The impact of coordinator failures on the performance of Zigbee networks in various topologies

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ABSTRACT

Zigbee, a key technology in the field of wireless networks for the Internet of Things, plays a significant role in the development of modern wireless network technologies. In this study, the analysis of coordinator failures in ZigBee networks with different topologies ("star", "tree", "mesh") was carried out using the OPNET Modeler software tool. The problems related to the reliability and efficiency of systems using Zigbee technology are considered. Simulation of successive coordinator failures allowed us to compare the performance of topologies, revealing that the tree topology provides high traffic speed and bandwidth, but suffers from significant packet loss and delays. In turn, the star topology demonstrates minimal latency and high speed, and the mesh topology has better reliability with less packet loss, but the lowest speed and bandwidth. The findings emphasize the importance of choosing the optimal topology to ensure the efficiency and reliability of Zigbee networks in a volatile environment and increased load.

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1. INTRODUCTION

Zigbee is a widely adopted wireless communication standard utilized in diverse domains such as home automation, healthcare, and industrial monitoring [1]–[3]. It facilitates seamless device and sensor interaction, supporting applications like smart lighting, controlled outlets, and interoperability with other communication protocols [4]–[7]. In healthcare, Zigbee is employed for real-time wireless monitoring, such as ECG data transmission [8], [9]. Within industrial environments, Zigbee aids in environmental monitoring, assisting in data collection and air quality management [10], [11]. Due to its broad application spectrum, ranging from small-scale setups to complex systems like nuclear control, ongoing research continues to explore and enhance its capabilities [12], [13].

According to the IEEE 802.15.4 standard, Zigbee networks consist of two device types: full function devices (FFD) and reduced function devices (RFD) [14]. FFDs support comprehensive network operations and can act as coordinators, routers, or end devices, typically relying on AC power for continuous operation. In contrast, RFDs have limited functionality, do not participate in packet routing, and must connect to FFDs for communication [15]. RFDs are often deployed in sensor roles, monitoring parameters like temperature, humidity, and motion [16], [17]. Efficient power management is crucial for battery-operated FFDs to ensure prolonged network functionality [18], [19].

Zigbee networks can adopt star, tree, and mesh topologies [20]. Each topology consists of a coordinator, routers, and end devices [21]. The coordinator, an FFD, oversees network formation and management, while routers (also FFDs) help extend network coverage, especially in tree and mesh configurations [22], [23]. RFDs serve as low-power endpoints, transmitting data to the coordinator or routers [24]. The star topology features direct connections between devices and the coordinator, offering simplicity but with centralized control [25]. The tree topology expands the network by integrating multiple star configurations, enhancing coverage but also introducing potential points of failure [26], [27]. Mesh topology, with its interconnected routers, provides a self-healing mechanism, increasing network resilience against link failures [28], [29].

Nimi *et al.* [30] identified Zigbee as a critical standard for short-range wireless communication. Their study highlighted the superiority of mesh routing over tree routing due to its ad-hoc nature, reducing the need for centralized control. They proposed a Zigbee model using mesh routing with priority mechanisms, demonstrating improved performance metrics such as throughput, data loss, MAC delay, and queuing metrics.

Dymora *et al.* [31] focused on the fault tolerance (FT) challenges in designing IoT systems using Zigbee-based wireless sensor networks (WSNs). Their analysis emphasized that the choice of routing algorithm directly impacts sensor power consumption, often resulting in node failures due to battery depletion. This underscores the importance of robust routing strategies for maintaining network stability and prolonging sensor lifespan.

Ibrahim [32] analyzed the advantages of Zigbee's low power consumption, particularly for sensor applications requiring efficient short-range communication. Their comparative evaluation of the star and cluster tree topologies revealed that the cluster tree configuration offers better efficiency, reduced latency, and higher data throughput, making it more suitable for demanding applications.

Manohara Rao *et al.* [33] conducted a performance analysis of different topologies supported by the IEEE802.15.4/Zigbee standard, including cluster-tree, mesh, and star topologies. Their study, using Riverbed Modeler simulator, concluded that the cluster-tree topology was more efficient and better suited for applications such as environmental monitoring, volcano monitoring, air pollution, and habitat monitoring, as it covered a larger area compared to other topologies. The study emphasized that the cluster-tree topology provided the best performance in terms of throughput, data traffic sent and received.

Abdulhussien and Ibrahim [34] compared the mesh and star topologies of ZigBee networks in terms of throughput, dropped traffic, and latency. The results showed that mesh topology outperformed the star topology in throughput, while star topology demonstrated better latency characteristics. This evaluation highlights the differences between the two topologies and their suitability for various applications.

Haka *et al.* [35], [36] conducted research focusing on the reliability and quality of service (QoS) improvements in ZigBee networks. In their studies, they compared Received Signal Strength Indicator (RSSI) results between simulation and real-world experiments in ZigBee sensor networks, as well as proposing an improved routing algorithm to form hierarchical topologies based on priorities. Their findings contributed to better QoS and energy-efficient routing, enabling the optimization of traffic in IoT applications.

Despite advancements in Zigbee's development, a significant gap exists in understanding the impact of coordinator failures across different topologies. Such failures can disrupt data flow, degrade throughput, and increase network delays, particularly in setups reliant on centralized control.

This article investigates the effects of coordinator failures on Zigbee network performance in star, tree, and mesh topologies. A comparative analysis is provided based on key performance metrics, including throughput, data loss, delay, and network reliability. The findings aim to guide the selection of the most resilient topology for various application scenarios, contributing to improved fault tolerance in Zigbee-based systems.

2. METHOD

This research uses OPNET Modeler to simulate computer networks, enabling the creation of complex topologies, protocols, and traffic scenarios without physical hardware [37], [38]. The model, as shown in Figure 1, features three subnets (subnet_1, subnet_2, subnet_3) connected through a switch (switch_1) linked to a router (router_1) for Internet access. This setup connects to a server (server_1) that stores data from each subnet. A workstation (wrkst_1) accesses the server via a separate router (router_2).

2.1. The first subnet of the Zigbee network with a star-shaped topology

Let's examine the first subnet (subnet_1), shown in Figure 2. This subnet features a Zigbee network with a star topology, including a coordinator (ZC_subnet_1), routers (ZR_1, 2_subnet_1), and end devices

(ZED_1 – 6_subnet_1). The coordinator manages communication among all devices. Additionally, the subnet includes a switch (switch_subnet_1), a router (router_subnet_1), and a workstation (wrkst_subnet_1). The switch connects the subnet to the broader network through the router, while the workstation connects to the router via a wireless network.

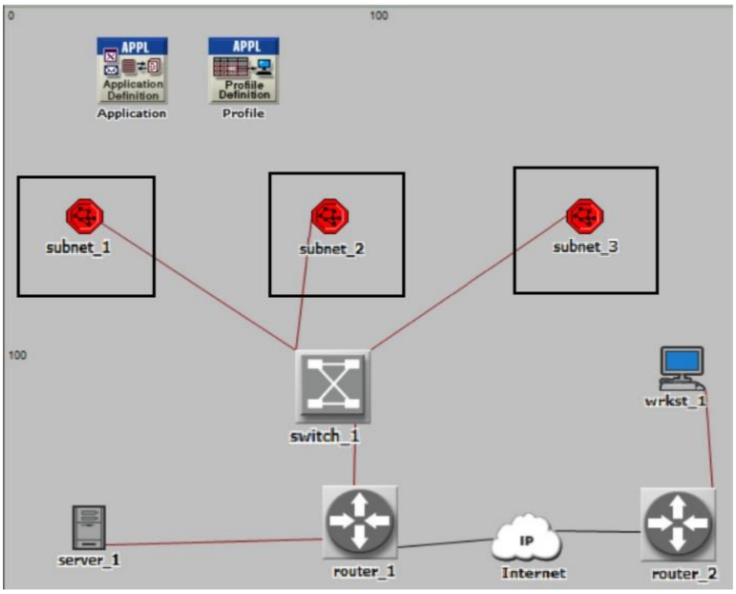


Figure 1. General modeling scheme

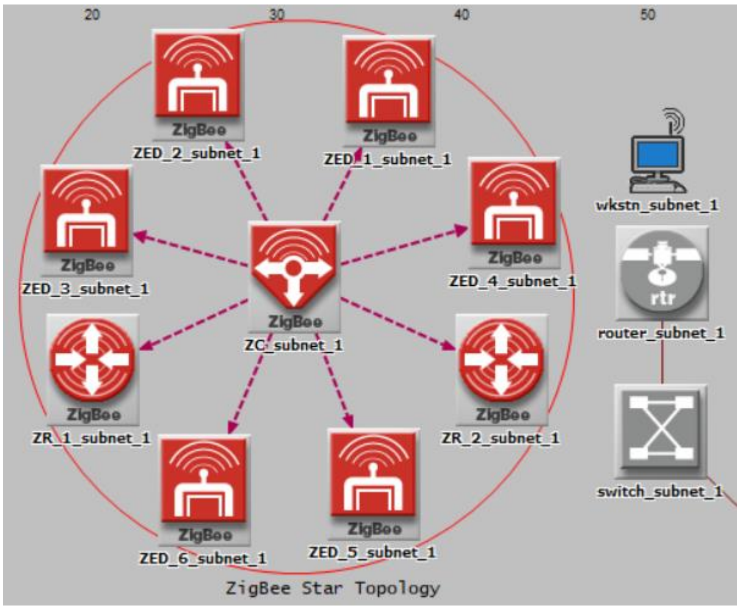


Figure 2. The first subnet of the Zigbee network organized in a star-shaped topology

2.2. The second subnet of the zigbee network with a tree-shaped topology

The second subnet (subnet_2), shown in Figure 3, features a Zigbee network with a tree topology, including a coordinator (ZC_subnet_2), routers (ZR_1, 2_subnet_2), and end devices (ZED_1 – 6_subnet_2). The coordinator connects to 2 end cevices and 2 routers, with each router linking to 2 additional end devices. The subnet also includes a switch (switch_subnet_2), a router (router_subnet_2), and a workstation (wrkst_subnet_2). The switch connects the subnet to the main network through the router, and the workstation connects to the Router wirelessly.

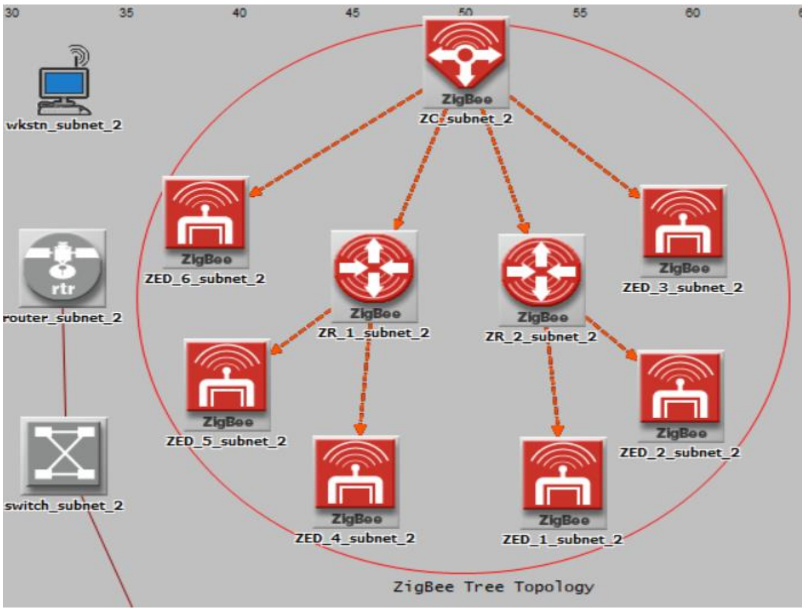


Figure 3. The second subnet of the Zigbee network with a tree-shaped topology

2.3. The third subnet of the Zigbee network with a mesh topology

The third subnet (subnet_3), shown in Figure 4, features a Zigbee network with a mesh topology, including a coordinator (ZC_subnet_3), routers (ZR_1 – ZR_3_subnet_3), and end devices (ZED_1 – ZED_7_subnet_3). The coordinator connects to 2 end devices and 3 interconnected routers, each linking to 5 end devices. The mesh topology allows end devices to connect to the nearest router if a node fails. The subnet also includes a switch (switch_subnet_3), a router (router_subnet_3), and a workstation (wrkst_subnet_3). It connects to the main network through the switch and router, with the workstation connecting wirelessly to the router.

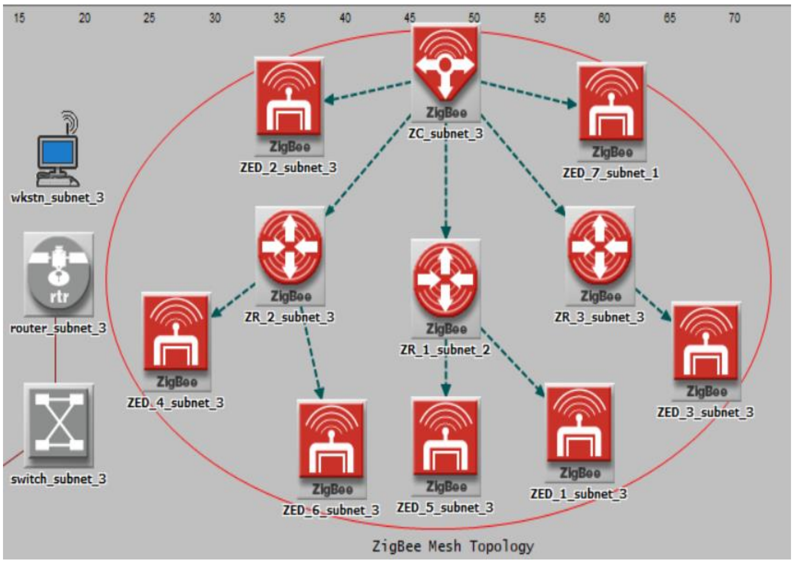
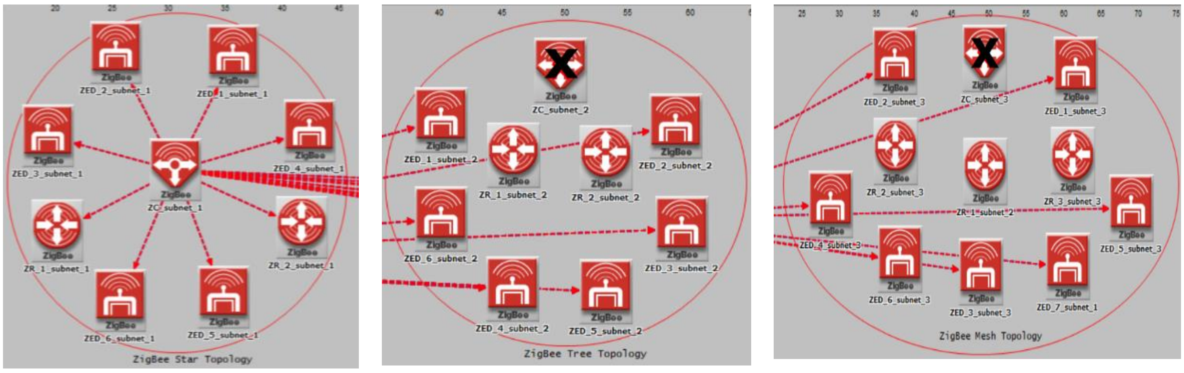


Figure 4. The third subnet of the Zigbee network with a mesh topology

2.4. Analysis of coordinator failures in various Zigbee network topologies

The study aims to analyze the resilience of Zigbee networks to coordinator failures across different topologies: star, tree, and mesh. Experiments were conducted to evaluate this resilience by simulating coordinator failures in three scenarios. In each scenario, different topologies were tested under device load conditions, with sequential disconnections of two out of three coordinators.

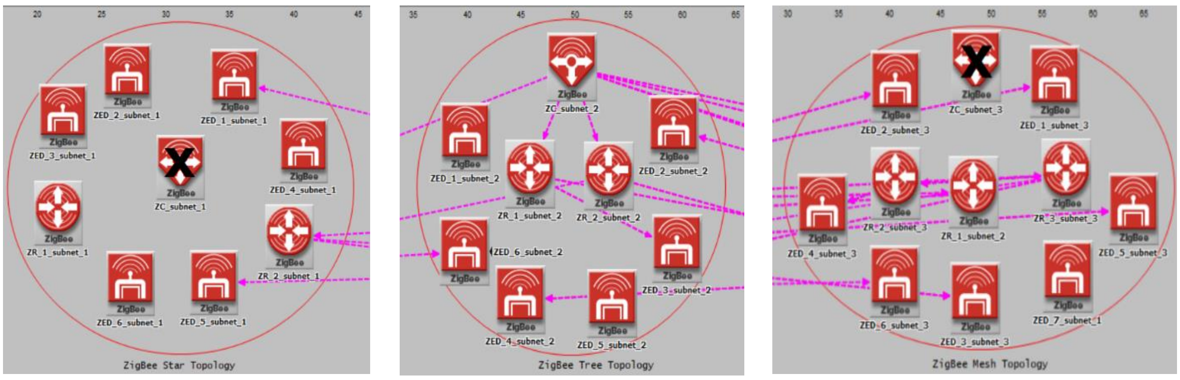
Figure 5 illustrates Zigbee networks with three different topologies: star, tree, and mesh. It demonstrates how the star topology manages additional load after coordinator failures in tree and mesh networks, marked with a black cross. Figure 5(a) shows the star topology, where the coordinator directly manages its devices and takes over devices from networks with failed coordinators in the tree and mesh topologies. Figure 5(b) depicts a tree topology network, where devices first attempt to reconnect through available parent nodes after a coordinator failure. If unsuccessful, they connect to the coordinator of the star topology. Figure 5(c) illustrates the mesh topology, where devices redistribute connections among the remaining nodes in the network after a coordinator failure. In the event of a complete failure, they connect to the coordinator of the star topology.



(a) (b) (c)

Figure 5. Scenario of connecting Zigbee network devices to a star topology: (a) Zigbee star topology, (b) Zigbee tree topology after coordinator failure, and (c) Zigbee mesh topology after coordinator failure

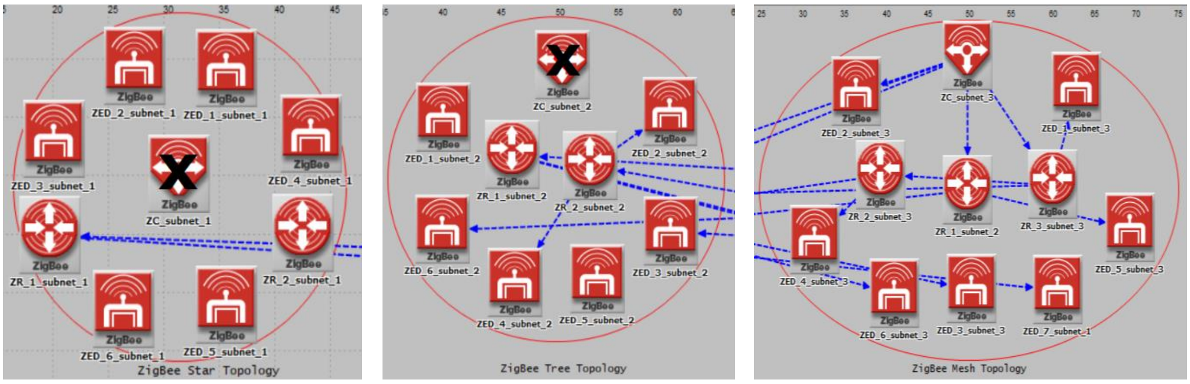
Figure 6 illustrates Zigbee networks with three different topologies: star, tree, and mesh. It shows how the tree topology accommodates additional load by accepting devices from networks with failed coordinators in the star and mesh topologies, marked with a black cross. Figure 6(a) shows a star topology network, where devices reconnect to the tree topology network in case of a coordinator failure. Figure 6(b) depicts a tree topology network, where, in addition to devices from this network, devices from star and mesh networks also connect. Figure 6(c) illustrates the mesh topology, where devices attempt to redistribute their connections within the network after a coordinator failure. In the case of a complete failure, they reconnect to the coordinator of the tree topology network.



(a) (b) (c)

Figure 6. Scenario of connecting Zigbee network devices to a tree topology: (a) Zigbee star topology after coordinator failure, (b) Zigbee tree topology, and (c) Zigbee mesh topology after coordinator failure

Figure 7 illustrates Zigbee networks with three different topologies: star, tree, and mesh. The figure shows how all devices reconnect to the mesh network after the failure of coordinators in the star and tree networks, marked with a black cross. Figure 7(a) shows a star topology network, where devices reconnect to the mesh network after the coordinator failure. Figure 7(b) depicts a tree topology network, where devices reconnect to the mesh network in the case of a coordinator failure. Figure 7(c) illustrates the mesh topology, where devices redistribute their connections within the network after a coordinator failure and connect to the remaining mesh network nodes.



(a) (b) (c)

Figure 7. Scenario of connecting Zigbee network devices to a mesh topology: (a) Zigbee star topology after coordinator failure, (b) Zigbee tree topology after coordinator failure, and (c) Zigbee mesh topology

3. RESULTS AND DISCUSSION

Zigbee is a communication protocol for low-power devices, widely used in wireless monitoring and control systems [39]. It utilizes the IEEE 802.15.4 standard at the MAC level for basic message processing, congestion control, and network management [40]. This includes CSMA for channel checking and mechanisms for retries and acknowledgments to ensure reliable communication. The Zigbee network layer builds on these basics for end-to-end communication [41]. The effectiveness of Zigbee technology and IEEE 802.15.4 can be assessed through various parameters [42].

The key parameters considered in this study are:

– Data traffic received – the total volume of traffic successfully received by the MAC layer from the physical layer, measured in bits per second, including retransmissions.
– Data traffic send – the traffic transmitted by all 802.15.4 devices in the network, measured in bits per second, including physical layer packet headers and MAC addresses. This statistic covers all traffic sent through the MAC layer using CSMA-CA, excluding management, control traffic, and acknowledgments.
– Throughput – the total number of bits per second transmitted from the 802.15.4 MAC to higher layers across all nodes in the WPAN network.
– Packet dropped (rejected data) – packets dropped by the layer due to lack of network connectivity.
– End-to-end delay – the total delay between the creation and receipt of a packet at the application level.
– Number of hops – the average number of hops that application traffic traverses within the PAN network.

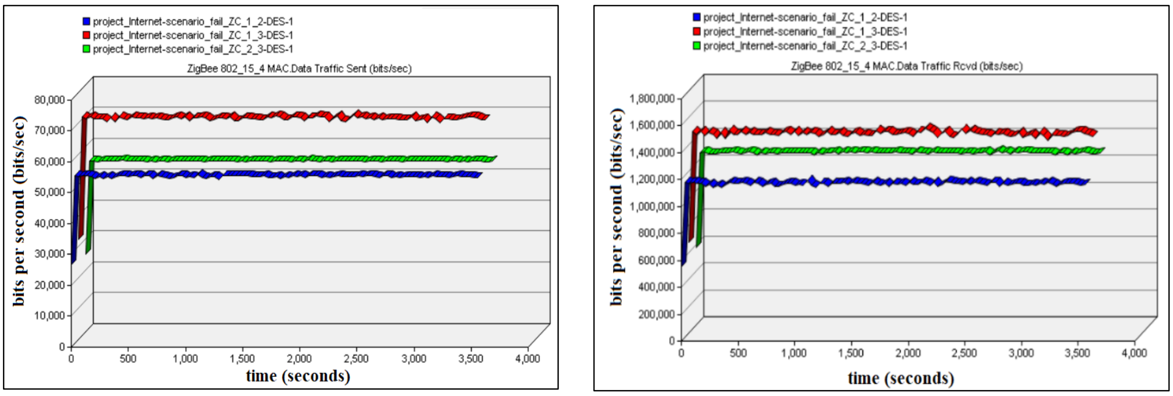
To obtain the research results, simulations were conducted using the following scenarios:

– scenario_fail_ZC_1_2 – a scenario where coordinators are disabled in Zigbee networks with “star” and “tree” topologies. All end devices in these networks connect to the mesh topology network.
– scenario_fail_ZC_1_3 – a scenario where coordinators are disabled in Zigbee networks with “star” and “mesh” topologies. All end devices in these networks connect to the tree topology network.
– scenario_fail_ZC_2_3 – a scenario where coordinators are disabled in Zigbee networks with “tree” and “mesh” topologies.

To obtain simulation results and run scenarios in real time, the OPNET Modeler environment was used. Each scenario was simulated for 1 hour. Next, we will review the results of these simulations.

3.1. Data traffic send and data traffic received

Figure 8 provides a comparative analysis of the performance of three Zigbee network topologies: tree, star, and mesh, in scenarios involving coordinator failures. Figure 8(a) illustrates the transmitted traffic for all three topologies. The tree topology (scenario_fail_ZC_1_3) achieves the highest average traffic speed of 71,202.25 bits per second, demonstrating superior performance (represented by the red line). The star topology (scenario_fail_ZC_2_3) shows the lowest traffic speed at 52,714.6 bits per second (depicted by the blue line), while the mesh topology (scenario_fail_ZC_1_2) falls in between, with an average speed of 55,082.25 bits per second (shown by the green line). Figure 8(b) presents the successful reception of total traffic. Here, the tree topology again leads with an average speed of 1,478,549.7 bits per second (represented by the red line). The star topology follows with 1,272,503.75 bits per second (depicted by the green line), and the mesh topology records the lowest average speed of 1,168,280.4 bits per second (shown by the blue line). These results indicate that the tree topology is the most efficient for both transmitting and receiving traffic, while the star and mesh topologies perform comparatively less efficiently.

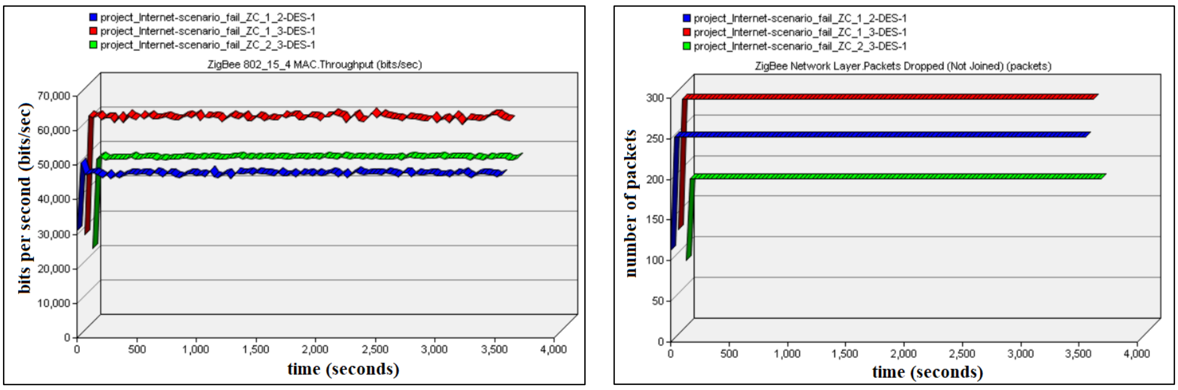


(a) (b)

Figure 8. Data traffic sent (a) data traffic received and (b) for scenarios scenario_fail_ZC_1_3, scenario_fail_ZC_2_3, and scenario_fail_ZC_1_2

3.2. Throughput and packet dropped

Figure 9 provides a comparative analysis of the performance of three Zigbee network topologies: tree, star, and mesh in terms of throughput and packet loss. Throughput is a key indicator of the data transfer rate, while packet loss reflects the reliability of the network in terms of successful data reception [43]. Figure 9(a) shows that the tree topology (represented by the red line) achieves the highest throughput, with 61,061 bits per second, indicating superior data transfer rates compared to the mesh topology (depicted by the blue line), which has 45,882.5 bits per second, and the star topology (shown by the green line), with 44,959.5 bits per second. Figure 9(b) illustrates packet loss for each topology, which represents the number of data packets that failed to be acknowledged by the receiving node. The tree topology (in red) experiences the highest packet loss at 286.4 packets, followed by the mesh topology (in blue) with 250.6 packets, while the star topology (in green) shows the lowest packet loss at 179 packets. This indicates that while the tree topology provides the best throughput, it is less reliable in terms of data transmission, as it suffers from higher packet loss compared to the other topologies.



(a) (b)

Figure 9. Throughput (a) packet dropped and (b) for scenarios scenario_fail_ZC_1_3, scenario_fail_ZC_2_3, and scenario_fail_ZC_1_2

3.3. End-to-end delay

End-to-end delay in a Zigbee network is the time from sending data to its receipt at the destination [44]. Figure 10 shows that the star topology (in green) has the lowest average delay at 0.024 s, followed by the mesh topology (in blue) at 0.026 s, and the tree topology (in red) with the highest delay of 0.035 s. The star topology excels in both throughput and minimal delay, making it ideal for high-speed and low-delay requirements, while the tree topology has the highest packet loss and delay, making it less suitable.

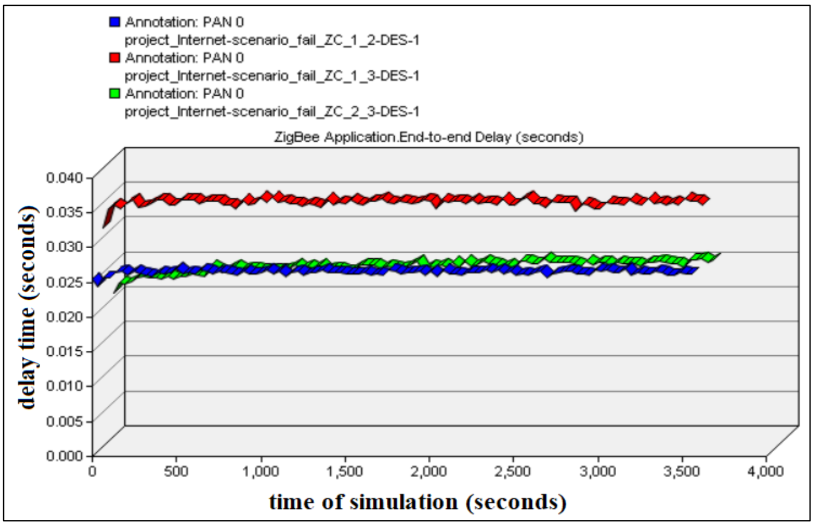


Figure 10. End-to-end delay for scenarios scenario_fail_ZC_1_3, scenario_fail_ZC_2_3, and scenario_fail_ZC_1_2

3.4. Number of Hops

The number of hops in a Zigbee network refers to the intermediate nodes a data packet passes through to reach its destination [45]. This varies with network topology, routing, and node distance [46]. In a star topology (represented by the green line), data typically travels through 1 hop, but Figure 11 shows it is 2 due to an additional router. The tree topology (depicted by the red line) has a maximum of 3 hops, reflecting the network's depth in the simulation. In a mesh topology (illustrated by the blue line), data can pass through multiple nodes, initially showing more than 3 hops before stabilizing at an average of 2.2 hops.

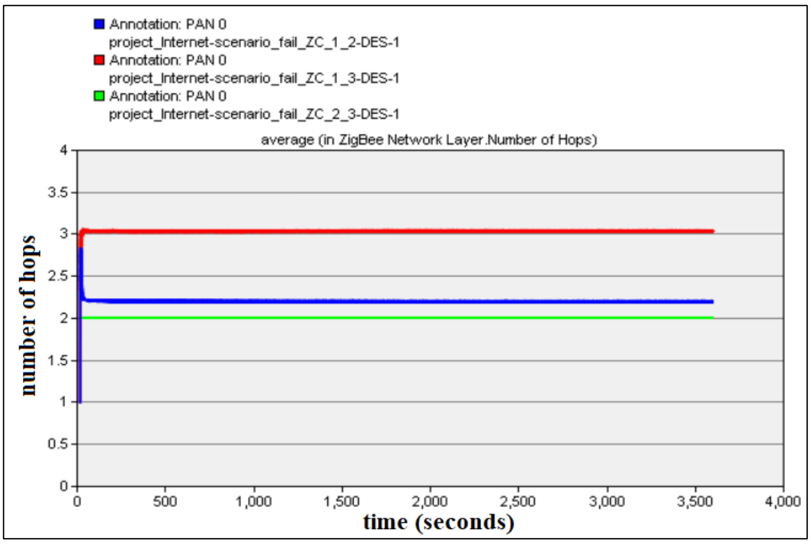


Figure 11. Number of Hops for scenarios scenario_fail_ZC_1_3, scenario_fail_ZC_2_3, and scenario_fail_ZC_1_2

If data passes through multiple hops, it can increase end-to-end delay and the likelihood of data loss. Fewer hops are generally preferable, as this indicates lower delay and reduced energy consumption, which is important for Zigbee networks. However, complex networks may require multiple hops.

4. CONCLUSION

This paper presents an analysis of coordinator failures in Zigbee networks with various topologies using the OPNET Modeler software. The evolution of Zigbee technology offers numerous advantages but also presents challenges in designing fault-tolerant systems. To address these issues, simulations were conducted to model coordinator failures in star, tree, and mesh topologies sequentially. The analysis revealed that the tree topology exhibits the highest traffic throughput and capacity but also experiences the greatest packet loss and has the highest end-to-end delay. The star topology shows favorable performance in terms of traffic speed and minimal end-to-end delay, making it the preferred choice for scenarios requiring high data transfer rates and minimal latency. However, it has lower throughput and average speed compared to the tree topology. The mesh topology, while having the lowest average traffic speed and throughput among the topologies studied, demonstrates superior reliability with fewer packet losses compared to the tree topology.

These findings highlight the unique characteristics and trade-offs of different Zigbee network topologies and their relevance for various applications. The results confirm that the star topology is more suitable for applications prioritizing low latency and high-speed data transfer, while the tree topology is preferable for scenarios requiring high throughput despite delays and packet losses. The mesh topology is ideal for applications demanding high reliability and scalability.

Future research could focus on exploring advanced mechanisms to mitigate coordinator failures and improve network performance across topologies. This study underscores the importance of designing Zigbee networks that address failures and data losses, contributing to the development of reliable and efficient IoT systems in the context of modern technological advancements.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Daulet Naubetov	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Mubarak Yakubova	✓	✓		✓	✓	✓		✓			✓	✓	✓	✓
Bahodir Yakubov	✓			✓	✓	✓	✓	✓	✓		✓			✓
Nurzhigit Smailov	✓			✓	✓	✓	✓			✓			✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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