Evaluation of the Performance of IEEE 802.15.4 based Wireless Sensor Network for Large Scale Application

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Summary
This paper evaluates the performance of IEEE 802.15.4 standard Wireless Sensor Network (WSN) in star, tree and mesh topology for large scale applications. This evaluation is performed to study the effect of deeply employed wireless sensor network on throughput, end to end delay, number of hops and packet drop caused by collisions when the number of nodes is increased. The network simulator Opnet (version 14.5) is used to perform our simulation. Based on this performance analysis, a comparison, and as a result a decision can be made on choosing the appropriate topology for the required application.

***Keyword*:**
Wireless Sensor Network, IEEE 802.15.4, Performance Analysis, Star topology, Opnet.

1. Introduction

The networks which are based on Zigbee (IEEE 802.15.4 standard) designed to replace the diversities of individual remote controls. Zigbee standard which is placed in Physical (PHY) and Medium Access Control (MAC) layer is basically designed and established to meet the market needs for cost-efficient, standards-based wireless networks that support low data rates application, low power consumption, reliability, and security. Higher layer mentioned in the Zigbee standard is for industry alliance. The Zigbee application can be seen in home monitoring system, collection of data in small area, climate sensors communication and industrial control etc. The major application of Zigbee transceiver is found in wireless sensor networking and automatic control system such as home controlling, biotelemetry, personal caring (for senior citizens) etc. Light (Power) control, Light machinery control, SCADA networking … etc are some more important application areas of Zigbee technology [1] [2] [3]. At present days, wireless sensor network (WSN) is among the most talked about research fields in the area of information and communication technologies. WSN is a collection of sensor nodes distributed over an area, either large or small, in order to collect and distribute data for achieving some specific goals. There exist a number of communication protocols for the wireless sensor networks, among those ZigBee is the leading global standard for low-cost, short-range wireless networks with longer battery life [4].

This paper presents an evaluation of the performance of ZigBee based Wireless Sensor Network, where there is a need for a large scale topology. The evaluation is performed for different topologies: star, tree and mesh. Simulation analysis is made to measure the impact of increasing the number of nodes on throughput and end to end delay, and also to clarify the effect of packet drop and number of hops on the network performance. This work, unlike other previous works, implements WSN in a large scale topology, which can be useful for those who want to deploy these sensors in the field. From this work the behavior of the network according to the packet size, which is used in the simulation, can be predicted and the best number of nodes that can be implemented in star, tree or mesh topologies according to the required application is illustrated, as well as the effect of multi-hops that can be seen more clearly in the results of this simulation analysis.

2. Brief overview of IEEE 802.15.4 standard

In March 1999, IEEE establishes the 802.15 working group as part of the IEEE Computer Society's 802 Local and Metropolitan Area Network Standards Committee. The specific goal of this group is to develop standards for short range wireless networks (known as Wireless Personal Area Network-WPAN). There are four groups within the 802.15 working group. Group one works on the (802.15.1) standard which defines the WPAN based on the Physical and Medium Access Control level of Bluetooth version 1.1 [5][6]. Group two works on the (802.15.2) which develops a model for coexistence of WLAN (801.11) and WPAN (802.15). Group three which works on the (802.15.3) standard aims to develop a 20Mbps and higher data flow model in WPAN. Group four is responsible for developing 802.15.4 standards at PHY and MAC level for a small flow of data but with very complex solutions that will extend battery lifetime to years.
IEEE 802.15.4 standard defines physical (PHY) and Medium Access Control (MAC) sub-layers [7]. The structure includes the physical layer, the network layer and the application layer. The physical layer is used for data transmission and reception; channel sensing, channel selection, link quality determination and node state setting. It interacts with wireless channel and supply information to and from the upper layer. This function is important for

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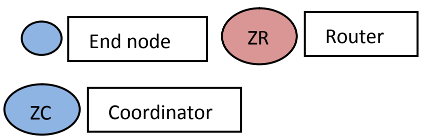
NNGT Int. J. on Networking and Communication, Vol. 1, July 2014

(CSMA/CA) mechanisms where its detailed combination found in [8].

The IEEE 802.15.4 protocol performs energy detection scan (ED) and clear channel assessment (CCA). The different frequency bands, over which the standard works, are available in the Industrial Scientific Medical (ISM) bands [8]:

- 1 channel in the 868 MHZ band with data rate of 40 Kbps.
- 10 channel in the 915 MHZ band with data rate of 40 Kbps.
- 16 channel in the 2.4 GHZ band with data rate of 250 Kbps.

This protocol generally defines three types of nodes: *PAN (Personal Area Network) coordinator*. The main network coordinator identifies its PAN and can be connected to other nodes. In addition, it proposes global synchronization services to other nodes in the network through transmission of beacon frames that contained the identification of PAN and other relevant information. *Coordinator*. It has the same functionality as PAN coordinator, except that it does not create its PAN. Coordinator is connected to the PAN coordinator and provides services for local synchronization of the nodes in its range with significant transfer beacon frames containing the identification of the PAN. *Simple (secondary) node*. It is a node with no Coordinated functionalities. To be able to synchronize with the other nodes in the network, it is connected as a secondary node with the PAN Coordinator (or with the coordinator) [9]. In the IEEE 802.15.4 2003 standard, the first two types of nodes are defined as Full Function Devices – FFD, which means that they implement all the functionalities of the IEEE 802.15.4 protocol. IEEE 802.15.4 supports three types of topologies: Star, Mesh and Tree (that can be considered as a special case of Mesh topology). *Star topology* In this simple topology as shown in Figure 1, a coordinator is surrounded by a group of either end devices or routers. This type of topology is attractive because of its simplicity, but at the same time presents some key disadvantages. In the moment when the coordinator stops functioning, the entire network is functionless because all traffic must travel through the center of the star. For the same reason, the coordinator could easily be a bottleneck to traffic within the network, especially since a ZigBee network can have more than 6000 nodes. *Tree topology* In a Tree network as shown in Figure 2, a coordinator initializes the network, and is the top (root) of the tree. The coordinator can now have either routers or end devices connected to it. For every router connected, there is a possibility for connection of more child nodes to each router. Child nodes cannot connect to end devices because it does not have the ability to relay messages. This topology allows different levels of nodes, with the coordinator being at the highest level. In order the messages to be passed to other nodes in the same network, the source node must pass the messages to its parent, which is the node higher up by one level of the source node, and the message is continually relayed higher up in the tree until it is passed back down to the destination node. Because the number of potential paths a message can take is only one, this type of topology is not the most reliable topology. If a router fails, then all of that router's children are cut off from communicating with the rest of the network. *Mesh topology as shown in Figure 3* is the most flexible topology of the three. Flexibility is present because a message can take multiple paths from source to destination. If a particular router fails, then ZigBee's self-healing mechanism will allow the network to search for an alternate path for the message to be passed [10].



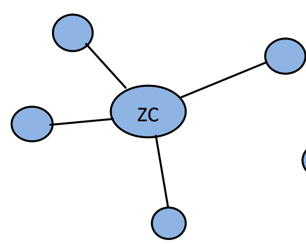


Fig. 1

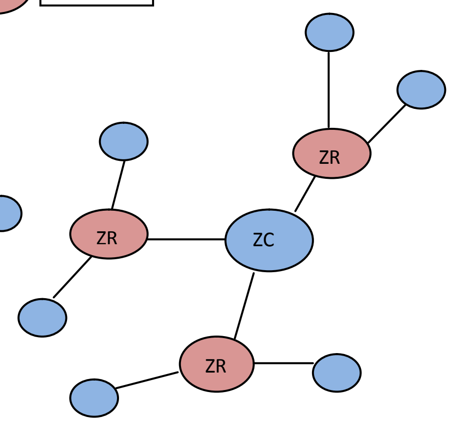


Fig. 2

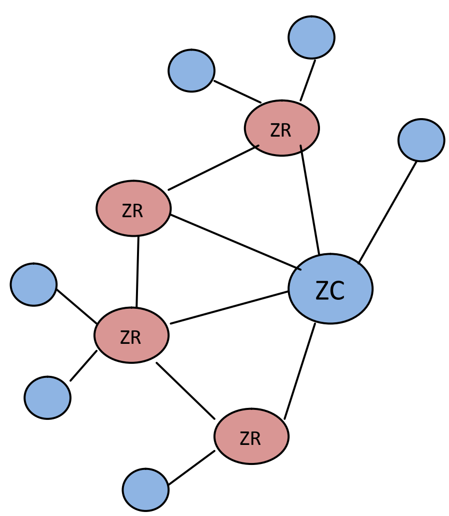


Fig. 3

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3. Network experimental models and simulation parameters

The network models that are used in the simulation for modeling the three topologies are as shown in Figures (4, 5 & 6) bellow:-

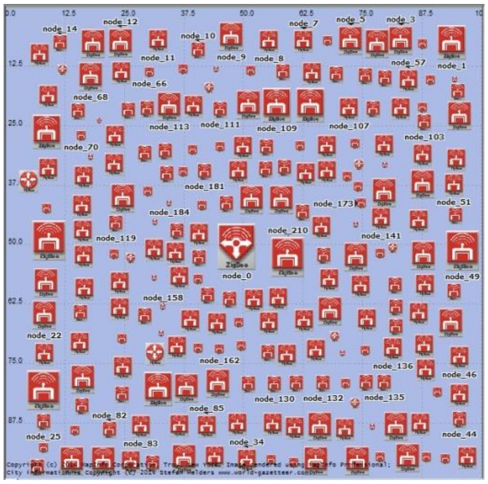

Fig. 4 mesh

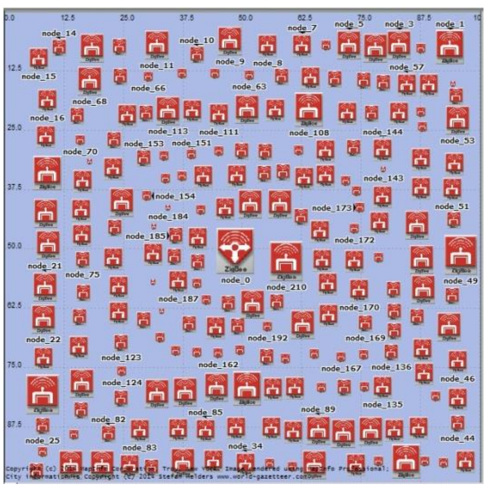

Fig. 5 star

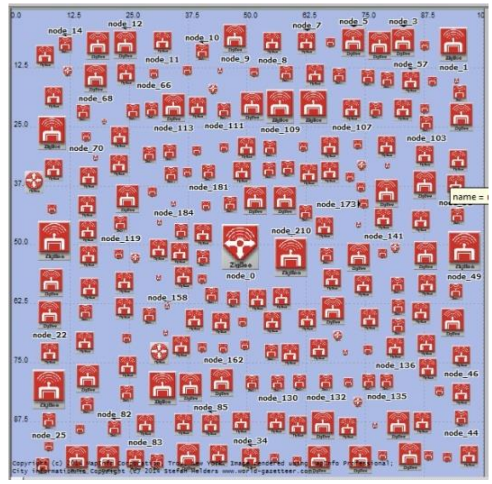

Fig. 6 tree

The settings of parameters that are used in the configuration of network model layers are shown in the tables 1, 2 & 3 as follows:

Table 1: Network layer parametes

Max. number of children	255
Max. number of routers	10
Route discovery timeout (sec)	10
Max. depth	10
Mesh routing	Enable in mesh topology only
Beacon Enabled mode	Disable

Table 2: Application layer parameters

Destination	Random
Packet interval time (sec)	Constant (1.0)
Packet size (bits)	Constant (1408)

Table 3: MAC layer parameters

Ack mechanism	Disable
Minimum value of backoff	3
Maximum number of backoff	5
Channel sensing duration (sec)	0.2
Packets reception power threshold (dbm)	-90
Transmit power (Watt)	0.1
Transmission band	2.4 GHz

It is worth to mention that the parameters beacon enabled mode and acknowledged are disabled because beacon enabled is not supported in this version of Opnet, also acknowledgement can't be used in the case of a large scale topology because it will add an additional load to the network, although it can make the performance better only in the case of small scale topology.
The packet size and backoff values are chosen according to what have been confirmed by previous researchers to ensure maximum throughput.

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4. Models simulation results and analyses

The performance of IEEE 802.15.4 based Wireless Sensor Network is evaluated by changing the number of nodes while keeping the packet size constant. Throughput, number of hops, end to end delay and packet drops are computed for the different network topologies (star, tree and mesh) as follows:-

4.1 Star topology

Network performance is evaluated by changing the number of nodes from 210 to 260 nodes in order to obtain the best performance at which the global throughput is at its maximum (220) value. The throughput increases by increasing the number of nodes up to a certain number (230) of nodes, then it starts to decline, as shown in Figure 7.

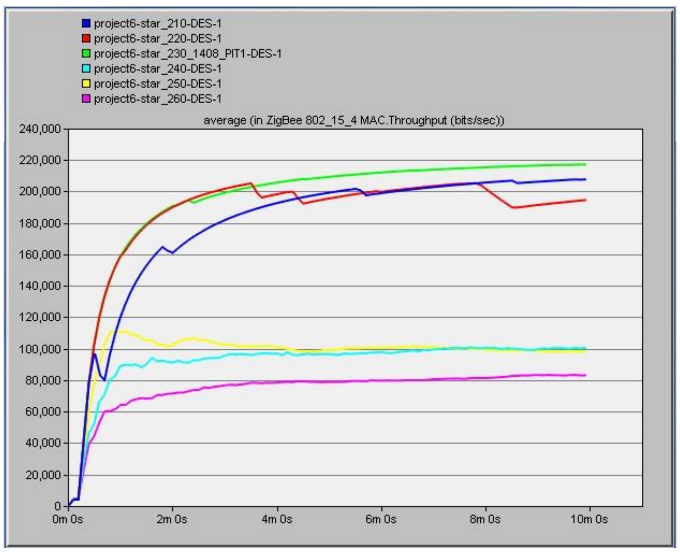

Fig. 7 global throughput

The throughput curve in Figure 7 shows that it is very stable at 230 nodes, while there is a sharp decline in the case of 240, 250 & 260 nodes. The reason behind that is the increased probability of packet collisions by increasing the number of nodes and consequently the probability of packet drops is increased as shown in Figure 8.

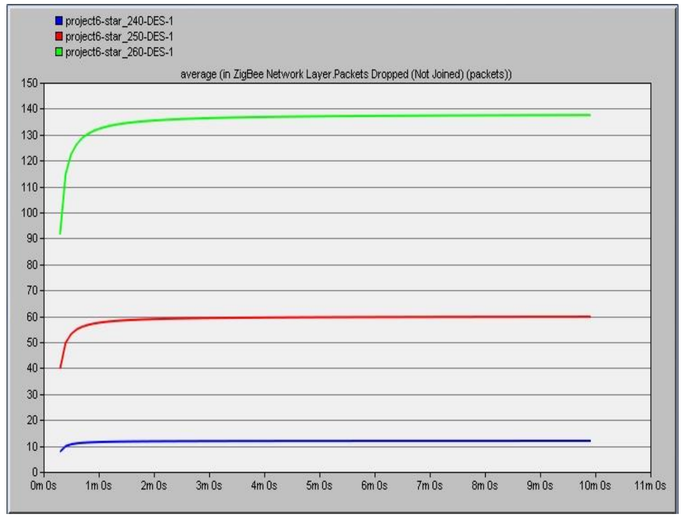

Fig. 8 packet drop

It can be seen that there are 12, 60 & 138 packets drop for the case 240, 250 & 260 nodes respectively, while there is no packet drop in the case of using 210, 220 & 230 nodes. This means that, with respect to the maximum number (240) of nodes (where there is a minimum (12) noticeable number of drop in the packet), an increase of 4.3% in the offered load results an increase of 400% in packet drops, while an increase of 8.3% in the offered load results an increase of 1050% in packet drops.

It can be seen that with channel capacity of 250 kbits/sec there is no packet drop up to node number of 230 (offered load 1408*230 = 323.8 kbits/sec), however as the number of nodes increases to 240, 250 & 260 (i.e. with offered load 337.9, 352 & 366.8 kbits/sec respectively) the packet drops are about 12, 60 & 138 packets respectively. Figure 9, shows that the least average number of hops (1.4) is at 230 nodes which reflect the best throughput.

DOI : 01.IJNC.2014.1.13

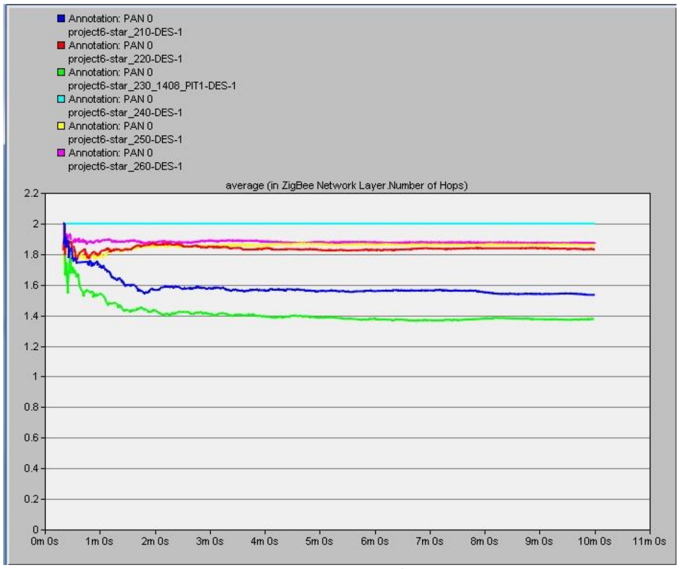

Fig. 9 average number of hops

The least end to end delay is also seen at 230 nodes which is equal to (135 sec) as shown in Figure 10. This is true because it reflects the actual network performance where throughput increases as the delay decreases.

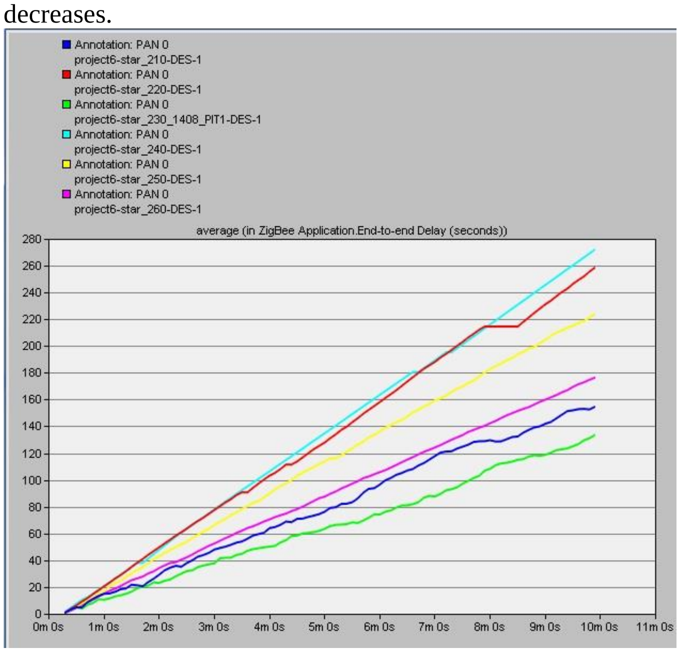

Fig. 10 end to end delay

4.2 Tree topology

For the case of tree topology network modeling; the performance is optimized and the best throughput is seen at 210 nodes and its maximum value is 130 Kbits/sec, then it starts to decrease as the number of nodes increases, as shown in Figure 11.

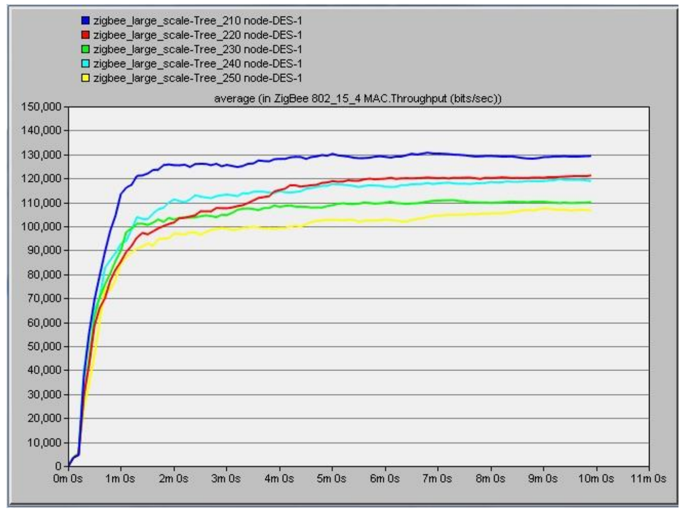

Fig. 11 global throughput

The maximum channel utilization ratio is 52% (130/250) in comparison with star maximum throughput where the maximum channel utilization ratio is 88% (220/250). The reason behind that is the higher probability of packet collision caused by the random access mechanism (CSMA\CA) which occurs at the routers when their child nodes try to access the channel and send their information, as well as the coordinator. Consequently, packet drops and end to end delay increases upon increasing number of nodes as well. With respect to star topology, as number of nodes increase the percent decrease in throughput is lower than that of star topology.

In general, as illustrated in Figure 12, the number of dropped packets increases as the number of nodes increases with maximum value of ~114 at node number of 240. Also increasing the nodes from 210 to 220 (4.7% increase) and 210 to 240 (14.2% increase) causes an increase in packet drops from 60 to 83 (38% increase) and 60 to 114 (90% increase) respectively.

In comparison with star topology the packet drops is lower and for the same increase in the node number, the percent increase in packet drops is much lower. The reason behind that again is that the nodes are distributed on the routers and every group (child nodes) are competing to access the channel through a certain router, while with the star topology case all the nodes are competing on the same coordinator, this results an increase in the end to end delay which has a higher impact on decreasing throughput.

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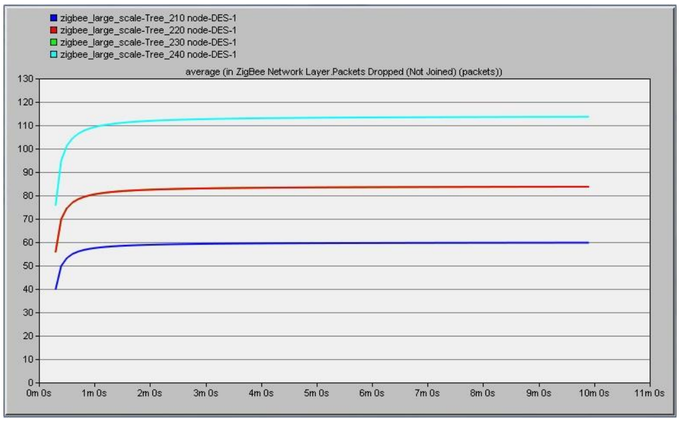

Fig. 12 packet drop

Figure 13, shows the end to end delay variation for different number of nodes; and it can be seen that 210 nodes, (where the throughput is maximum), has the highest end to end delay (about 250 sec).

The reason for that is in tree topology WSN there are multiple hops for the node data to reach the tree root (coordinator), depending on how many hops the router is far away from the coordinator. The main target of using routers is to make load balance because the nodes are not directly connected with the coordinator, so the data takes more than a single hop to reach their coordinator (unlike the star topology which is a single hop topology), and this has an impact on the delay. To get the highest throughput more nodes should be involved in the data transmission over the whole network as a result and again due to the multihops mechanism the highest average end to end delay is associated with the highest throughput.

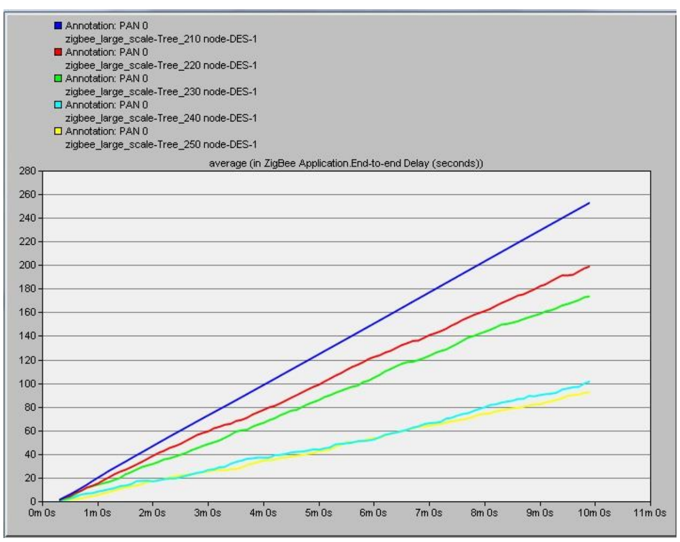

Fig. 13 end to end delay

It is worth to mention that the end to end delay decreases as the number of nodes increases beyond 210, the reason for that and as it has been mentioned earlier (and shown in Figure 12) for a certain percent increase in node number beyond 210, the percent increase in packet drop is much higher.

Figure 14 shows the average number of hops variation for different number of nodes values, again it can be seen that the maximum (~2.05) average number of hops is seen at node number of 210 where the throughput and end to end delay are maximum (i.e. where the maximum number of nodes are taking part in the data transmission over the tree networks)

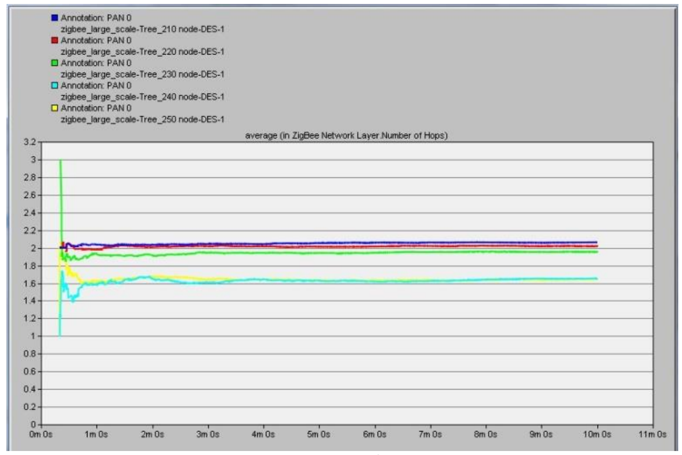

Fig. 14 numbers of hops

4.3 Mesh topology

Figure 15 shows that despite of the maximum throughput value (around 168 kbit/sec) which is seen at the beginning of simulation for 240 node number , however on the long time the best stable throughput performance (around 138 kbit/sec) is seen at node number of 210. For the 240 nodes case, at the beginning of simulation, this is justified by the relatively higher number of children nodes that can join the first and second hop routers for shortest or fastest (less congested) routes to destination, while for the steady state (long time) performance region, there will be a relatively higher number of children nodes that will join the third and higher number of hop routers, this will result comparatively higher number of drop packets and as a result lower steady state throughput performance (around 130 kbit/sec). Also it is worth to mention that the throughput for this network topology is relatively higher than that for the tree network topology, the reason behind that is the data from end nodes in the mesh network topology can take different (the best shortest or fastest) routes or paths to reach the destination depending on the mesh routing algorithms.

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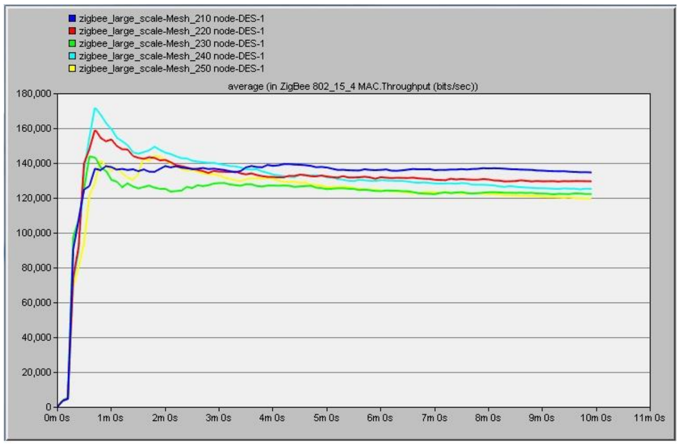

Fig. 15 global throughput

Figure 16, shows that the packet drop increases as the number of nodes increase, it can be seen that the steady state packet drop, are about 56, 78 and 102 for the node number 210, 220 and 240 respectively. It can be concluded that, (with respect to the 56 packet drop at 210 node number), for a 4.7% and 14.2% increase in the node number the percentage increase in packet drop are about 39.3% and 82% respectively.

In comparison with tree topology, the percent increase in packet drops as number of nodes increases is slightly lower than that of the tree topology, again the reason for that is the different or multipath routes that can be taken by the data to reach the destination according to the mesh routing algorithms.

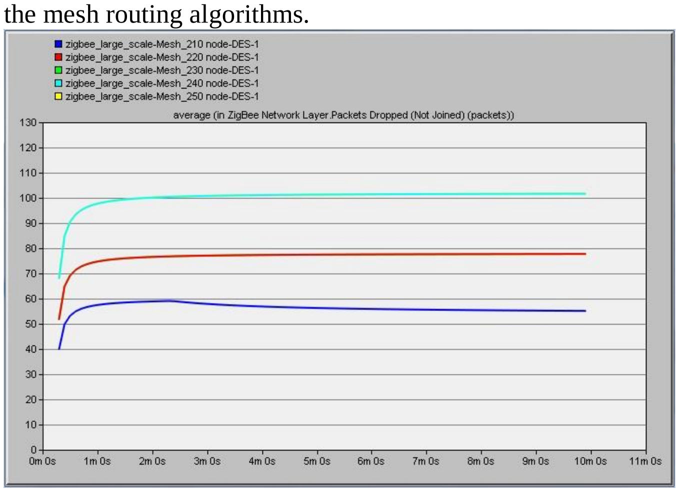

Fig. 16 packet drop

Figure 17 shows the end to end delay. It is seen that the delay is high at 220 nodes.

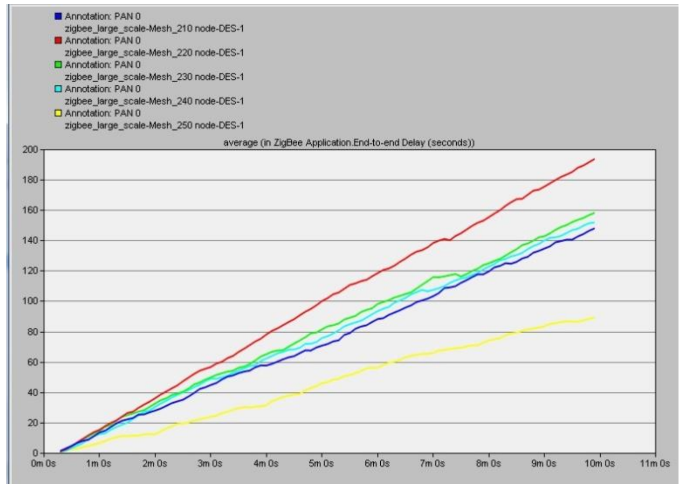

Fig. 17 end to end delay

Figure 18 shows number of hops. It is seen that the highest average number of hops (2.1 hops) is found at 220 nodes.

In a compression with tree topology, we can see that end to end delay is lower while the number of hops is almost the same. As its mentioned before the reason behind that is in mesh topology the data can take multiple paths or roots (shortest or fastest) to reach the node coordinator according to the mesh routing algorithms.

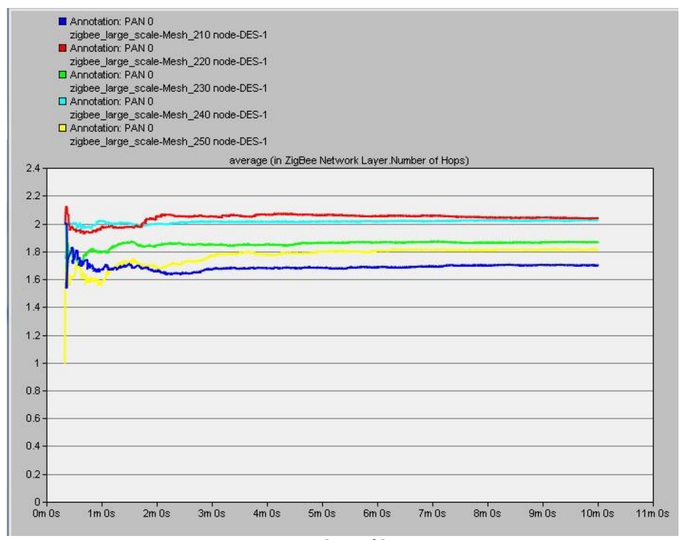

Fig. 18 number of hops

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5. Conclusion

In this paper the designed models are simulated to trace the effect of changing the number of nodes on end to end delay, throughput, packet drop and number of hops for different network topologies. For a network with size of 255 nodes it is found that the maximum throughput is at 230 nodes/ star topology (about 220 bits/sec) with end to end delay equals to 138 sec and average number of hops equals to 1.4, without any packet drop. In the second place is the throughput of 210 nodes/ mesh topology (about 140 bits/sec) with end to end delay equals to 147 sec and an average number of hops equals to 1.4, with packet drop of 55 packets. In the last place is the throughput of 210 nodes/ tree topology (about 130 bits/sec) with end to end delay equals to 258 sec and number of hops equals to 2.1 and packet drop of 60 packets. There are many different types of applications of wireless Sensor Networks, but each application needs its own topology. We can conclude that a star topology, for example, is very suitable for biomedical applications because of its single hop and fast delivery of information with a stable and saturated throughput, so that it can be used with up to 210 nodes almost without any problem, but in different applications, where the range is required to be expanded, routers are introduced to form a tree or mesh topology; therefore the maximum number of nodes can be employed in the field according to the desired topology and relevant application.

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