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Fixed and Mobile Sensors: ZigBee-Based WSN Topologies – A Comparison

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Abstract: ZigBee-based WSNs are widely used in applications requiring low power, low data rate communication, such as smart homes, industrial automation, and environmental monitoring. The performance of these networks is heavily influenced by their topology, with star, mesh, and tree being the most common configurations. This paper aims to provide a comparison of these three ZigBee-based WSN topologies, focusing on key performance metrics such as throughput, data traffic sent, data traffic received and delay. Through detailed simulations and empirical evaluations, we analyze how each topology performs under varying network conditions and scales. Our findings reveal that mesh topologies excel in terms of throughput and reliability due to their multiple routing paths, making them suitable for large and dynamic networks; meanwhile, tree topologies are efficient in data aggregation but have higher delays as the network size increases, and finally, star topologies are energy-efficient but limited in scalability and data traffic handling due to their reliance on a single central node. The study also reveals that the choice of topology significantly impacts data traffic patterns, with mesh networks handling higher volumes of sent and received data more effectively. A second simulation was conducted by reassigning sixteen out of the twenty sensors from fixed to mobile mode, and then a number of WSN topologies were investigated based on key performance metrics of the WSNs. These insights provide a foundation for selecting the appropriate ZigBee-based WSN topology based on specific application requirements and performance considerations.
Keywords: WSN, ZigBee, RIVERBED, OPNET, mobile sensors.

I. INTRODUCTION

A Wireless Sensor Network (WSN) is composed of sensor nodes that collect data from their surroundings with certain capabilities and then communicate that data to a base station via other sensors after being processed [1]. The importance of micro electromechanical systems has grown in light of recent advances in wireless communication, such as improved processor quality, memory capacity, and reduced power consumption [2]. Networks which rely on small-sized devices are relatively inexpensive, and inter-sensor communication has become much easier with self-organising devices. A common example is where some sensors function as primary sensors, processing raw data from neighboring sensors and temporarily storing it in their internal storage for use at predetermined times. Other sensors pick up analogue information from their surroundings and relay it to one or more nearby sensors. WSNs are applicable practically anyplace, including hospitals, homes, business, the military, and the physical environment. Additionally, they can be used in hazardous areas as well as inaccessible areas such high mountains [3-5].

In this paper, a simulator was used to analyze the performance of wireless network topologies utilizing the IEEE 802.15.4 ZigBee version. Outcomes can be used to provide solutions to the challenges that arise when building a real-world system adaptations. Researchers use many simulator technologies, including TOSSIM, J-Sim, OMNET++, QUALNET, Network Simulator (NS-2), EmStar, GLOMOSIM, JIST/SWANS, and SensorSim. However, because it offers a thorough performance analysis of ZigBee based networks in terms of quality of service (QoS) parameters, the RIVERBED (OPNET) Modeller Academic Edition 17.5 simulation software was used in this study. Two different network simulations were conducted using this application. In the first simulation, three ZigBee topologies—mesh, tree, and star—were evaluated based on QoS parameters such as throughput, data sent and received traffic and delay. In the second simulation, sixteen out of the total of twenty fixed sensors were converted to mobile mode, and the key performance metrics of the three WSN topologies were subsequently evaluated. The results are significant in that they provide insights into the performance trade-offs between different Zigbee topologies, which can then be applied to the design and optimization of real-world sensor networks.

What are WSNs': WSNs are distributed network designs that allow several sensors to communicate wirelessly with each other. Wireless communication uses light or electromagnetic waves to transport data from a transmitter to a receiver without the use of a cable. Sensors, also known as detectors or probes, are detection components of electronic systems. Sensors can detect a variety of physical units, including area, volume, mass airflow, length, temperature, voltage, strength, heat transfer, flux density, electric current, resistance, magnetic torque, condensation, content, and oxidation/reduction.

Components of Zigbee Sensors: A ZigBee sensor's main components include a microcontroller, receiver-transmitter, memory, power supply, and one or more extra elements.

Types of Sensor Nodes: Today, there are several types of sensor nodes available on the market that may be used to build WSNs, including eMote, mica2, micaZ, TelosA, Sensenode, TelosB, and IMote2 [6].

WSNs employ the Open Systems Interconnection layer structure, which has five layers: physical, data link, network, transport, and application. More specifically, the network layer sends data packets through several tiers using various routing techniques [7]. Among the different Zigbee-based topologies supported by WSNs, the most frequently used ones are tree, star, and mesh [8]. ZigBee distinguishes itself from other communication technologies such as WiFi, Bluetooth, and WiMAX because of its tiny data transmission size and low power consumption [9]. Furthermore, ZigBee outperforms competing wireless sensor communication standards such as ISA100.11a (a wireless communication standard designed for industrial automation), 6LoWPAN (a protocol that allows IPv6 packets to be sent over low-power wireless networks), and Wireless Hart because It is self-organised and provides scalability and changeable bandwidth [10].

There are several standards of wireless communication used in industrial applications. For example, IEEE 802.11x is a standardized communication protocol more commonly known as WiFi. It supports data transfer speeds ranging from 1Mbps to 50Mbps. A conventional antenna can transport data over distances of up to 100 meters; however, a high-power antenna can transmit data over considerably greater distances. In contrast to WiFi, Bluetooth [9] is a more widely used personal area network standard designed for short range data transfer between devices such PCs and cell phones [11].

One of the most valuable technologies in the wireless sensor network industry today is ZigBee. The IEEE 802.15.4 standard, which was published by the IEEE in 2003 [12-13], serves as the foundation for the new wireless communication standard ZigBee [14]. The robust MAC (Medium Access Control) and radio (physical) layers that ZigBee uses are defined by the IEEE 802.15.4 standard. It supports mesh, tree, and star topologies and makes use of the common CSMA/CA media access protocol. Three license-free frequency channels are specified by IEEE 802.15.4. The first band, often known as the ISM band, has 16 channels and operates at 2.4 GHz. The second band, which operates between 902 and 928 MHz, includes ten channels. The other has a single channel and works in the 868-870 MHz frequency range. These frequency bands have capabilities of 250 kbps, 40 kbps, and 20 kbps, respectively [13, 15-16]. ZigBee is concerned with the transmission of data between devices in personal area networks, as well as network measurements, detection, monitoring, and application testing. It is not, however, suitable for large file transfers, such as WiFi or Bluetooth. ZigBee varies from WiFi and Bluetooth in that it communicates with devices over basic networks with lower power consumption and cost, as well as providing communication with less bandwidth demands. The battery life of Bluetooth is 1-7 days, whereas ZigBee's is 100-1000 days. Furthermore, whereas WiFi is well-known for its speed and versatility, ZigBee's popularity can be linked to its longevity, low cost, and power-consumption [13,17].

Smart Home Systems use the IEEE 802.15.4 ZigBee based WSN standard to manage lights, HVAC (ventilation, heating and air-conditioning), security systems, and appliances [18-20].

Industrial Processes: In addition, WSNs are used for monitoring and managing industrial processes, such as equipment condition monitoring, energy management, and safety systems [21].

Healthcare: ZigBee is used by wearable technology and remote patient monitoring systems to collect and transmit health data, including blood pressure, glucose levels, and heart rate [22-23].

Smart Cities and Agriculture: Furthermore, they are also used in smart cities and agriculture to monitor environmental factors like temperature, humidity, air quality, and soil wetness. For instance, crop management and irrigation can be optimized with precision agriculture systems [24].

Energy Management: Smart grids and household energy management systems, including demand response systems and smart meters, use ZigBee WSNs to track and regulate energy consumption [25-26].

Logidtics and Retail: WSNs are used in logistics and the retail industry to track assets, manage inventory, and streamline the supply chain. For instance, warehouses' real-time inventory tracking [27-28].

Building Management: ZigBee is used in building management systems to regulate lighting, detect occupancy, and increase energy efficiency, such as smart office systems that adjust lighting and temperature based on occupancy [29].

Disaster Management: ZigBee-based WSNs are also used in disaster-prone locations to provide early warning and emergency communication systems, such as earthquake or flood monitoring [4, 30].

Transportation: ZigBee is used in intelligent transportation systems to monitor traffic, track vehicles, and manage parking spaces, e.g., smart parking systems that direct cars to available parking spots [31].

II. LITERATURE REVIEW

Numerous recent studies have focused on the performance of Zigbee-based WSNs [32]. Several of them examined factors such as throughput, delay, data traffic and load in these networks, with ZigBee-based, WSN topologies being of particular interest.

Several research publications have focused on comparing different routing methods. For instance, one study compared tree routing to mesh routing in WSNs and discovered that tree routing performed better in terms of throughput, delay, traffic received, and MAC load [33]. Increasing the number of sensors in a ZigBee based WSN influences both delay and throughput; this is investigated, analyzed, and assessed using the RIVERBED simulation tool, as described in [34]. Using the OPNET module, throughput and delay for single and many coordinators were analysed in tree, star, and mesh ZigBee WSNs [35-37]. For four distinct system scenarios, a simulator application illustrates the consequences of data traffic scenarios, which encompass both sent and received data traffic [38-40]. Nguyen et al. conducted an assessment of modern power monitoring, control, and management systems, identifying co-channel interference and noise as major issues of ZigBee based WSNs [41]. According to articles in [42] and [43], having more routers in a WSN increases the traffic burden on the Personal Area Network. The primary issue with sensors in WSNs is that when packets are transferred from one sensor to another, throughput suffers due to high traffic and packet collisions [44]. The network performance from inside to outside was determined by testing the received signal strength indicator characteristics (distance, throughput, and delay) for various ZigBee communication topologies [45]. This study is significant in that it highlights the impact of routing methods on network performance, which is critical for the purposes of optimizing WSN efficiency.

III. DESIGN STRATEGY

In this study, a WSN system was created using several ZigBee topologies with the Riverbed Modeller Academic Edition 17.5 as the simulation tool. This program allows for the creation of strong network connections and diverse system models, enabling detailed analysis of ZigBee standard performance in various WSN topologies. To analyze the performance of different WSN topologies using the ZigBee standard, three distinct scenarios were considered: mesh, tree, and star topologies. These scenarios were compared based on factors such as delay, throughput, traffic received, and traffic sent. In each of the three topologies, the ZigBee networks use one coordinator and twenty sensors. The simulation time was set at one hour. A destination was selected at random, and the size of the data packets sent was set at 1 kbytes.

In the first simulation, all twenty sensors are fixed. The second simulation features four fixed sensors, while the remaining sixteen sensors are mobile. In the mesh and tree topologies, the four fixed sensors are immediately connected to the coordinator before being connected to the mobile sixteen sensors, whereas in the star topology, the four fixed sensors are chosen randomly.

Fig. 1, demonstrates a mesh WSN topology; Fig. 2, a tree topology, and Fig. 3, a star WSN topology.

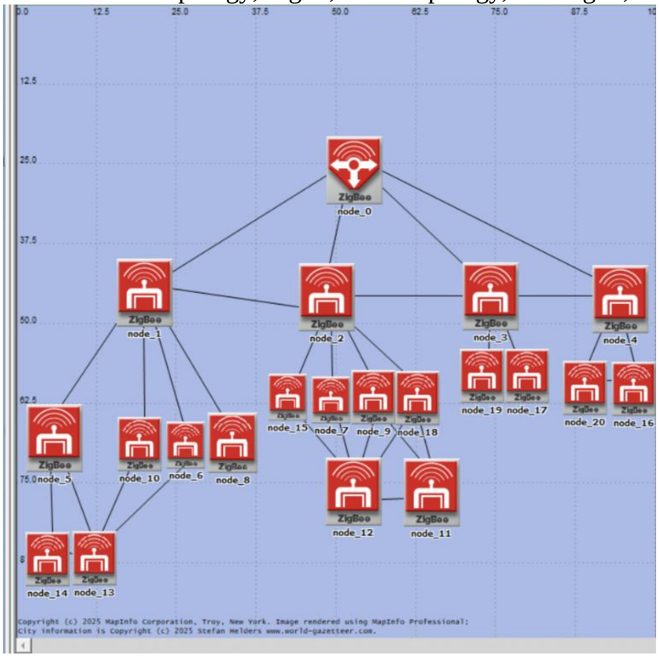

Fig. 1A Mesh Network

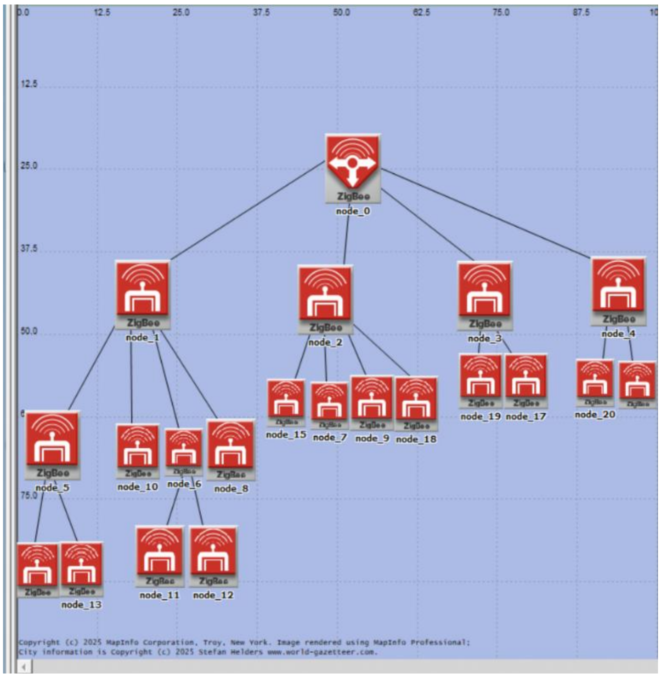

Fig. 2A Tree Topology

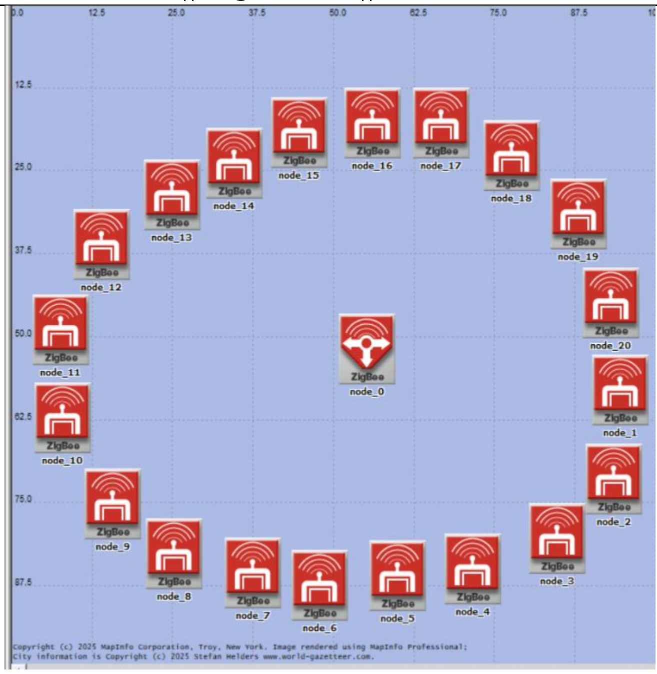

Fig. 3A star topology

IV. OUTCOMES

A. First Simulation (Fixed Sensors)

Fig. 4 shows the average throughput for the three WSN topologies: mesh, tree and star. At the steady state, the throughput is best in the star topology while it is worst in the tree topology. It is clear that throughput increases when all the sensors are connected directly to the coordinator. At the end of the simulation time (one whole hour), the values of the throughput for the three topologies are 35.55 kbps (star), 23.2 kbps (mesh), and 20.8 kbps (tree).

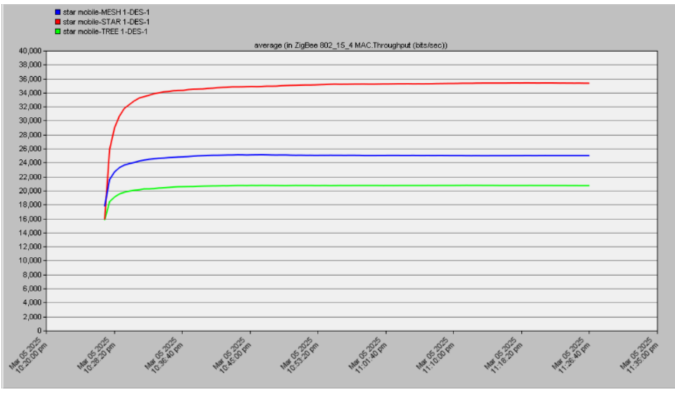

Fig. 4: Throughput for the three WSN topologies in the first simulation

Fig. 5 depicts the average data traffic sent (DTS) for the three WSN topologies being tested, namely: mesh, tree, and star. The tree topology has the highest steady-state DTS, while the star topology has the lowest. At the end of the simulation time (an hour), the DTS values for the three topologies are 40.1 kbps (mesh), 38.6 kbps (tree), and 4.05 kbps (star).

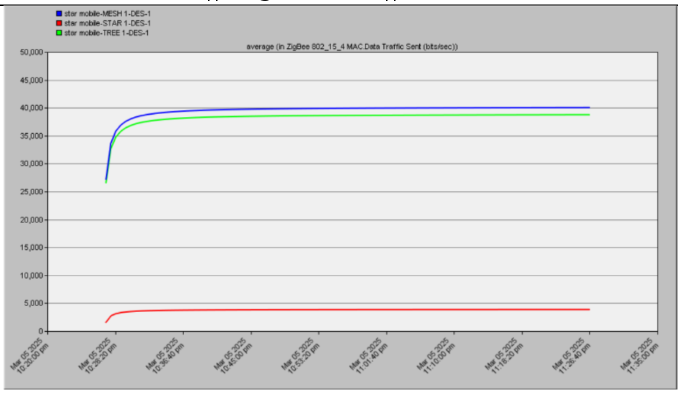

Fig. 5: DTS for the three WSN topologies in the first simulation

The average Data Traffic Received (DTR) for the three WSN topologies under consideration is displayed in Fig. 6. The star topology has the highest DTR at steady state, while the tree topology has the lowest. As regards the star topology, it is clear that DTR increases with the number of sensors connected directly to the coordinator. At the end of the hour long simulation, the DTR values for the three topologies are 39.9 kbps for star, 28.1 kbps for mesh, and 23.5 kbps for tree.

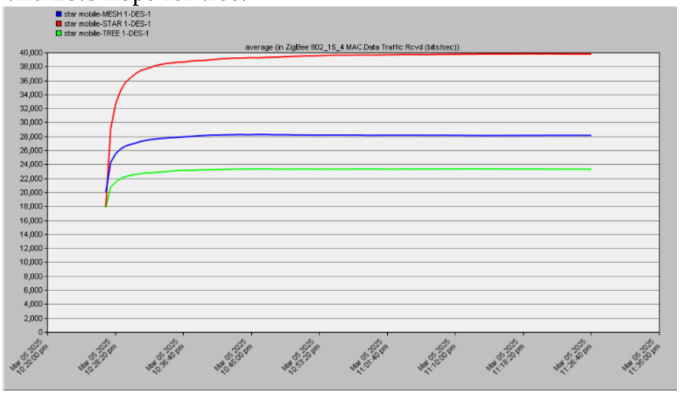

Fig. 6: DTR for the three WSN topologies in the first simulation

Fig. 7 shows the average delay for the three network topologies being investigated. It is evident from the results that the delay is almost identical in the hour-long simulation for the mesh and tree topologies with values of 0.0125 sec and 0.0216 respectively. However, the star topology shows a slightly lower delay of 0.0185. Accordingly, the WSN topology has minimal effect on the delay for both mesh and tree.

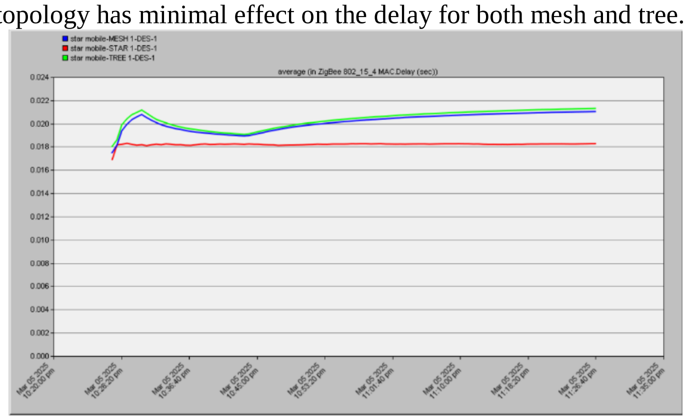

Fig. 7: Delay for the three WSN topologies in the first simulation

B. Second Simulation (Mobile Sensors)

In the second simulation, the sixteen sensors (see Fig.s 1, 2, and 3) are reassigned from fixed to mobile status. The average throughput, DTS, DTR and delay are displayed in Fig.s 8, 9, 10 and 11 respectively. Once again, the simulation time was one full hour.

From Fig. 8, it can be seen that the average throughput for the star topology is the greatest, while the tree topology has the lowest value. At the end of the simulation time, the values of the throughput for the three topologies are 35.2 kbps (star), 25.15 kbps (mesh), and 20.9 kbps (tree). Comparing these values to Fig. 4 (throughput of the fixed sensors), we observe that the throughputs are nearly comparable. As a result, we can conclude that throughput is unaffected by sensor mobility in all three WSN topologies.

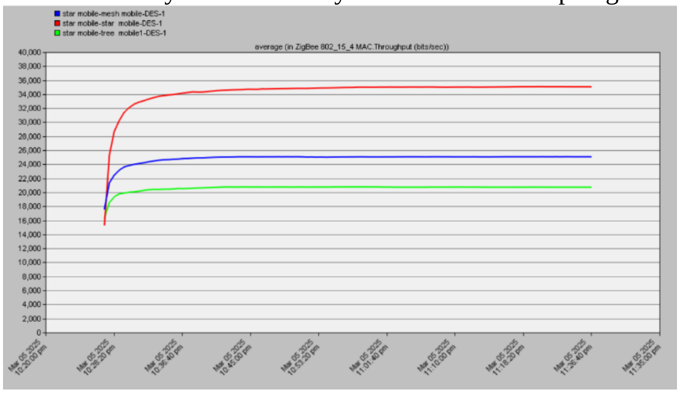

Fig. 8: Throughput for the second WSN simulation

Fig. 9 shows that the mesh topology has the highest average DTS (data traffic sent) while the star topology has the lowest value. At the end of the simulation time, the values of the DTS for the three topologies are 40.16 kbps (mesh), 38.6 kbps (tree), and 28.5 kbps (star). When comparing these results with those in Fig. 5 (DTS for the fixed sensors), we can see that the DTS is almost identical for mesh and tree topologies. Furthermore, the DTS has increased dramatically in star topology (about 24 kbits/sec in the steady state). In summary, while the mesh and tree topologies show consistent DTS values regardless of sensor mobility, the star topology demonstrates a significant increase in DTS, making it a more suitable choice for mobile sensor networks.

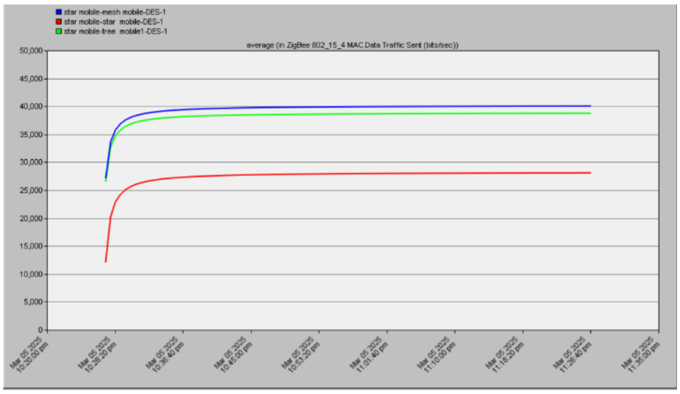

Fig. 9: DTS for the second WSN simulation

Fig. 10 shows that the star topology has the highest average DTR (data traffic received) value while the tree topology has the lowest value. At the end of the simulation time, the DTR values for the three topologies are 39.78 kbps (star), 28.2 kbps (mesh), and 21.78 kbps (tree). When comparing these results with those in Fig. 6 (DTR for fixed sensors), we can deduce that the DTR is almost identical for all the three topologies, indicating that sensor mobility has no significant effect on the DTR.

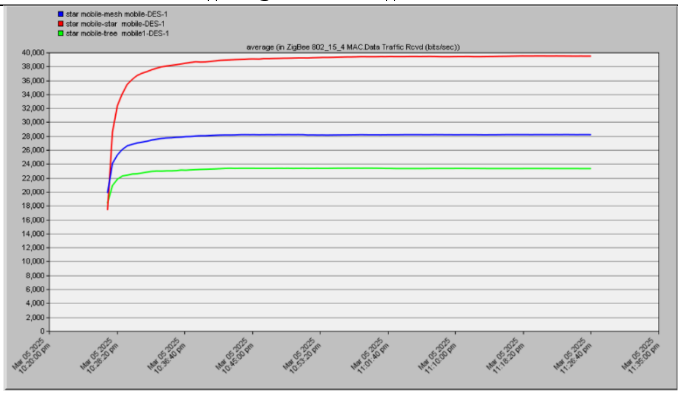

Fig. 10: DTR for the second WSN simulation

Fig. 11 shows that the star topology has the highest average delay while the tree topology has the lowest value. At the end of the simulation time, the values of the delay for the three topologies are 0.02187 sec (star), 0.02126 sec (mesh), and 0.021 sec (tree). When comparing these values with those in Fig. 6 (delay for fixed sensors), we can deduce that the delay is almost identical for mesh and tree topologies, while the delay has increased in star topology. This suggests that sensor mobility significantly impacts the star topology but not the mesh and tree topologies.

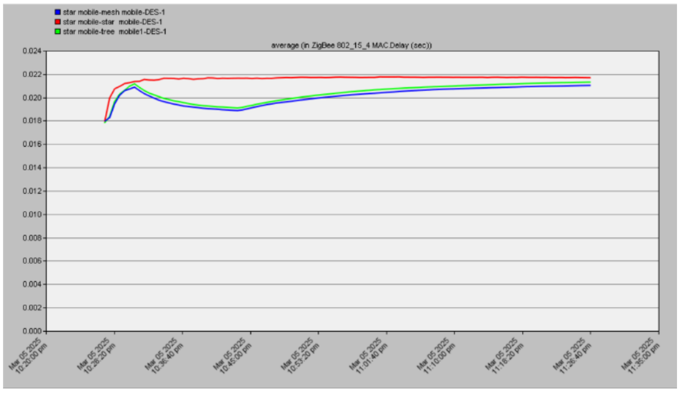

Fig. 11: Delay for the second WSN simulation

V. OUTCOMES SUMMARY

Table I displays the findings at the end of the simulation (one full hour) from Fig. 4 to Fig. 11.

Table I
Summary of Outcomes of the Two Simulations

Parameter Type	**1st simulation**			**2nd simulation**		
	Mesh	**Tree**	**Star**	**Mesh**	**Tree**	**Star**
Throughput (kbps)	23.2	20.8	35.55	25.15	20.9	35.2
DTS (kbps)	40.1	38.6	4.05	40.16	38.6	28.5
DTR (kbps)	28.1	23.5	39.9	28.2	21.78	39.78
Delay (sec)	0.0215	0.0216	0.0185	0.02126	0.021	0.02187

VI. CONCLUSION

This paper used the RIVERBED Academic Edition V17.5 simulation program to analyze the performance of three specific WSN topologies based on the IEEE 802.15.4 ZigBee standard.

Two simulations were conducted:

- The first simulation was conducted to evaluate the WSN topologies from the throughput (throughput refers to the rate at which data is successfully transmitted over the network), Data Traffic Sent (DTS), Data Traffic Received (DTR) and delay point of view; and
- The second simulation was conducted to evaluate the impact of mobile sensors on the three WSN topologies.

The findings for our chosen WSN topologies based on key performance metrics are as follows:-

- **Star Topology (red curve):** Despite connection issues over long distances, star is most suitable for throughput, DTR, and delay. Throughput and DTR remained stable, while delay and DTS improved with mobile sensors.
- **Tree Topology (green curve):** The throughput and DTR have the lowest performance, while delay and DTS are identical in both tree and mesh topologies. When applied in the mobile sensors setting, all the key performance metrics: throughput, DTS, DTR and delay, had no impact on network performance.
- **Mesh Topology (blue curve):** Its performance is between star and tree from the throughput and DTR perspective while mesh performance is identical to tree topology and better than star from the DTS and delay point of view. For mobile sensors, all the key performance metrics: throughput, DTS, DTR, and delay had no impact on the performance of the WSN.

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