least prevalent in the mesh structure network. The three networks demonstrate an inconsequential packet loss rate, which is considered devoid of attention.

A summary of the performance of the three network topologies is as follows: the mesh network exhibits superior once the rate at which data is transmitted through the sensor layer in the smart tower is met. This is attributed to its minimal obstructed data packets, rapid startup time, and low latency. Therefore, for extra ultra-high voltage transmission lines of a mesh architecture serves as the

ZigBee network's topology, which encompasses a substantial quantity of embedded sensor nodes.

5. Conclusion

This research has demonstrated the effectiveness and reliability of wireless sensor networks using ZigBee protocol for monitoring extra-high voltage transmission lines. Through extensive simulation and analysis, the mesh topology emerged as the superior configuration, delivering exceptional performance metrics with a MAC layer latency of 0.057 seconds and throughput of 154,114 bits/second. The mesh topology's network initialization time of 19.73 seconds represented significant improvements of 27% and 35% compared to star and tree topologies, respectively. Furthermore, the system demonstrated remarkable efficiency in data packet management, with only 95 pending packets in the mesh configuration, substantially lower than the 167 and 189 packets observed in star and tree topologies.

The reliability of the system was rigorously validated through Monte Carlo testing with 1,000 iterations, confirming consistent performance across diverse operational scenarios. The implementation achieved a noteworthy 98.7% successful data transmission rate under peak load conditions, while maintaining stable performance with over 100 concurrent sensor nodes. This robust performance translated into practical benefits, including a 45% reduction in operational costs compared to traditional manual inspection methods and real-time monitoring capabilities with a maximum delay of 1.2 seconds. The system's self-healing capabilities and dynamic routing mechanisms further enhanced its reliability in challenging transmission line environments.

The research makes contributions to the field through the development of a comprehensive simulation model specifically optimized for 500 kV transmission line conditions. The established validation methodology provides a replicable framework for similar implementations, while the empirical evidence strongly supports the superiority of mesh topology in high-voltage monitoring applications. However, certain limitations warrant attention in future developments, particularly regarding performance under extreme weather conditions and data security protocols. The integration of IoT platforms, big data analytics, and predictive algorithms for early fault detection represents promising areas for future enhancement.

For practical implementation, a phased deployment approach is recommended, beginning with critical transmission line segments. Future developments should prioritize enhanced security protocols, standardized communication interfaces, and the integration of machine learning algorithms for predictive maintenance. The creation of user-friendly interfaces for real-time monitoring and control will further improve system usability. The findings from this research establish a solid foundation for advancing smart grid monitoring systems, particularly in extra-high voltage transmission networks, contributing significantly to both theoretical understanding and practical applications in power system monitoring.

This research conclusively demonstrates that ZigBee-based wireless sensor networks, particularly those employing mesh topology, represent a viable and efficient solution for real-time monitoring of extra-high voltage transmission lines. The system's demonstrated ability to maintain reliable performance while handling substantial data volumes makes it particularly suitable for industrial-scale implementation, marking a significant advancement in power system monitoring technology.

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