International Journal on Computational Engineering

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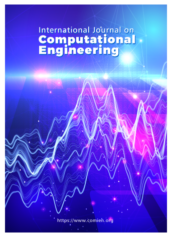

A Study of WSN Topologies for IEEE 802.15.4 ZigBee Standard

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***Abstract*— Network systems made up of hundreds or even thousands of sensor nodes connected to one another wirelessly to make the WSNs. Sensor nodes perform sophisticated tasks like detecting, gathering, calculating, and routing surrounding data based on predetermined criteria by dispersing into various locations at random or in accordance with a predetermined plan. The IEEE 802.15.4/ ZigBee wireless communication standard was used in this study. It has several advantages over other wireless communication standards, including low power consumption and battery usage. It also offers high performance for short-range sensors and allows for the use of three different band frequencies globally. Furthermore, the RIVERBED Academic Edition 17.5 simulator was employed, which possesses the ability to produce accurate outcomes and conduct analysis to discern the genuine behavior of the actual system. Through the use of this simulator application, the total delay, throughput, mac load, data traffic received, and data traffic sent parameters of the star, tree, and mesh topologies offered by the ZigBee standard were compared. The goal of this paper is to know the optimum topology of the three main topologies star, tree, and mesh. It is discovered that while the star topology outperforms the tree and mesh topologies in terms of data receiving rate, it excels in productivity and data transmission rate. When compared to other scenarios, the mesh topology offers the highest data reception rate. The tree architecture is appropriate for networks with few sensor nodes because it can send data to its destination quickly and without overloading the central node.**

***Keywords*— Wireless sensor networks; ZigBee; RIVERBED (OPNET); wireless network topologies.**

Manuscript received 19 May 2024; revised 6 Jun. 2024; accepted 20 Aug. 2024. Date of publication 30 Sep. 2024.

I. Introduction

A wireless sensor network (WSN) is a network structure made up of sensor nodes that, using their specified abilities, gather data from their surroundings and, once processed, send it to a base station via other sensor nodes [1]. Micro electromechanical systems have become more important due to recent advancements in wireless communication and advancements in areas like processor quality, memory capacity, and low power consumption [2]. The cost of installing sensor networks with small-sized devices has decreased, and sensors can now communicate with one another more easily because of self-organized devices. In this context, sensors play a variety of tasks. Some are thought of as primary sensors, processing raw data from other sensors and temporarily storing it in internal storage for usage at certain periods. Other sensors send analog data they pick up from their surroundings to one or more other sensors. Almost anything that a WSN is required can use one: homes, workplaces, industries, outdoor spaces, military bases, hospitals, etc. They can also be utilized in dangerous regions and high mountains, among other inaccessible locations [3].

In this paper, a simulator utilizing the IEEE 802.15.4/ ZigBee standard carried out a performance analysis of wireless network topologies. The outcomes can suggest a fix for the issues that come up when creating a genuine system adaption. A variety of simulator programs are used by researchers, including Network Simulator (NS-2), OMNET++, J-Sim, TOSSIM, GLOMOSIM and QUALNET, JIST/ SWANS, SensorSim, and EmStar. The simulation program RIVERBED Modeler Academic Edition 17.5 was utilized in this paper, nevertheless, since it provides a thorough performance analysis of ZigBee networks in relation to quality service criteria. Four distinct scenarios were created for ZigBee networks utilizing RIVERBED. In terms of quality service metrics including total delay, throughput, Mac load, data traffic received, and data traffic sent using three ZigBee topologies (star, tree, and mesh) that compared.

II. MATERIAL AND METHOD

A. Wireless Sensor Networks

Numerous sensors connect wirelessly to form distributed network topologies called wireless sensor networks (WSNs), which allow the sensors to communicate with one another. Transmission via light or electromagnetic waves between a transmitter and a receiver without the need for a cable connection is known as wireless communication. In electronic applications, sensors are the parts that do detection. Numerous physical units, including length, area, volume, mass air flow, flux density, magnetic torque, resistance, temperature, heat transfer, strength, voltage, electric current, condensation, content, and oxidation/ reduction, can be detected by sensors. A sensor node's primary parts include the memory, receiver-transmitter, power supply, microcontroller, and one or more other components. To create WSNs, a range of sensor node types are available on the market, including Sensenode, eMote, micaZ, mica2, TelosA, TelosB, and IMote2 [4].

Similar to the Open Systems Interconnection structure, WSNs have a layer with a physical layer, data link layer, network layer, transport layer, and application layer. Through these layers, data packages are transmitted in the network layer using various routing methods [5]. The most common ZigBee-based sensor network topologies are star, mesh and tree, even though wireless networks often support several topologies [6]. When it comes to features like low power consumption and small-sized data transfer, ZigBee stands out from other communication technologies like Wi-Fi, Bluetooth, and WiMAX [7].

WSNs are generally considered to be a significant area of research, and numerous researchers have attempted to leverage this knowledge to develop a variety of systems involving tracking, control, or monitoring. Examples of these systems include smart buildings [8], smart grids, IoT [9], [10], localization [11], smart alarms, computer networks [12], track cycling [13], energy monitoring [14], [15], management [16], health care [17], [18], [19], solar cell [20], and agriculture [21], among many other applications.

B. IEEE 802.15.4 Zigbee Based WSN

Different wireless communication protocols are in use in industrial settings. Among these is IEEE 802.11x standard, an 802.11-based standard communication technology that is commonly referred to as Wi-Fi. Data transfer rates ranging from 1Mbps to 50Mbps are possible with it. A conventional antenna can transmit data over lengths of up to 100 meters; however, a high-power antenna can transmit data over considerably longer distances. Bluetooth is a personal area network protocol that is stronger than IEEE 802.11x. It was created to be used in applications involving short-range data transfer between mobile and computing devices [22]. In the field of WSNs, one of the most helpful technologies available today is ZigBee. ZigBee is a new wireless communication standard that is built upon the IEEE 802.15.4 standard, which was released by the IEEE in 2003 [23]. Physical layer (powerful radio) and medium access control (MAC) layer, as specified by IEEE 802.15.4, are the foundation of ZigBee. It supports mesh, star, and tree topologies and makes use of the common CSMA/ CA media access method. Three frequency bands are defined as license-free by IEEE 802.15.4. The first band contains 16 channels and operates in the 2.4 GHz frequency range. Ten channels in the 902-928 MHz frequency spectrum are used by the second band. The other has a single channel and operates in the 868–870 MHz frequency range. These frequency bands have respective capabilities of 250kbps, 40kbps, and 20kbps [24]. ZigBee handles network measurements, detection, monitoring, and application verification in addition to the transport of specific amounts of data between devices utilized in personal area networks. However, unlike Wi-Fi or Bluetooth, it is not appropriate for large size file transfers. When it comes to the method of communication between many devices, ZigBee differs from Wi-Fi and Bluetooth. It operates via straightforward networks that use less power and money, and it also offers communication with reduced bandwidth requirements. A feature comparison between ZigBee and a few other wireless technologies is displayed in Table 1 [25]. As can be seen from the table, ZigBee has a battery life of 100–1000 days compared to Bluetooth's 1-7 day duration. Additionally, it may be claimed that ZigBee's success is based on cost, power consumption, and durability, whereas Wi-Fi's typical success factors are speed and adaptability.

TABLE I
ZIGBEE AND OTHER WIRELESS TECHNOLOGY FEATURES COMPARISON

Features	GPRS/ GSM	Wi-Fi	Bluetooth	ZigBee
Focusing area	Wide range of audio and data	Web, email and video	Instead of cable	Monitoring and control
System resource	16 Mb+	1 Mb+	250 kb+	4-32 kb
Battery life (day)	1-7	0.5-5	1-7	100-1000+
Size of Network	16 Mb+	32 Mb	7 Mb	~Infinite (2^{64})
Network data width in (kbps)	64-128+	11000-54000	720	100-1000+
Range in meters	1000+	1-100	1-10+	1-100+
Success area	Accessibility, quality	Speed, flexibility	Cost, convenience	Durability, cost, power consumption

Three types of nodes are supported by the ZigBee protocol: coordinator (ZC), router (ZR), and end device (sensor, ZS) [26]. As shown in Fig. 1, there are three fundamental topologies used by ZigBee technology: star, tree, and mesh. Fig. 1a depicts the structure of the star topology, which features centralized management and communication. The center node forms the basis of its architecture. ZSs communicate with one another via the ZC at the center rather than directly speaking with one another. No other ZigBee network in the vicinity has a PAN ID defined other than the ZC. Because star topology points in the direction of the center, it uses battery power very quickly. Furthermore, ZigBee clustering is difficult to use on large-scale networks. The star topology is therefore not very appropriate for traditional WSNs [26]. Similar to the star topology, the mesh topology seen in Fig. 1b is centralized, allowing any node within the network to connect and exchange messages with any other node. This increases the flexibility of the network but also adds complexity to end-to-end communication. Compared to the star design, the mesh topology better controls battery consumption and power efficiency. because it doesn't choose a single path between nodes [26]. With its inexpensive and low power consumption [27], the tree topology displayed in Fig. 1c is an excellent choice for WSNs. The IEEE 802.15.4/ ZigBee Mac frame provides the power protection mechanism [28]. Tree topology has limitations with regard to band utilization and routing operations, despite being effective for WSNs. Any break in the tree topology causes data flow to be delayed, and the recovery processes result in a significant workload. There is no use of numerous paths in the topology. Because just one route is taken from the source node to the destination node and extra memory is not preserved, tree topology uses less memory than mesh topology [26].

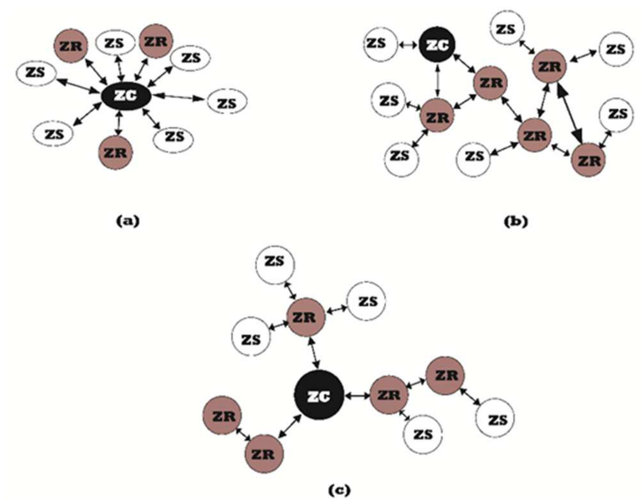

Fig. 1 .ZigBee topologies a) star b) mesh c) tree

The primary issue with WSNs' sensor architecture is that high traffic volumes and packet collisions cause throughput to drop when packets are transferred between sensors [29]. When creating a strategy, the delay needs to be low enough to reduce errors and prevent collisions and retransmissions [30]. The delay includes all latency in coordinators, switches, routers, and other WSN components [31]. The average time taken throughout the process from the source node sending the data packet to the destination node receiving it is known as the end-to-end delay [32].

The performance analysis of Zigbee-based WSNs has been a topic of interest in recent research. Various studies have focused on parameters such as throughput, delay, load, and data traffic in these networks. Also, special interest was concerned about the ZigBee-based WSN topologies in various research papers. One study compared tree routing and mesh routing in WSNs and found that tree routing was better suited for WSNs in terms of throughput, delay, traffic received, and MAC Load [33]. Increasing the number of sensors in ZigBee based WSN would affect both delay and throughput, this is discussed, analyzed and tested using RIVERBED simulation program as in (Nourildean, Mohammed, and Abdulhadi, 2022) [34]. Also, the throughput and delay were discussed for single and multiple coordinators in tree, star, and mesh ZigBee WSNs using the OPNET modular [33], [35]. A simulator application displays the effects of data traffic scenarios, including sent and received data traffic, for four different system scenarios [12], [36], [37]. Nguyen et al. present a review of some of the most contemporary power monitoring, control, and management systems that covered and found that co-channel interference and noise pose the biggest challenges [38]. A greater number of routers in a WSN results in a higher traffic load on the Personal Area Network, according to [39]. The main problem with the sensors in WSNs is that when packets are sent from one node (sensor) to another node, the throughput decreases as a result of high traffic and packet collisions [29]. For various topologies of ZigBee communications, the received signal strength indicator parameters (distance, throughput, and delay) were tested to determine the network performance from indoors to outdoors [40].

III. Result and Discussion

This paper describes the construction of a WSN system using several ZigBee topologies. A simulation programme called RIVERBED (OPNET) Modeller Academic Edition 17.5 has been used to simulate the evaluation and analysis of the system that was constructed, as well as to predict whether the actual system findings would be accurate. The Opnet Company was acquired by a company by the name of RIVERBED. This version of the program allows for several system models, robust network connection, and communication between the administrator, Personal Area Network coordinator, routers, and end devices. This study uses the ZigBee standard to undertake a performance analysis of WSN topologies. In order to do this, four distinct scenarios- two star WSNs, one tree WSN, and one mesh WSN topology—have been taken into consideration. The total-delay, throughput, Mac load, data traffic received, and data traffic sent of these four scenarios were compared. 12 ZSs, 5 ZRs, and a single ZC were used in the four scenarios except the 2nd scenario where no ZR was used.

A. First Scenario (Star topology)

In this scenario, 12 end devices (sensors or ZSs), 5 routers (ZRs), and a single master node (coordinator or ZC) are arranged as star topology that shown in Fig. 2. The traffic should transverse from all the 12 sensors to the coordinator and vice versa.

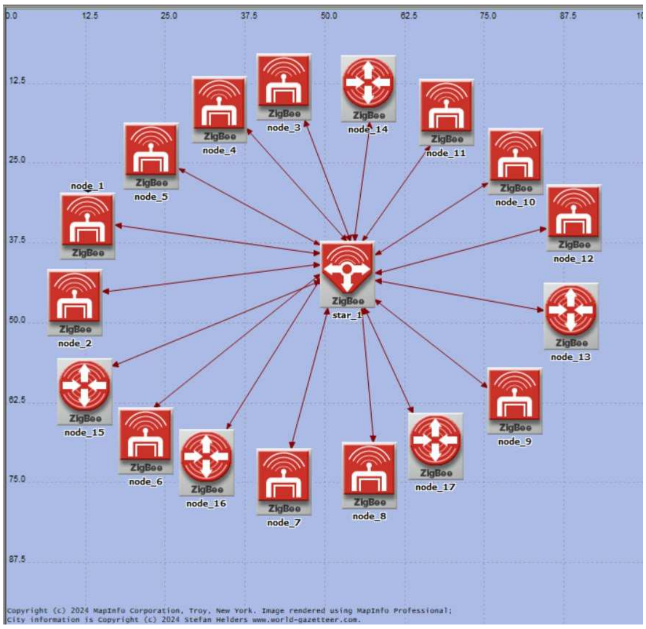

Fig. 2 First Scenario (Star topology)

B. *Second Scenario (Star topology without routers)*

In this scenario, 12 ZSs connected as star with a single coordinator (ZC) as shown in Fig. 3. We create this scenario to see the effect of routers in this type of topology by checking delay, throughput, load and traffic received (and sent).

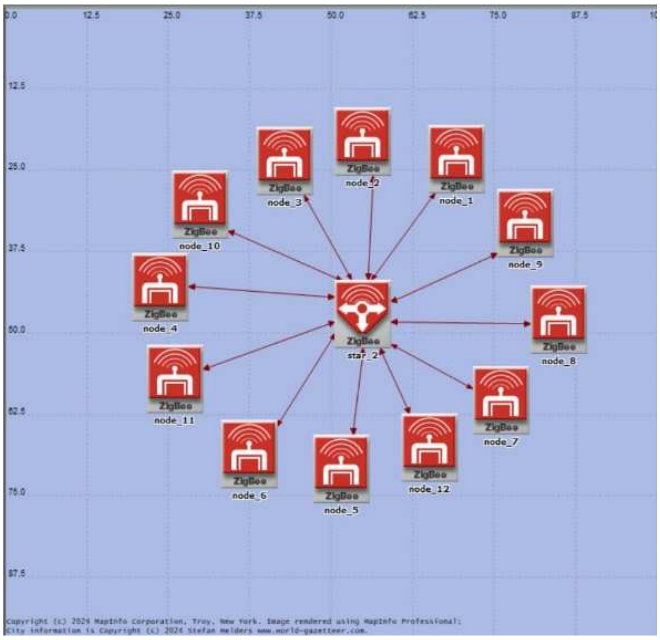

Fig. 3 Second Scenario (Star topology without routers)

C. *Third Scenario (Tree topology)*

In this scenario, 12 ZSs, 5 ZRs, and a single ZC are arranged as tree topology shown in Fig. 4. The coordinator is connected directly to three routers and one sensor. Accordingly, these three routers are connected to the other routers and sensors. All the twelve sensors are peripheral of the ZigBee WSN.

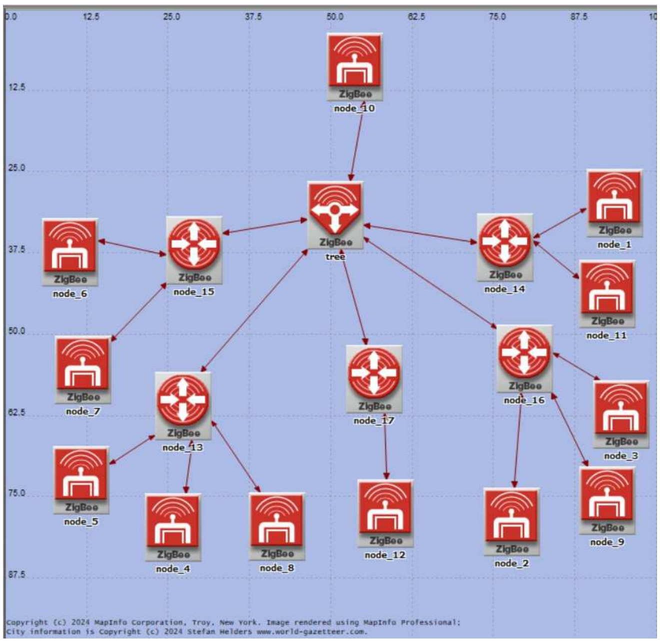

Fig. 4 Third Scenario (Tree topology)

D. *Fourth Scenario (Mesh topology)*

In this scenario, 12 ZSs, 5 ZRs, and a single ZC are arranged as mesh topology shown in Fig. 5. The coordinator is connected directly to two routers and one sensor. Accordingly, these two routers are connected to the other three routers and eleven sensors. All the twelve sensors are peripheral of the ZigBee WSN.

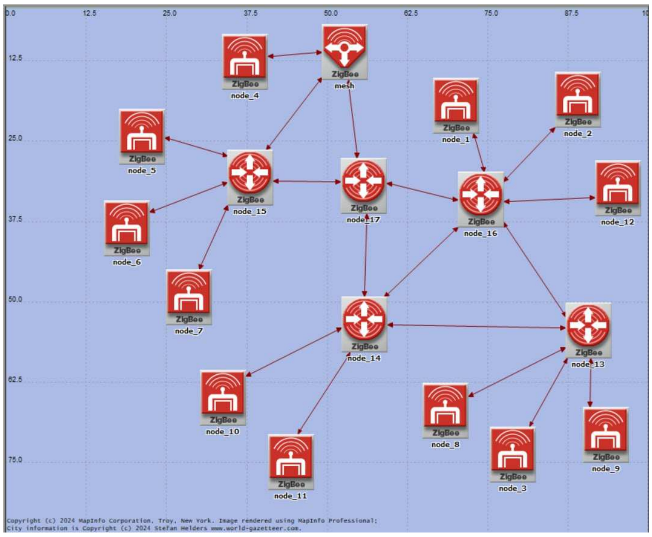

Fig. 5 Fourth Scenario (Mesh topology)

The four scenarios were implemented for one hour using the RIVERBED modeler. The results were statically analysed to identify the networks performance in terms of throughput, delay, load, and data traffic sent and received. The aim of studying these parameters is to check which network topology is the best. In all the following combined results, the red curve represents scenario1, while the green one is for scenario2. The sky-blue colour is for scenario3 while the dark blue is the curve for scenario4. The outcomes are as follows:

E. Throughput

The total number of bits (in bits per second - bps) that are forwarded from the 802.15.4 MAC to higher layers in all wireless personal area network nodes within the network is known as throughput [41]. Fig. 6 shows the throughput curves of all the four WSN scenarios. If we compare the star scenario1 with the star scenario 2, it can be seen that adding five routers exceeds the throughput 5.688kbps at one hour running of the program. It is obvious also from the figure that star topology has the highest throughput while the mesh scenario is the worst. At the steady state (15minuets of running), the throughput values are 19.03kbps for scenario1 (star), 14.55kbps for scenario3 (tree), and 5.64kbps for scenario4 (mesh). So, the star topology is the best topology from throughput point of view.

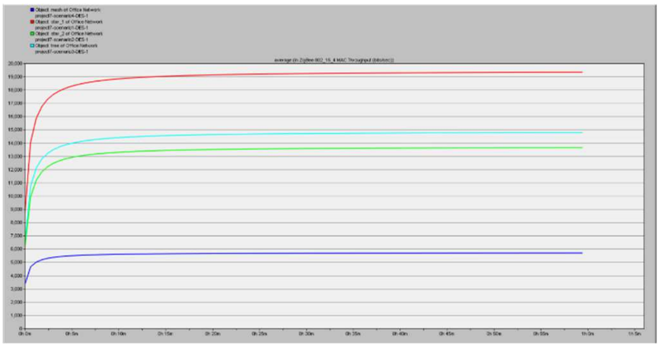

Fig. 6 The average throughput of the four scenarios

F. Delay

Fig. 7 shows the total delay for the four WSN scenarios discussed previously. It is clear from the figure that the average delay is identical in scenario1 and scenario2 after 10minuets which means that routers existence does not affect the delay in the star topology. Also, the delay is almost identical in scenario3 and scenario4 after 10minuets from running the program. So, the tree and mesh topologies have the same delay. Lastly, the star topology is better compared with tree and mesh topologies from delay point of view independent the number of routers we have in the ZigBee WSN. At the steady state (30minuets), the values of the average total delay for the four scenarios from 1 to 4 are 11.236ms, 11.255ms, 12.061ms, and 11.900ms respectively.

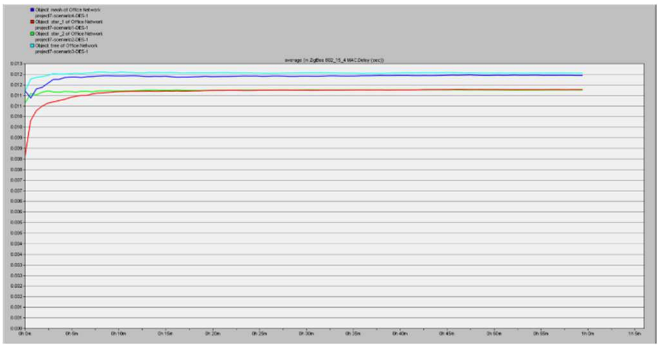

Fig. 7 The average total delay of the four scenarios

G. Data Traffic Received (DTR)

The MAC-layer receives all successful traffic, including retransmissions (in bits per second- bps), and the DTR for four scenarios is displayed in Fig. 8. The DTR of the mesh topology is the highest (46.11kbps at the end of the program running) while the DTR of the tree topology is coming later (39.7kbps at the end of the graph). After that, the star topology is the lowest (21.77kbps for scenario1 and 15.37kbps for scenario2).

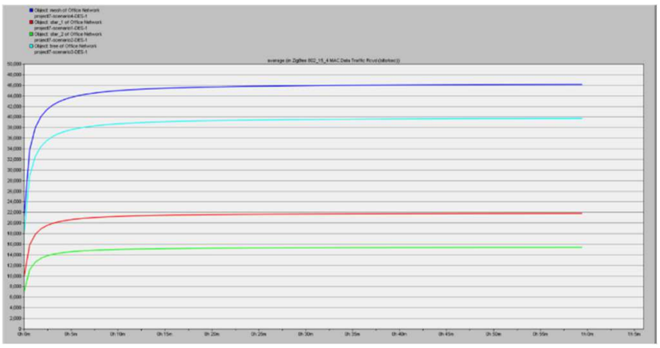

Fig. 8 The average DTR of the four scenarios

H. Data Traffic Sent (DTS)

Fig. 9 shows the average DTS of the four WSN scenarios. It is obvious from the figure that the DTS for the star is greater than tree while the tree topology is greater than mesh. Also, when we add routers to the star topology, the DTs exceeds. The values of the DTS of the four scenarios at the end of running the program are 23.05kbps, 16.65kbps, 14.09kbps, and 6.41kbps respectively from scenario1 to scenario4.

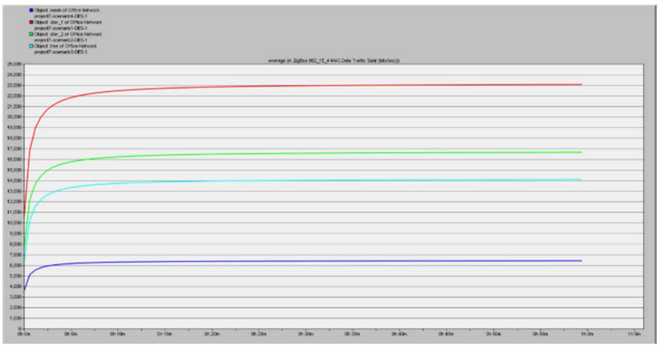

Fig. 9 The average DTS of the four scenarios

I. Load

The average load of the four ZigBee WSN scenarios is shown in Fig. 10 below. The load progression is the same as DTS, the tree topology is the best then tree topology and lastly the mesh topology. The values of the loads from scenario1 to scenario4 are 19.96kbps, 14.42kbps, 12.2kbps, and 5.58kbps at the steady state (10 min of running the program).

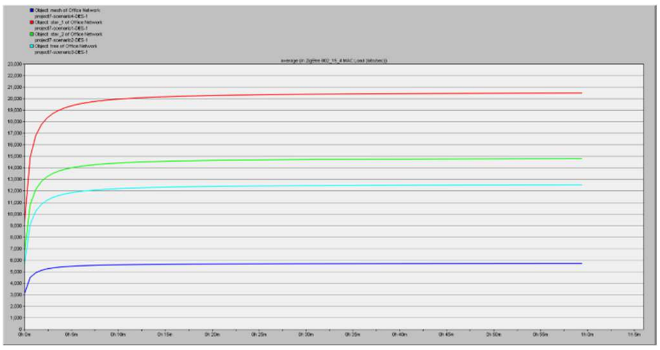

Fig. 10 The average load of the four scenarios

J. Outcomes Summarization

The results are summarized at the end of running the program as shown in Table 2 below.

TABLE II
OUTCOMES SUMMARY

Scenario	**Type of Topology**	**Number of ZSs**	**Number of ZCs**	**Number of ZRs**	**Delay (ms)**	**DTR (kbps)**	**DTS (kbps)**	**Throughput (kbps)**	**Load (kbps)**
1	Star	12	1	5	11.26	21.77	23.05	19.34	20.47
2	Star	12	1	Non	11.24	15.37	16.65	13.65	14.79
3	tree	12	1	5	12.04	39.7	14.08	14.78	12.51
4	mesh	12	1	5	11.93	46.11	6.41	5.69	5.69

IV. CONCLUSION

This paper used the RIVERBED Academic Edition V17.5 to analyse the performance of wireless network topologies based on ZigBee standard. Four scenarios were conducted, and the conclusions are as follows: Star and tree topologies were compared based on five criteria: total delay, throughput, load, data reception and data sent. It was found that the star topology excels in productivity and data transmission rate but performs worse than the tree and mesh topologies in terms of data reception rate. The mesh topology, however, provides the best data reception rate compared to other scenarios. In complex networks with a large number of nodes, the mesh topology is more efficient. This conclusion is based on previous studies. In terms of network quality, the tree topology performs better than the mesh and second star topologies. On the other hand, the tree topology works well for networks with a small number of sensor nodes since it can send data to its destination quickly and without overloading the central node. Additionally, designers have an advantage when it comes to transporting small-sized data in WSNs because communication protocols like ZigBee reduce energy usage in these networks. Overall, the choice of network topology depends on many factors such as network complexity, node count, desired performance metrics, and the ZigBee protocol offers advantages in energy efficiency and data transmission for various applications.

REFERENCES

[1] S U. Aslan, "The effects of hierarchy on mobile wireless sensor network coverage," M.S. thesis, Middle East Technical Univ., Ankara, Turkey, 2006.

[2] F. Othman, and K. Shazali, "Wireless sensor network applications: study in environment monitoring system," *International Symposium on Robotics and Intelligent Sensors (IRIS '12)*, vol. 41, pp. 1204–1210, Dec. 2012.

[3] S. K. Gharghan, R. Nordin, and M. Ismail, "A Survey on Energy Efficient Wireless Sensor Networks for Monitoring Application," *J. of Sensors*, vol. 12, pp 1-17, 2014.

[4] S. Kumagai and H. Higaki, "Signal Processing and Communication Systems (ICSPCS)," 8th International Conference, Vol. 8, pp 1-8, 2014.

[5] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless micro sensor networks," *IEEE Trans. on Wireless Commun.*, vol. 1, no. 4, pp. 660–670, Nov. 2002.

[6] M. Youn, and J. Lee, "Topology Control Algorithm considering Antenna Radiation Pattern in Three-Dimensional Wireless Sensor Networks," *Int. J.of Distributed Sensor Networks*, vol. 2014, pp 1-11, Jun. 2014.

[7] U. Pesovic, J. Mohorko, S. Randic and Z. Cucej, "Hidden node avoidance mechanism for IEEE 802.15.4 wireless sensor network," *J. of Microelect., Electronic Comp. and Materials*, vol. 43, no. 1, pp 14 – 21, Mar. 2013.

[8] A. Ding, D. Song, E. Zhang, Z. Tong, Pan, and X. You, "Interference Aware wireless networks for home monitoring and performance evaluation," *IEEE Trans. Autom. Sci. Eng.*, vol. 15, no. 3, pp. 1286–1297, Jul. 2018

[9] K. Gulati, R. S. Boddu, D. Kapila, S. L. Bangare, N. Chandnani, and G. Saravanan, "A review paper on wireless sensor network techniques in Internet of Things (IoT)," Materials Today: Proceedings, vol. 51, pp. 161–165, 2022.

[10] S. W. Nourildean, M. D. Hassib, and Y. A. Mohammed, "Internet of things based wireless sensor network: a review," *Indones. J. of Electr. Eng. and Comput. Sci*, vol. 27, no. 1, pp. 246–261, Jul. 2022.

[11] A. Elkenawy, J. Judvaitis, "Transmission Power Influence on WSN-Based Indoor Localization Efficiency," *Sensors*, vol. 22, no. 11, pp 1-18. May 2022. doi: 10.3390/ s22114154. PMID: 35684775; PMCID: PMC9185369.

[12] M. T. Coboi, V. N. Nguyen, T. C. Vu, M. D. Nguyen, and D. T. Nguyen, "ZigBee Based Mobile Sensing for Wireless Sensor Networks," *Comput. Net. and Commun.*, vol. 1, no. 2, pp. 325-341, Dec. 2023.

[13] S. K. Gharghan, R. Nordin, and M. Ismail, "A Wireless Sensor Network with Soft Computing Localization Techniques for Track Cycling Applications," *Sensors (Basel)*, vol. 16, no. 8, pp. 1-23, Aug. 2016. doi: 10.3390/s16081043. PMID: 27509495; PMCID: PMC5017318.

[14] A. Muscat, S. Bhattacharya, and Y. Zhu, "Electromagnetic Vibrational Energy Harvesters: A Review," *Sensors,* vol. 22, no. 15, pp. 1-17, Jul. 2022. doi: 10.3390/s22155555. PMID: 35898058; PMCID: PMC9331882.

[15] S. Sadeq, R. Hassan, H. Sallehudin, A. H. Aman, and A. H. Ibrahim, "Conceptual Framework for Future WSN-MAC Protocol to Achieve Energy Consumption Enhancement," *Sensors*, vol. 22, no. 6. Mar. 2022. doi: 10.3390/s22062129. PMID: 35336298; PMCID: PMC8955616.

[16] J. Phengsuwan *et al.*, "Use of Social Media Data in Disaster Management: A Survey," *Future Internet*, vol. 13, no. 2, pp. 46-70, Feb. 2021.

[17] S. K. Swami, B. Duraisamy, and A. J. Thirukrishna, "Certain Investigation on Healthcare Monitoring for Enhancing Data Transmission in WSN", *Int. J. of Wireless Inf. Net.*, vo. 30, pp.:103–110, Aug. 2021.

[18] D. Naranjo, J. Reina-Tosina, and L. M. Roa, "Body Sensors Networks for E-Health Applications," *Sensors (*Special Issue*)*, vol. 20, no. 14, Jul. 2020. doi: 10.3390/s20143944. PMID: 32708538; PMCID: PMC7412528.

[19] T. A. Le, A. Jivalagian, T. Hiba, J. Franz, S. Ahmadzadeh, T. Eubanks, L. Oglesby, S. Shekoohi, E. M. Cornett, and A. D. Kaye, "Multi-agent Systems and Cancer Pain Management," *Curr Pain Headache Rep.* Sep., vol. 27, no. 9, pp. 379-386, Jun. 2023. doi: 10.1007/s11916-023-01131-4. Epub 2023 Jun 29. PMID: 37382870.

[20] L. Liu, and S. Choi, “Miniature microbial solar cells to power wireless sensor networks,” *Biosensors and Bioelectr.,* vol. 177, pp. 1-26. Apr. 2021. doi: 10.1016/j.bios.2021.112970. Epub 2021 Jan 4. PMID: 33429201.

[21] Y. Sun *et al.*, "On Enabling Mobile Crowd Sensing for Data Collection in Smart Agriculture: A Vision," *IEEE Sys. J.*, vol. 16, no. 1, pp. 132-143, Mar. 2022. doi: 10.1109/JSYST.2021.3104107.

[22] K. Chang, “RF and microwave wireless systems,” *John Wiley& Sons*, New York, 2000.

[23] D. M. Amzucu, H. Li, and E. Fledderus, “Indoor radio propagation and interference in 2.4 GHz wireless sensor networks: measurements and analysis,” *Wireless Per. Commun.*, vol. 76, no. 2, pp. 245–269, May 2014.

[24] K. Benkic, P. Planinsic and Z. Cucej, "Custom wireless sensor network based on Zigbee,” *49th Int. Symp.*, ELMAR, UAE, 2007, pp 259-262.

[25] S. Safaric and K. Malaric, "ZigBee wireless standard," *48th Int. Symp.*, Elmar, UAE, 2006, pp: 259-262.

[26] S.W. Nourildean, “A study of ZigBee network topologies for wireless sensor network with one coordinator and multiple coordinators,” Tikrit J. of Eng.Sci., vol.19, no.4, pp. 65-81, Dec. 2012.

[27] G. Hong and S. Jianxiu, “Design of the temperature signal wireless receiver and display system on polishing interface in chemical mechanical polishing,” Procedia Eng., vol. 24, pp. 417–421, Dec. 2011. doi: 10.1016/j.proeng.2011.11.2668. 2011

[28] Y. Yan, B. Zhang, H. T. Mouftah, and J. Ma, “Practical coding aware mechanism for opportunistic routing in wireless mesh networks,” 2008 IEEE Int. Conf. on Commun., Beijin, China, 2008, pp. 2871–2876. doi: 10.1109/ICC.2008.541.

[29] B. Chen, “Wireless Communication Chip Designs: analysis of the Wireless Integrated Network Sensors,” Highlights in Sci., Eng. and Techn., vol. 70, pp. 580-587, Nov. 2023. doi: 10.54097/hset.v70i.13989.

[30] S. Dutt, S. Agrawal, and V. Renu, “Delay-Sensitive, Reliable, Energy-Efficient, Adaptive and Mobility-Aware (DREAM) Routing Protocol for WSNs,” Wireless Pers. Commun, vol. 120, no. 1, pp. 1675-1703. Sep. 2021. doi: 10.1007/s11277-021-08528-7.

[31] S. Ihsan, “Comparison between AODV and DSDV Protocols in WSN Based on End to End Delay,” 4th Int. Integ. Sci.Conf., Baghdad, Iraq, 2021, pp. 1-5.

[32] R. Tang, N. K. Aridas, and M. S. Abu Talib, “Design of Wireless Sensor Network for Agricultural Greenhouse Based on Improved ZigBee Protocol,” Agriculture, 2023, vol. 13, pp. 1-13.

[33] S. W. Nourildean, “ZigBee-Based wireless sensor network topologies using one and multiple coordinators”, Period. of Eng.and Nat. Sci., vol. 8, no. 3, pp. 1625-1640, Aug. 2020.

[34] S. W. Nourildean, Y. A. Mohammed, and M. T. Abdulhadi, “Investigating the impact of network topologies on the IoT-based WSN in smart home monitoring system,” East.-Europ. J. of Enterp.Techn., vol. 6, pp. 6-14. Dec. 2022.

[35] N. K. Baqer, A. M. Al-Modaffar, and G. H. Shahtoor, “Throuphut Study of IEEE 802.15.4 ZigBee-Based WSNs for Greenhouse Environment,” Int. J. of Sci. Res. Eng. & Technol., vol. 7, pp. 171-176, Mar. 2018.

[36] N, K. Baqer, A. W. Abbas, and B. A. Salih, “Data and Management Traffic of IEEE 802.15.4 ZigBee-Based WSN,” Int.J.of Advanced Sci. Comput. and Eng., to be published.

[37] N. K. Baqer, A. M. Al-Modhaffar, and E. A. AlKadly, “A study of Delay and Data Traffic of IEE 802.15.4 ZigBee-Based WSN in a Smart Home,” Int. J. on Advanced Sci. Eng., vol. 8, no. 3, pp. 956–962, Mar. 2018.

[38] V. Nguyen, A. E. Coboi, N. V. Bach et al., “ZigBee based data collection in wireless sensor networks,” Int. J. of Inf. and Commun. Technol., vol. 10, no. 3, pp. 211–224, Dec. 2021. doi:10.11591/ijict.v10i3.

[39] O. Mau, T. C. Lam, and T. H. Nguyen, “Performance Evaluation of MAC Layer Protocol over Wireless Body Area Sensor Networks,” EAI Endorsed Trans on Industrial Net. and Intell.Sys., vol. 8, no. 5, pp. 1–7, Apr. 2021.

[40] D. Setiabudi, D. I. Atmaja, D. W. Herdiyanto, and G. A. Rahardi, “RSSI Measurement Analysis of ZigBee-Based Wireless Sensor Networks in Various Topologies for Solar Panel Monitoring,” Majalah Ilmiah Teknologi Elektro, vol. 22, no. 2, Jul. 2023. doi: 10.24843/MITE.2023.v22i02.P14.

[41] M. A. Indrajaya, R. Fauzi and E. A. Sapultra, “ZigBee-Based Wireless Sensor Network Topology Design and Comparison in Residential Areas, Jurnal Ecotipe,” Elect., Cont., Telecommun., Inf, and Power Eng.,” vo. 10, Issue1, pp. 42-51, Apr. 2023. ISSN 2355-5068; e-ISSN 2622-4852 doi: 10.33019/ jurnalecotipe.v10i1.3704.