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A Comparative Analysis of Network Topologies: Impact on Lifetime of WSN with Adaptive Duty Cycle

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Abstract
Wireless Sensor Network is an architecture structure of a network that interconnects sensor nodes to communicate wirelessly in return for collecting information about the surrounding environment. In intercommunication between nodes, there are major issues with network lifetime. Each sensor node communicates with one another to pass the data to the sink where the data is collected. The energy of each node is wasted during this activity due to known issues such as idle listening, overhearing, and collision packets. In the network structure, it can determine the behavior needed for the nodes to send data from their origin to the sink. Different network topologies offer different scenarios and responsibilities to the nodes. In these studies, we will compare different network topologies such as mesh, star, ring, and tree topology to see the effectiveness of each topology in delivering the results of network efficiency. To determine the network efficiency, there major parameters that are required are the Packet Delivery Ratio, Packet Loss, and Energy Consumption. In addition, all the simulation uses an enhanced adaptive duty cycle (ESMAC). Simulation results conclude with mesh topology as the best network efficiency among the tested network topologies as the packet delivery ratio is the highest followed by the lowest packet loss.
Keywords: Adaptive Duty Cycle, Wireless Sensor Network, Wireless Network Topology, Energy Efficiency.

1. Introduction

A wireless sensor network is one of the results of recent developments in Wireless communications and electronics for compact, low-power, multipurpose sensor nodes that can communicate untethered across short distances and at low costs [1]. WSN is defined as an infrastructure-free wireless network deployed in geographical areas with several wireless sensor nodes in an ad-hoc fashion. The nodes collect data from the monitoring sensors that monitor environmental physical activities such as seismic vibrations of the earth plate, the humidity of air and soil, heat sensor for detection, sound, and changes of environmental pressure. The raw data are collected and transferred to a central location which is used in the analysis and analytics information in expertise such as geographical expertise, industrial applications, and smart agriculture [2].

Sensor nodes, sink nodes, and base stations are the basic components of a Wireless Sensor Network [3]. A sensor is a tiny device that includes three basic components: a sensing subsystem for data collecting from the surrounding events, a processing subsystem for local data process and storage, and a wireless communication subsystem for data transmission in which a significant improvement over the traditional sensors [4]. The power source of the sensor is provided by a battery with limited energy storage[5]. Having limited power sources with the responsibility to provide real-time data, there is no room for energy to be wasted.

Implementation of WSN is expected to grow significantly over the coming years due to the growing network of infrastructure demand and advances in AI and ML and big data analytics. In the current IoT potential, every sector/industry focuses on collecting information to become meaningful data for further study and data analysis. Many sector such as agricultures [6], weather industry [7][8] and traffic controller [9][10] use the advancement technology of wireless sensor network to improve its scalability and growth performance.

Even with this huge industry growth, the drawbacks of WSN being used widely are major to energy wasted. This drawback reduces the lifetime of WSNs, opening an end to the degradation of the quality of services. The primary sources of energy waste in WSNs are collisions, idle listening [11], overhearing[12][7], and over-emitting[7] that occur at the medium access control layer. The protocols must be created from the start with the goal of effective energy resource management to maximize the network's lifespan. There are a lot of protocols that are used nowadays to reduce energy usage. The protocol can be divided into two categories asynchronous MAC protocol [12] and Synchronous MAC Protocol [6]. In these studies, we will focus on the Enhanced Synchronous MAC protocol.

Synchronous Mac Protocol is considered as a start where researcher starts to enhance to make the duty cycle more adaptive adaptable to the situations and usage. Enhanced adaptive duty cycle schema will be explained in detail on how it counters the drawbacks and how it reduces the energy consumption and eventually bring up the energy efficiency to the next level of improvement.

Adaptive Duty Cycle requires selective variable to be changed adaptively according to the cases or situations[13]. For example, AD-MAC[13] uses a concept of short and concise listening time. This method is designed to achieve a low duty cycle and a smaller number of collisions in a network specifically designed for clustered network. In addition, it also introduces adaptive power control to determine the cluster head where increase the network lifetime where its useful for network topology that having a coordinator or gateway. AD-MAC use variables of energy information and channel access schema TDMA and FDMA to propagate the task evenly between all the nodes in the network. This adaptation is specifically designed for clustered network topology such as star, tree, or hybrid topology. In this schema, its specifically designed for clustered network topology such as star topology, tree topology and hybrid topology. It’s observed that this topology enhanced the clustered network topology in creating more dynamic approaches on the cluster head assignment where there help to deal with single nodes suffering from main assignments as cluster head. This energy model to propagate the task evenly between the cluster nodes improved the longevity of the nodes battery per changed and help to keep the communication from breakdown due to cluster head die.

EEQ (Queue and Priority Aware) [14] use a different variable which is the queue length and packet size. EEQ designed to provide for priority packets with an exponential weighted moving average to solve the problem of starvation suffered by low priority classes by keeping the value of the average queue length below the minimum threshold. In this schema, the packets priority is determined by the average of high priority class, this will be estimated using a low pass filter with an exponential weighted moving average of 0.01 low-pass filter. This low-pass filter act as a weightage pre-configured to adjust the delay of packets. The weighted average is then compared with two thresholds, the minimum, and the maximum. This threshold is used to benchmark acceptable queue delays. This threshold range are calculated by the Random Early Detection (RED) algorithm. If its smaller than the threshold the packet is queued and its larger it dropped. This phase is used in determining each of the queue priority length (low, medium, and high). After determining the packets priority queue, the nodes communicate to the duty cycle and do the adjustment needed. The protocol determines the duty cycles based on the length of the queue and the packets priority class. The packet priority class is categorized to three, which is low, medium, and high. This protocol able to reduce end to end delay by selecting the nearest route to the destinations and significantly reduce the energy consumptions.

In nodes parameter there is scheduling time information. VTA-SMAC [15] schema motivation is to reduce the energy consumption of traditional S-MAC protocols. S-MAC has a fixed listen period, and the listening period are configured two to main task which is SYNC and Data periods. Nodes received a synchronization call during SYNC period and exchange of data packets happen during data period. This fixed duty cycle produces idle listening during listening period and creates high latency when high traffic occurs. In VTA-SMAC main target to reduce the idle listening and collisions. 3 Algorithm are used in this schema, Virtual Clustering Algorithm, Dynamic Sleep Algorithm and Adaptive Duty cycle algorithm. Each of these algorithms requires information and variables such as node location information, node energy information and scheduling time information. Virtual Clustering information is an algorithm to determine the nodes in the group responsibilities whether it’s a synchronizer or follower nodes. In each round the energy information of each node is shared to the base stations and nodes with highest energy information remaining will be choose as synchronizer and others as followers. Additionally, to this method, only when the followers finish transmission to synchronizer it will turn off the radio and synchronizer will start aggregate the data and transmit it to the base stations. On next cycle the algorithm will rerun again and select the new synchronizer that have the highest energy left. Dynamic Sleep Algorithm mainly used in the case during very low data traffic. This algorithm checks the data queue, if there is no data in the queue, it remains sleeps. It further checks last data duration and adds it to the data time. If the last data duration is smaller than the current time, it remains asleep. Adaptive Duty Cycle Algorithm give the nodes ability to determine their own duty cycle and each of different nodes can assigned different duty cycle. Algorithm uses the scheduling time information and adapts it with the algorithm. Shown in (1) activity values S is calculated using T_r Time spent receding packets T_t time spent in sending the packet and T_i time for which the node is idle.

$$S = \frac{T_r + T_t}{T_r + T_t + T_i} \tag{1}$$

S_{high} shows a greater traffic load and S_{low} vice versa. An allowed modification factor percentage value is also introduced to control the duty cycle and it also adapts accordingly to the traffic loads S. Another controller for the duty cycle is also introduced to control the maximum D_{max} and minimum of duty cycle D_{min}. In (2) formula shows how the sleeps time average L_{avg} is calculated and benchmarked with L_{max} and L_{min}. This sleeps time is to keep the latency within the allowed limits.

$$L_{avg} = \frac{L}{Noofpackets} \tag{2}$$

The activity factors S and average sleeps time L_{avg} that are dynamically changed based on the node's information each time. Both parameters are calculated to achieve an adaptive duty cycle where the active states duration is determined by the activity factors and sleep state duration is by average sleeps time. Energy consumptions, data collisions, and data latency are QOS metrics that we observed from this paper. Based on the stated algorithm above, each of the QOS metrics are tested in different sized of topology using random and grid nodes positions of multi hop network topology. VTA-SMAC shows positive result when handling large quantities of network. This is due to the ability of the duty cycle to adapts and changes based on the network conditions. Virtual clustering algorithm shows its ability when the network sized increased by virtually create a nodes cluster and select the cluster head based on its energy information.

ESMAC[16] is an enhanced adaptive duty cycle that recognizes packet data based on size and suitable priority. It determines the packet priority based on the packet size of 3kB for high, 2kB for medium and 1kB for low. the higher the priority the longer the sensor nodes will be active and so on. In this the duty cycle d_c are determine based on the packet size P_s, number of packets $P_n$and the queue length Q_l as shown in (3). In this method the queue length is set to a static number of 50, different approach by EEQ where the queue length is set based on the exponential weighted moving average.

$$d_c = \frac{P_s * P_n}{Q_l} * 100\% \tag{3}$$

Using the packet priority class based on packet size it can dynamically change the duty cycle of the nodes based on the packets information that are transmitted to. In this research the QOS metrics are defined by packets delivery ratio, packet loss and energy consumption. Researcher uses Multi Hop Linear topology where the nodes a set to random positions and only one sink nodes to collect and process the data. The duty cycles are tested 3 times based on the packet priority category. The energy consumptions improved by 30% compared to 802.11 where there is no sleep mode. This shows the adaptive duty cycle achieved to close the gaps of the idle listening. This follows with the increasing ratio of packet delivery and decreasing in packet loss.

2. 2. METHOD

2.1 Network Topologies

Star topologies consists of nodes and sink whereby nodes are connected directly to the sink. The structure remains single link from a node to its sink or central coordinate. There is no buffer from nodes to sink as the nodes communicate directly without any gateway or middleman. The network did not down if one of the nodes channels is not working. Network lifetime dependent entirely on centralized nodes[17]. Sector that benefits low data buffering such as medical and safety measurement devices are most likely will used this topology as its unique characteristics[18]. One of drawback of star topology is limited area coverage as its fully dependent on the central node capabilities of transmission range [19]. This requires tree topologies to be implemented if requires more coverage area.

Tree topology structure consists of multi-level layer of nodes, gateway, and sink-coordinator. Sensor nodes are on the last layer of the structure where it communicates through gateway before data send to sink-coordinator[20][21]. Highly scalable network [20] as adding in additional nodes to the network is plug in to node at the last level of the current network. Data buffering as it requires the gateway to collect and send the data to sink. Higher packets drop due to multi hop requires from sender node to central coordinator. Tree topology is suitable for situations where need to cover large areas of sensory region, such as forest, ocean, and volcano, tree topology can adapt scalabilities as new regional area can be found in later stage after first deployment.

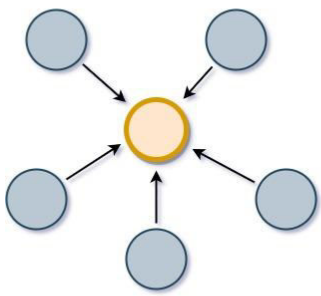


Figure 1. Star Topology

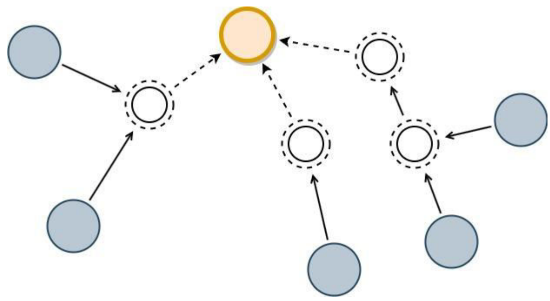


Figure 2. Tree Topology

Ring topology as its name showcases that each sensor nodes are connected to two other nodes to create a circle of the structure[22]. Each node has responsibilities of its neighbour as a gateway. Each nodes consider as repeater for the message to send from sender to its destinations.

Nodes can redirect to another directions if there is heavy traffic or loss of connections from another directions. The delay and buffering will increase higher as the nodes is getting further than the sink where requires more hopped to the sink[23].

Mesh topology is found later stage in network infrastructure as advancement in the network technology. It takes advantage of redundant path to create more robust network[24][25]. Each node is interlinked and connected to each other till the sink nodes. Its vice versa of star network where single point of network failure are reduced greatly. Mesh topology is the most robust network as there is no failure until there is no nodes left, due to no single point of network failure as each node can interlink and connected to each other[26]. It requires good routing algorithms to determine the best route to take from sender to sink and more ram to compute the routing algorithm as there are many possibilities and all possibilities are checked before it registers the route that the sender should take[27]-[42].

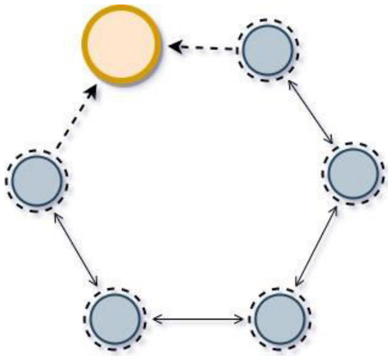


Figure 3. Ring Topology

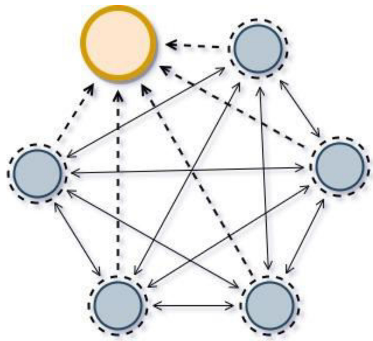


Figure 4. Mesh Topology

2.2 Simulations

There are 3 major components and parameters that need to be highlighted for these simulations before to begin with. Enhanced adaptive duty cycle, list of networks topologies and QOS Calculations. For Enhanced adaptive duty cycle, researchers use ESMAC where the variable that enhanced it is dynamic packet size. The packet size in ESMAC is categorized to three priorities in which low, medium and high. List of topologies that are in these simulations are listed in "Network Topologies". All these topologies shared the same parameter in the experiment shown in Table 1.

Table 1. Parameters and value initialization before simulation

Parameter	Value
Packet Size	2mb
Packet in Queue	50
Simulation Time	100s
Number of sender nodes	5
Adaptive Duty Cycle	ESMAC

For the QOS criteria, researchers expect outcome in 3 aspects in which packet delivery ratio, packet drop ratio and Energy Efficiency. For PDR it's measured by total packet sent from sender nodes and total packet received by destination nodes. The higher the PDR value the higher the QOS. PDR are calculated by using the equation (4).

$$P_d = \left(\frac{P_r}{P_t}\right) * 100$$
(4)

A packet is a small unit of data that travels through the network from its origin to the destination. When packets are not able to successfully reach their destination, the end users will experience disruptions, in WSN causing network congestion. Network congestion happens when a node handles data more than its thresholds, it will cause the data to drop or be blocked. The data dropped is known as Packet Loss. To calculate the packet loss, the equation (5) below is used where Packet Loss P_l equals packet delivery $P_d$over the number of packets sent P_t.

$$P_l = \left(\frac{P_d}{P_t}\right) * 100$$
(5)

For energy efficiency, there is a different output that researchers aim for. Energy consumption and Network Lifetime. Energy consumption and network lifetime relate to the energy information that requires to be setup before simulation which is shown in table below.

Table 2. Values for energy information initialize before simulations

Energy Information	Values
Initial Energy	30 kJ
Transmission Power	0.5
Receiving Power	0.5
Idle Power	0.5
Sleep Power	0.001

The nodes have their lifetime based on the battery performance. Higher energy consumption will lead to degenerate battery performance. When a node transmits or receives data, its energy usage decreases with time. The equation (6) below shows the calculation of the energy consumption of a node, $E_c$is the energy consumption, E_i is the initial energy and $E_f$is the final energy after the simulation ends.

$$E_c = E_i - E_f \tag{6}$$

Network lifetimes have a different perspective rather than just calculating the energy consumption. Total time duration of the network from initial deployments until network lost its capabilities to do the sensing, sending and receiving data is the measurement of network lifetime[26]. Snapshots of the simulation time and only capturing when the network is unusable where each node's energy is at its zero-battery level required to do the calculation. Using AWK scripting allows us to read the trace file from the simulations and captures timing where nodes in the topology have depleted to its 0 level. Below Figure 5 the code where it's reading the log simulation files to find the timing snapshots.

```
# Check if the current energy level is lower than the stored minimum
if (energy < min_energy[node]) {
    min_energy[node] = energy
    min_time[node] = time
}
```

Figure 5. AWK Scripting to capture time snapshot when energy below minimum values

As the results of the code, each of the nodes will be shown its energy left and time of the event happening shown in Figure 6 below.

Figure 6. Results of AWK scripting snapshots

```
----Nodes Timing Snapshot ----
Node     Energy Left      Time Snapshot
1        0.000000         71.60(s)
2        0.000000         70.95(s)
3        0.000000         70.95(s)
4        0.000000         70.70(s)
5        0.000000         71.24(s)
```

Energy efficiency can be seen in the effectiveness of each network topology output combined from packet delivery ratio, packet loss ratio, energy consumption and network lifetime results. By combining all these 4 aspects, energy efficiency can be observed and concludes the rate of its efficiency acceptance. Concluded as in Table 3 below.

Table 3. Energy Efficiency with QOS expectation

	QOS Expectation
Energy Efficiency	High Packet Delivery
	Low Packet Drop
	Low Energy Consumptions
	Longer Network Lifetime

.

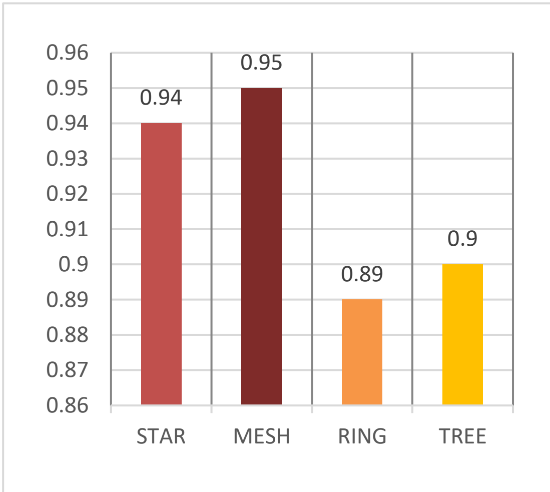
3. Results And Discussions

Static parameters of nodes and energy information have been set the same across the four wireless network topologies. The space difference in this study is left with the network topology structure that has been explained in Methodology section. To determine the efficiency of which topologies provide the most, the results will be discussed with packet delivery, packet loss, energy consumption and network lifetime.

Figure 8 below shows the packet delivery ratio between four of the topologies. The graph below shows that the mesh topologies have the highest ratio of delivery compared to other topologies. From the result also ring and tree shows the lowest ratio delivery and lowest packet send. Mesh topologies and star have a direct connection to the sink nodes where there is no hopping required for star and mesh topology. This is different from the other two topologies where the route needs to hop to gateway before to the sink nodes.

Packet loss happens when the sending packet fails to reach the sink nodes. This is mostly due to queue limits or collisions. Star and mesh have 0 to less for collision to happen compared to ring and tree where its characteristics of structure requires nodes hoping to the sink. As per results shown in Figure 7 star and mesh have lower percentage ratio of packet drop compared to the others.

Figure 7. Packet Delivery Ratio vs Network Topology



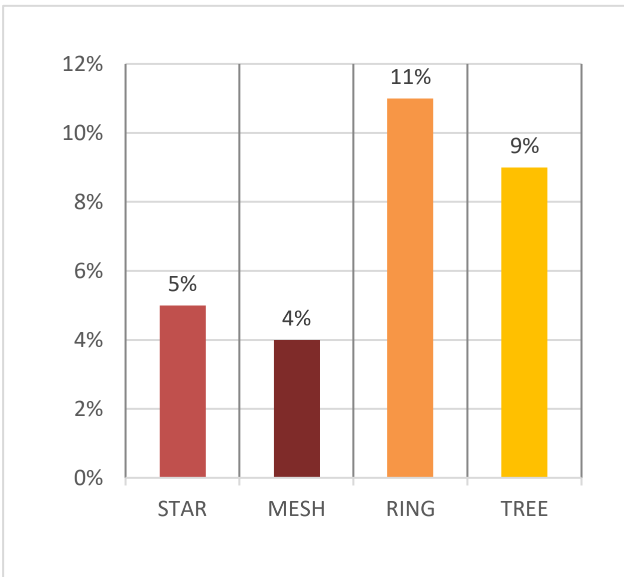


Figure 8. Packet Loss Ratio vs Network Topology

For energy consumption, observed here that all the topologies have the same consumptions rate which is 100% consumption from initial energy provided 30kJ in 100 second simulations time as in Figure 9. All the topologies have been provided with the same protocol which is ES-MAC and no different from one and another. In Figure 10 observed all node's energy in different topologies depleted to 0 in 96 second simulations time.

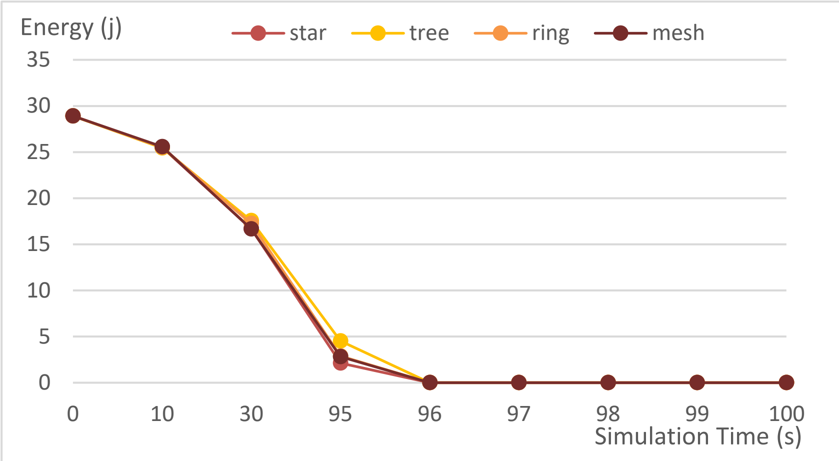


Figure 9. Network Lifetime vs Network Topology

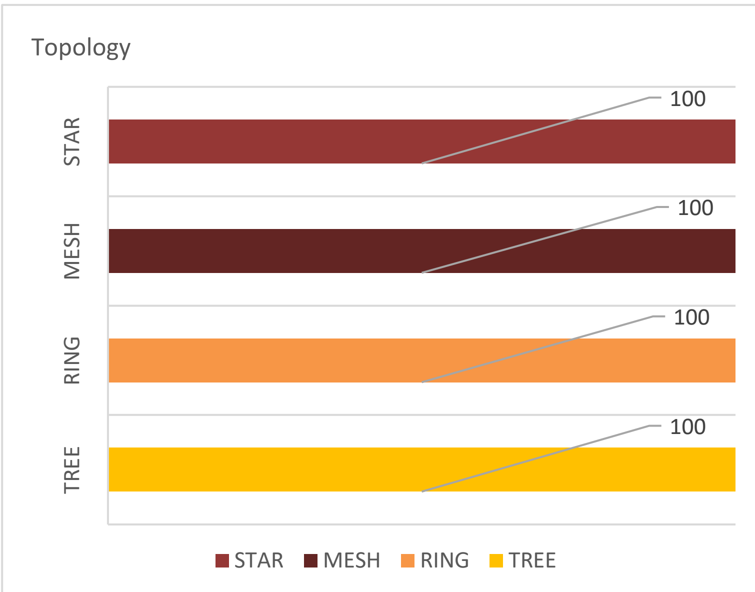


Figure 10. Energy Consumptions vs Network Topology

To determine the energy efficiency, the combined graph requires to understand the cost to profit ratio between topologies. As shown in Figure 11 below, the combined graph we can see the mesh has the highest packet delivery ratio and lowest packet drop ratio and followed by star, tree and ring. All the topologies used 100% of their energy but deliver significant difference results in packet delivery ratio, packet drop ratio. A need to highlight the total count of packets as well is delivered and received packets from different topologies as shown in Figure 12 below.

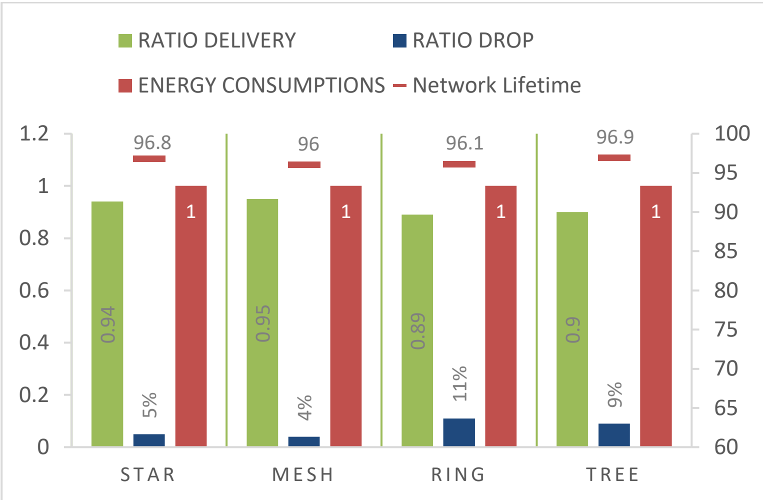


Figure 11. Combined results of Packet Delivery Ratio, Packet Drop Ratio, Energy Consumptions and Network Lifetime vs Network Topology

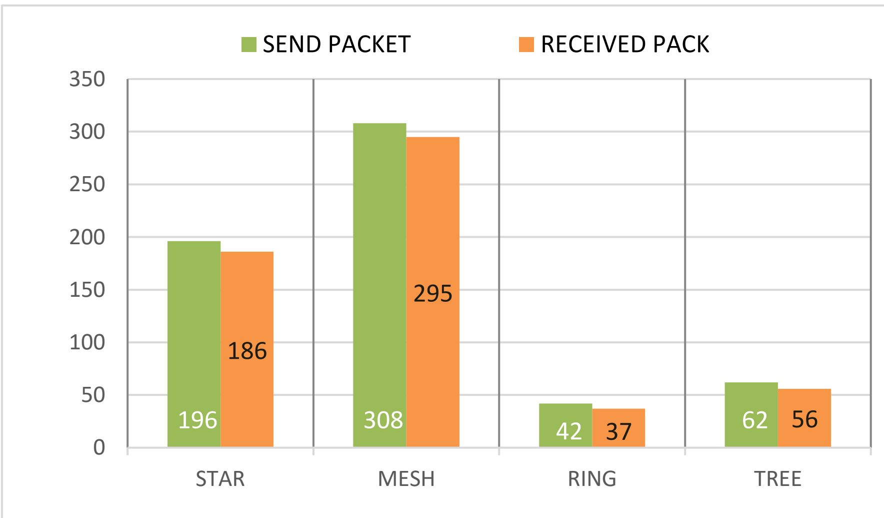


Figure 12. Packet Send and Received vs Network Topology

5. Conclusion

In this study, we compared enhanced adaptive duty cycle with 4 different network topologies which are star, mesh, ring and tree. The results show, mesh topologies offer the best energy efficiency all around compared to other topologies. Different network topologies have different characteristics of network infrastructure. For mesh topology, it has dynamic infrastructure of single or multi-hop for each node in the structure, which makes a big difference between other topologies. This is important as removing collision and buffering is the main key in energy efficiency of wireless sensor networks.

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