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ZigBee-Based wireless sensor network topologies using one and multiple coordinators

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ABSTRACT

Wireless Sensor Networks (WSN) have been a cost-effective and feasible solution for a wide range of applications, such as communications infrastructure, traffic networks, telecommunications systems, military operations and so forth. IEEE804.15.4 ZigBee network model is ideally suited to the constraints of WSN in terms of bandwidth, processing power and battery capacity. This paper investigated tree and mesh routing in WSN with multiple coordinators and the failure of single coordinator using OPNET Modeler v14 which is an efficient computational platform for data networks simulation. Throughput, delay, traffic received, MAC Load are studied in this system and the results showed that tree routing was better suited for WSN than mesh routing and mobility of end node in multiple coordinator network was the best.

Keywords: Wireless Sensor Networks, Mobile Sink, Energy**,** OPNET**,** IEEE804.15.4ZigBee

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1. Introduction

Wireless Sensor Networks (WSNs) [1] are spread in regions according to their importance. To achieve collaborative effort of sensor nods, these are low-resources devices that can be employed to meet the target of the network. The main purpose of sensors is to collect readings from many locations at different time slots and send them to the main rich-resources device through one-hop or multi-hop techniques.
Due to their properties in terms of size and price[2].
WSNs are used widely into different applications including military, environmental, commercial, health and biological application [3]. WSNs are the basic of Internet of Things (IoT) [4] which is the base of the smart cities based on different radio frequency communications media such as ZigBee[5].
In this paper, 802.15.4 ZigBee is used to introduce the WSN model. ZigBee is a communication standard of WSNs. It follows IEEE802. 15.4 [6] and Mac layer criteria. It takes the form as a structured network layer that supported by security services which allowed them to be used for embedded systems.
ZigBee is significant, because it corresponds with wireless censoring networks. Due to the decrease in data, low cost devices and long-life batteries qualifications.
OPNET Modeler v 14 is used for simulation[7]. The performance of different topologies is studied in order to show the suitable one for WSNs with mobile end device.

1.1. Wireless sensor networks

As aforementioned, WSNs are a group of sensors spread readings and information about a phenomenon that has been observed. Typical WSNs follows the hierarchical methodology where they are consist of poor-resources sensors that contact with single or multiple rich-resources Base Stations (BS) through internet or gateway as shown in figure 1[8, 9]. The topology is formed based on the requirements of the application and sensors should be able to process the income readings and communicate with the neighborhood.
figure 2 represented the typical WSN's topology where intermediate nodes forward data to the sink (BS) from other far away nodes. Sensor nodes are battery-supplied devices usually less than 0.5 Ah 1.2 V batteries[10] and theses batteries can be rechargeable and non- rechargeable and they are considered to be dead if they ran away of energy and the total network can be dead if a region of it is isolated from the other region or if a proportion of sensors are considered to be dead.

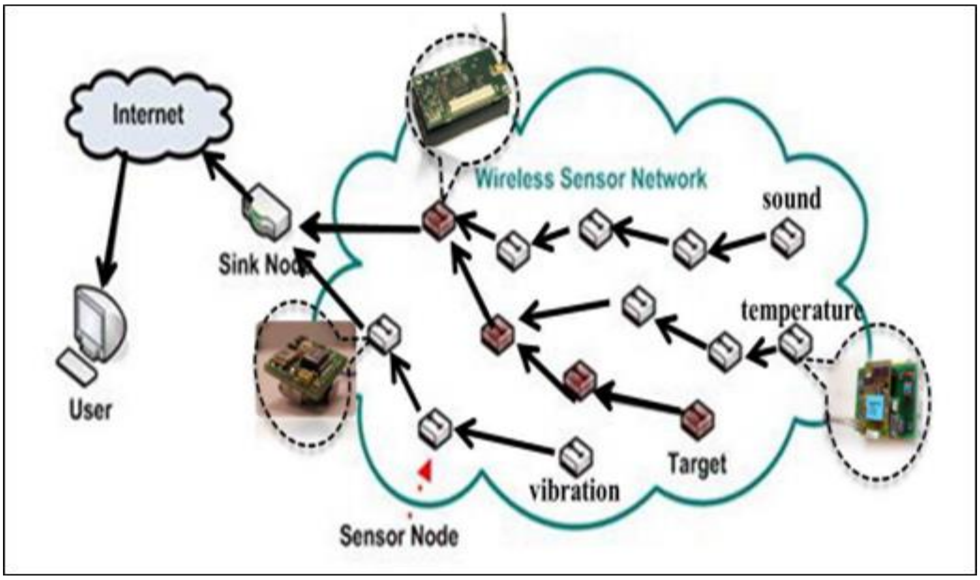

Figure 1. Wireless sensor network typical topology[9]

WSNs are belonged to the Low-Rate Wireless Personal Area Networks[11] referring to the limited range of communication.
The communication media[12] between nodes and the Base Station is the backbone of the network performance. Networks are designed based on applying requirements, data rates, scalability, consumed power, network life average and security. The communication protocol is employed according to these requirements. Usually, low-power communication systems are employed including Bluetooth[13] ZigBee [14] and the IEEE 802.15.4 [15]standard and TinyOS [16].

1.1. WSNs representation

WSNs differ from the conventional networks by their limits of power, size, no manual maintenance, environmental conditions and low bandwidth and processing capabilities. On the other side, their properties in terms of self-organization as well as dynamic network topology and multi-hop technique make them seemly for several applications. Due to the aforementioned critical limitations. Networks are usually simulated before being applied. This simulation helps to improve the network efficiency discover and avoid the expected errors and to test and validate the best situation topology and communication system of the network. ZigBee, which is IEEE 802.15-based specifications, is a common WSNs platform. Its importance stems from its properties in terms of energy consumption data rate and delay. These properties make it compatible to many and varied applications such as home automation and industrial control. ZigBee-based networks are difficult to be managed because of ZigBee dynamic structure. However, on the other side, they achieve their requirements and the desired stability.

1.2. ZigBee and IEEE 802.15.4

The ZigBee agreement is a consortium of companies that are working collaboratively providing wireless products with low-power and cost, in order to control networks, dependent on open standards.
It consists of 200 organizations including 14 promoter organizations like samsung, motorola and philips. Based on their version 1.0 which is released on Dec. On 2004 the next version is released on Sep. In 2006 supported by multicast, termination device and routing mobility.

1.3. IEEE 802.15.4

IEEE 802.15.4, is a very widely adopter protocol, where data rate, consumption and communication cost are low [17]. It is employed widely in the wireless personal area networks. Its properties qualify it to be used for different applications if its parameters are tuned appropriately. In addition and due to the use of GTS mechanism, IEEE 802.15.4 is considered to be suitable for real-time applications.
As defined in the ZigBee standard, GTS mechanism is very compatible with time-sensitive applications especially if employed into cluster-tree topologies. IEEE 802.15.4 MAC is based on CSMA/CA[18] mechanism of station sensing. Two variations of access are available: Beacon Networks, where slotted CSMA/CA is used

and Non-Beacon networks, where Un-slotted CSMA/CA is used. BPSK [19], ASK[20] and O-QPSK [21] are three modulation types specified by IEEE 802.15.4.
While BPSK and O-QPSK depend on phase modulation, ASK depends on signal amplitude modulation. The two energy-spreading techniques of direct and parallel sequence spread spectrum [22, 23]are detailed also. These techniques qualifythe IEEE 802.15.4 standard to be used for applications with multipath and accordingly is an important choice for many cases.
The main operation modes of IEEE 802.15.4 are:
PAN coordinator: its main function is to define the network and its configurations. In addition, to connecting other devices to the network. It is referred to in ZigBee as ZC.
The coordinator: this device uses beacons for synchronization purposes. It must be affiliated with the PAN controller and not construct its own network. It is referred to in ZigBee as ZR.
The End Device: it does not perform any of the aforementioned missions.
It should be connected with ZR or ZC before interacting with the network. It is referred to as ZED. The reduction function device is a terminal device that runs at least implementation of IEEE 802.15.4. it is used for simple functions as it is not capable to carry large amount of data.

1.4. ZigBee

The ZigBee layer is implemented that depends on IEEE 802.15.4 PHY/MAC to provide the typical network layer tasks, such as routing and neighborhood discovery. Network size can reach nearly 65535 devices of 16 bit adders. It could be a star or mesh topology. The network is highly robust due to the connections between devices where devices are only forbidden to communicate with PAN coordinator, and the self-formation property.

Published ZigBee devices automatically make the network and then modifies according to the joined and left devices. ZigBee has a small transfer rate with 250kb/s compared to bluetooth and WiFi with 1 Mbps and 54 Mbps data rate respectively. As applications are battery powered, ZigBee transceivers can be active for short time compared to longer sleep time where low energy is consumed, which allows the network lifetime to be extended for several years.
Frequency bands of ZigBee can be summarized as follows:
The 868 MHz frequency band: ranges from 868 to 868.6 MHz.It is used for low coverage radius networks in Europe.
The 915 MHz frequency band: ranges from 902 to 928 MHz. It is pieceof the industrial, scientific and medical frequency attach (ISM) that are used in North America.
The 2.4 GHz band frequency: ranges from 2400 to 2483.5 MHz. It isa part of ISM and used over the whole world.

1.5. ZigBee architecture

Application and networks layers of OSI model are defined in ZigBee [24] where each layer serves the upper one. The communication between the two layers is performed through SAPs. there are two type of topologies of entity exchange: the first type: sends data by using NLDE-SAP. The second type by which management, services are exchanged by using NLME-SAP management entity. The EndPoint 0 is reserved for ZDO, which provides describes the provided service while the set of locations between EndPoint 1 to 240 are reserved for the application objects. Each application object is addressed uniformly using the device address and available EndPoints. The ZigBee profile is a group of ZDOs including their configuration and jobs. It goals to be a unified that the acting of common application cases. Typically, the available ZigBee profiles consist of:
Network Definite (stack identifier 0).
Home Regulator (stack identifier 1).
Building Automation (stack identifier 2).
Plant Monitor (stack identifier 3).
Network management is the responsibility of the ZigBee network layer. It is answerable of the topology such as the nodes that join and leave the network. Moreover, to the security, routing procedures and ensuring the continuous update of the neighbor table. NLDE-SAP is the only type of interfaces provided by this layer which is responsible of data exchange with SAP.
The functionality of the IEEE 802.15.4/ZigBee devices classifies them into two categories: full and reduced function devices where the full stack is defined completely and partially respectively.
Network devices can be categorized based on their role into:

ZigBee coordinator: it is answerable for network setup, maintenance and control, where each network has just one coordinator. If the network follows the cluster-tree topology, then every ZR exchanges beacons with its neighbors for synchronization purposes.
ZigBee Router: the router forwards the sensor readings from their locations to the sink. It follows the multi-hop and associates with ZC or cluster-tree topology ZRs. It is a full functional device.
ZigBee End Device: the end device is poor for this guidance and forwarding capabilities. It it is not allowed to communicate with other devices or to route data. It behaves just as a sensor/actuator node.
As shown in figure 2, three network topologies are enabled by IEEE 802.15.4/ZigBee as follows:
The star topology: it is a centralized topology [25] where all communication and management between terminal nodes is performed through a central node which behaves as a ZC. ZC uses a unique PAN identifier through its neighborhood. This topology suffers from two main problems; a) the centralization of the node where much work depletes its energy and therefore stop the network and b) the limited coverage radius of IEEE 802.15.4/ZigBee which leads to scalability problems.
The mesh topology: to overcome the obstacle of node centralization this topology allows each node to communicate directly with other nodes in its range using one-hop or multi-hop techniques[26]. On the other side, this comfortable communication compounds the complexity and expected delay. The other benefit of this topology is the efficiency of power consumption where no node is prone to deplete its energy soon and therefore the lifetime of the network is extended.
The cluster-tree topology: this type of topologies is highly suitable for networks which are low power consumption and low-cost [27]. Due to these properties cluster-tree topologies are used widely in SWNs, but on the other hand they suffer from many disadvantages such as the cost of failure is very high in terms of network lifetime or maintenance overhead. in addition, there is a misuse of the bandwidth because of the prevention of many paths routing.
The sudden traffic is also possible if a particular region of network is needed to be accessed. In terms of architecture which is distinctive and high-interacted cluster-tree. The connection between any two nodes follows one path and they are disconnected if this path was corrupted. There is one ZC which sets the network fully and ZR for each cluster. Any device inside the group can be ZR.
Compared to AODV protocol of mesh networks routing protocols within the cluster-tree network is usually reduces the routing overhead because they don't need huge processing requirements. In addition, AODV provides many paths for one node to communicate with its neighbor node, while in cluster-tree network; these redundant paths are eliminated to one path which makes them more prone for failure.

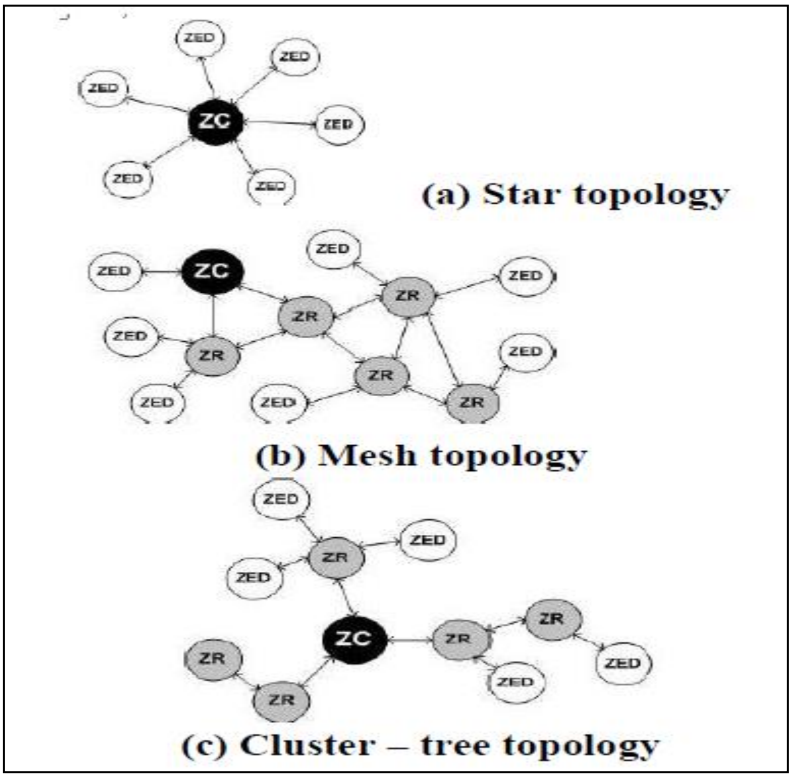

Figure 2. ZigBee network topologies[23]

1.6. ZigBee Routing

The following are the ZigBee routers and coordinators functions:
Route discovery: to deliver consequent data sent by the source node through relay nodes in their forwarding path to their destination, on behalf of higher layers and other ZR.
Data frames relay: on behalf of upper layers and other ZR.
Repairing and initiating routes includes local and end-to-end routes.
Metrics employment: metrics of ZigBee path cost are employed according to the route discovery and repairing specifications.

ZigBee routers and coordinators support three routing schemes as follows:
Neighbour Routing: in this scheme[28] each device has its own neighbour table where all of its discovered 1-hop neighbours are listed. If the destination is already listed in the table, the data frame is delivered directly, elsewise, it will be sent through the best neighbour can deliver it to the destination. Table 1 entities include PAN identifier, cluster expansion address, the used network address, the type of device containing information and the relation among them. In addition, as optional choice, information about beacon request, depth or declaration joining can be entered.
Table Routing: this scheme is more suitable for unicast and multicast routing[29]. It depends on AODV routing algorithm which is considered to be on demand routing. In other words, it means that the source initiates a route to the destination just when it needs that and maintains that route in its table as long as it is needed.
Tree Routing: in this scheme [30], The images are directed in the form of pyramid, rather with the current or against it, bared on the address. Cskip address allocation mechanism is adopted, where each device distributes its address space to its children. The device that hasn't routing table or route detection capabilities. It is simply forward its data to the next tree based on the destination address. The limited use of resources enables any device to participate in the network.

2. Research method

System simulation is to model the operation of the system and therefore study different system situations before real employment especially for critical and expensive models. Simulation helps to specify the expected bottlenecks of the system before it are employed actually which is an evaluation of requirements meeting optimal utilization and performance.

2.1. Wireless sensor networks simulators

The following are main three simulators are used for wireless sensor networks simulation[31]:
NS2: a discrete event-based simulator [32] that is appropriate for both wired and wireless networks. It allows extensive parameters to simulate TCP/IP, routings and multicast protocols. Its implementation takes into consideration the two-beam radio propagation model reversal approximations for the physical layer while link layer is built based on IEEE 802.11 MAC protocol. Monarch project has a developed network layer that is a dynamic source for routing.
J-Sim: a plug-and-play modular[33]. It is suitable for real time devices. It is component-based discrete event object-oriented simulator. Its efficiency stems from its ability to model the wireless sensor networks elements in terms of sensors, sinks communication systems and physical layer.
OPNET: it is more suitable for simulating finite state machines and their approaches and the top-level processes[34]. The connectivity between nodes is measured by using 13 stage pipelines. For communication models different properties can be determined such as the bandwidth, data rate, frequency and antenna gains.

2.2. Introduction to OPNET modeler

OPNET is an efficient computational platform for data networks simulation. Communication systems and distributed networks can be modeled efficiently due to OPNET powerful environment. In addition, its GUI makes it friendlier to designers, especially in terms of behavior and performance analysis.
OPNET identifies three hierarchical configuration levels:
The network level: which implements the investigated network.
The node level: which describes the node behavior and control the data flow through the node interfaces and functional elements.

The process level: it is represented by states and transitions between states according to the Finite State Machine (FSM) mechanism.
OPNET modeler is built on C/C++ programming language and different built-in functions which enables that the analysis results can be shown into different representations.
OPNET helps in simulating ZigBee networks by providing different fixed and mobile ZigBee objects including devices coordinators and routers according to the standard specifications. For simulation purposes, processing models are used includ:
ZigBee mAC model: it is built depending on IEEE 802.15.4 MAC protocol[35]. Processes of station scanning joining, and disaster recovery are built according to the un-cracked mode.
ZigBee application model: it is a low issuance of ZigBee application layer [36]. Processes are network joining and formation and generating traffic and reports.
ZigBee CSMA/CA model: provides the media acceptance protocol that is needed by the MAC layer[37].
ZigBee network nodel: in this model, the ZigBee network layer is implemented according to the standard specifications. Processes of beacon generation, routing, formation and network joining are provided by this layer.
These models can qualify to build a network very close to the real network behaviors and thus helps in its behavior and results analysis and to modify their parameters. To run the network, it is needed to build the topology according the required attributes and specify the required metrics of analysis. OPNET helps to analyze these metrics on the global network and individual node level.

2.3. Design methodology

In this paper, mesh and tree routing are studied. A part of the used routers and end devices use one PAN coordinator while the other part uses multiple PAN coordinators. One coordinator is proposed to have a failure to study its effect on the network performance. Fivescenarios are studied. Each scenario involves a number of end devices routers and one to three coordinators. The studied scenarios can be explained as follows:
Scenario 1 (tree routing): as shown in figure 3 this tree network consists of number of routers and termination devices that are linked to one controller.
Scenario 2 (mesh routing): as shown in figure 4 this mesh network consists of number of routers and end devices that are linked to one controller.
Scenario 3 (controller Failure): as shown in figure 5 this network contains of numbers of routers and end devices that are linked to two controllers where one of them is chosen to be failed.

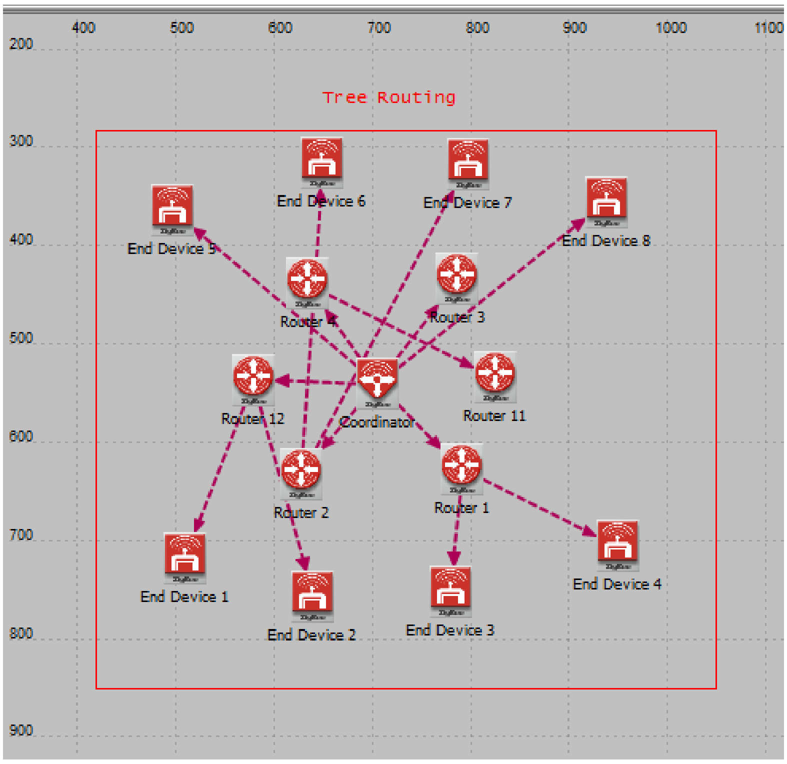

Figure 3. Tree routing

Figure 4. Mesh routing

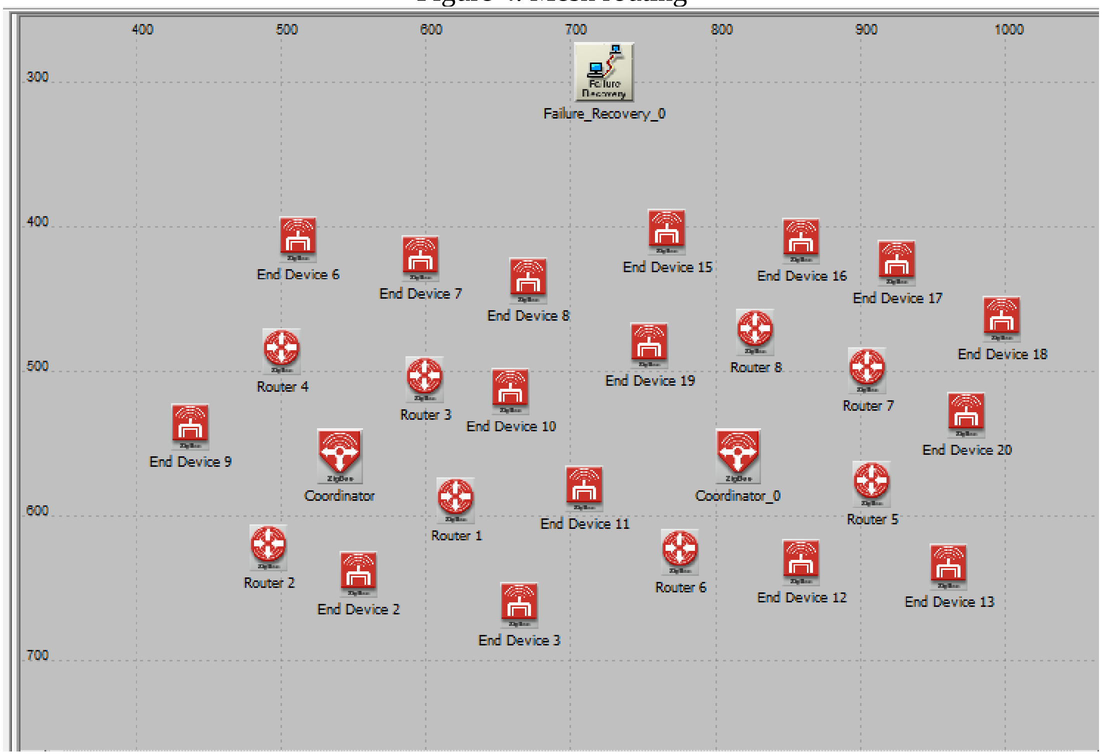

Figure 5. Coordinator failure

Scenario 4 (a mobile ZigBee node passing through the radius of double PANs): as shown in figure 6 this network involves of number of routers and termination devices that are linked to multiple controllers with a mobile node where the trajectory starts from there.

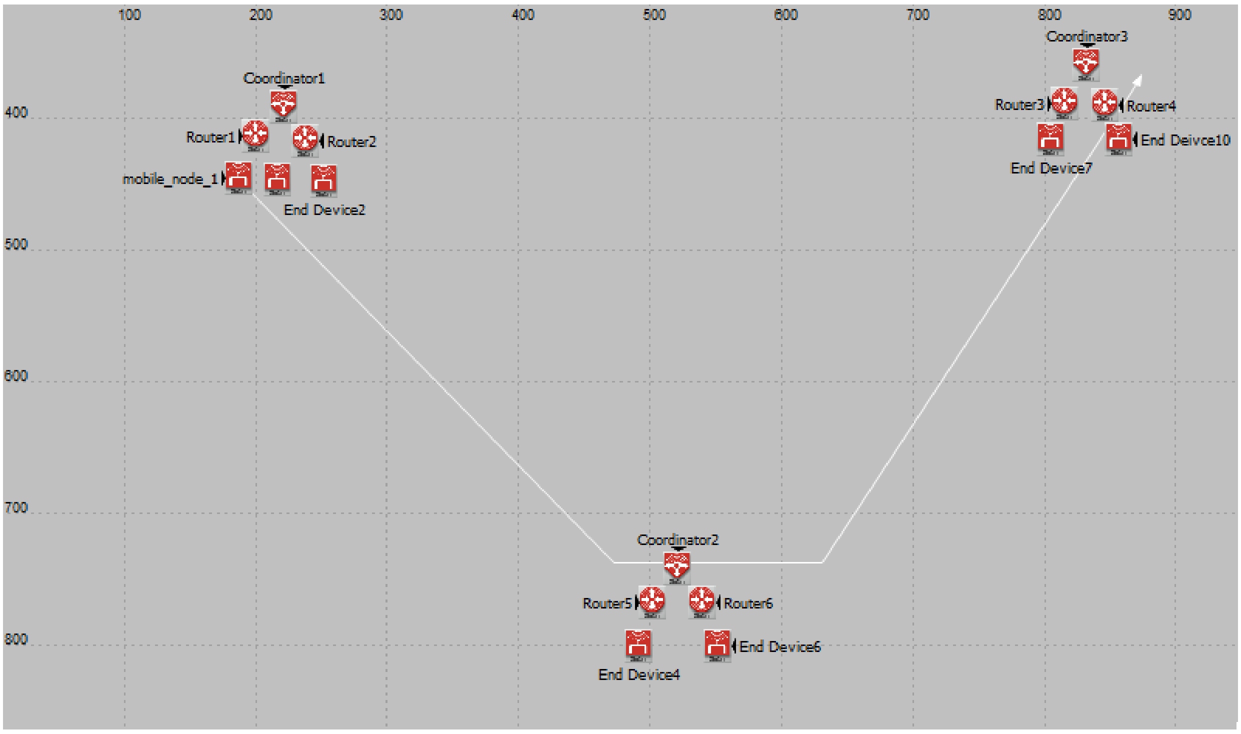

Figure 6. A mobile ZigBee node passing through the radius of double pans

Scenario 5 (the path was from termination device node): as shown in figure 7 this network contains of numbers of routers and termination devices that are connected to several controller. Direction is through moving nodes in which the path starts from the terminal nodes instead of the mobile nodes as in scenario 4.

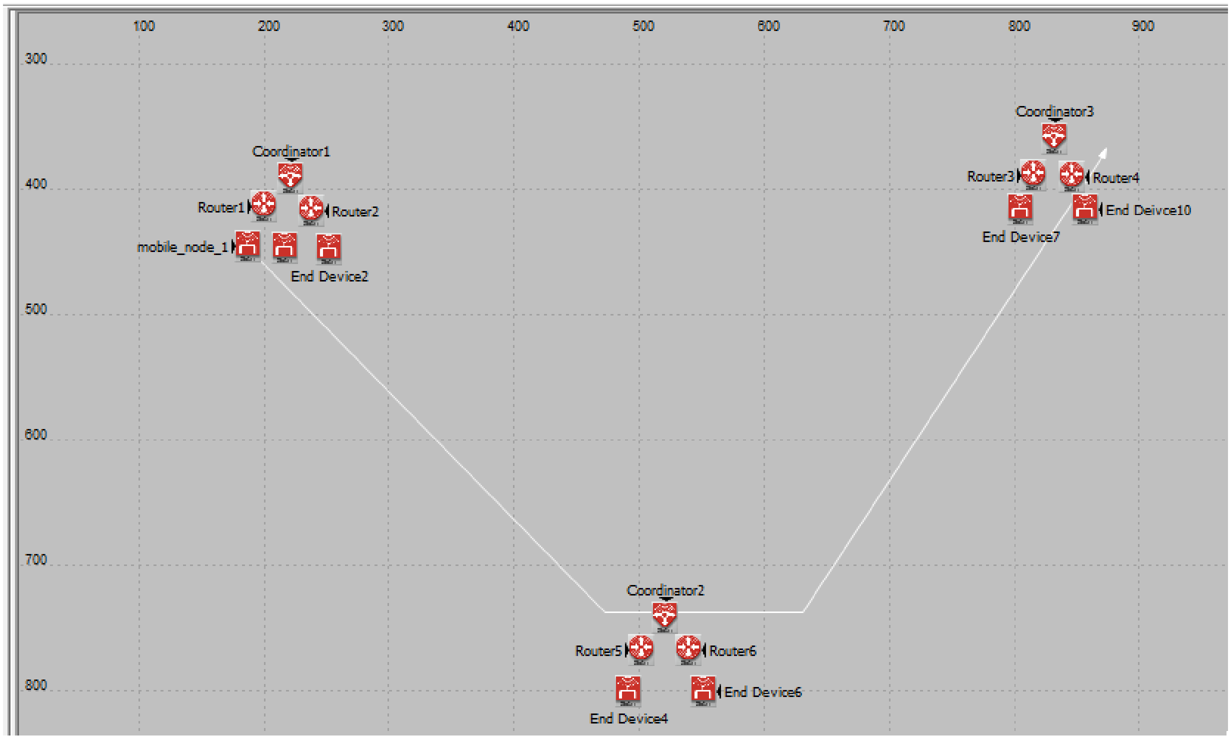

Figure 7. Multiple controllers with the path was from trmination device node

3. Results and discussion

To study and analyze the network performance, the following parameters are chosen to make statistics about them:
Throughput: measured by bits per second (bit/sec). It is the representation of the number of bits that are forwarded to the upper layer in whole nodes of the network. Figure 8 shows the Productivity for both the mesh and tree routing. The throughput of the termination node when the path was from it and when it is from the mobile node is shown in figure 9.

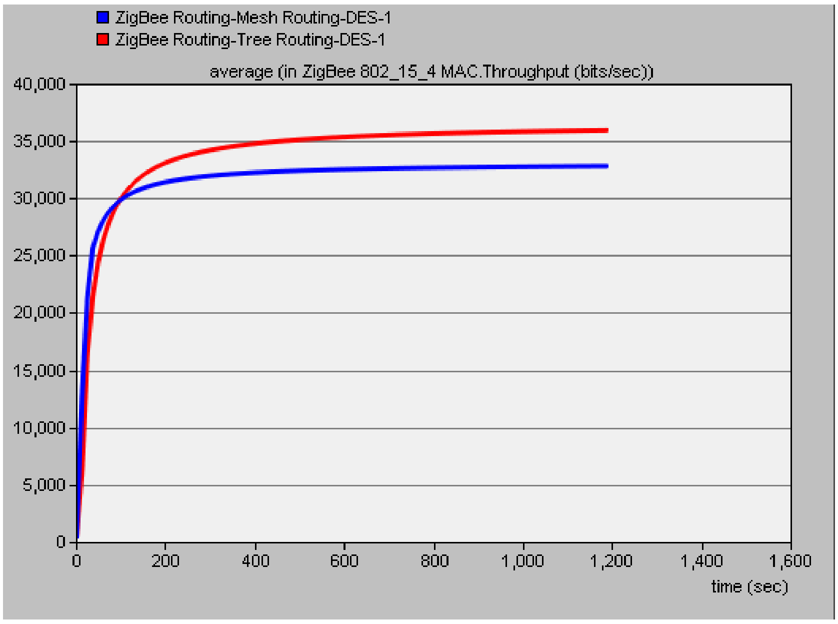

Figure 8. ZigBee 802_15_4 MAC throughput (bits/sec)

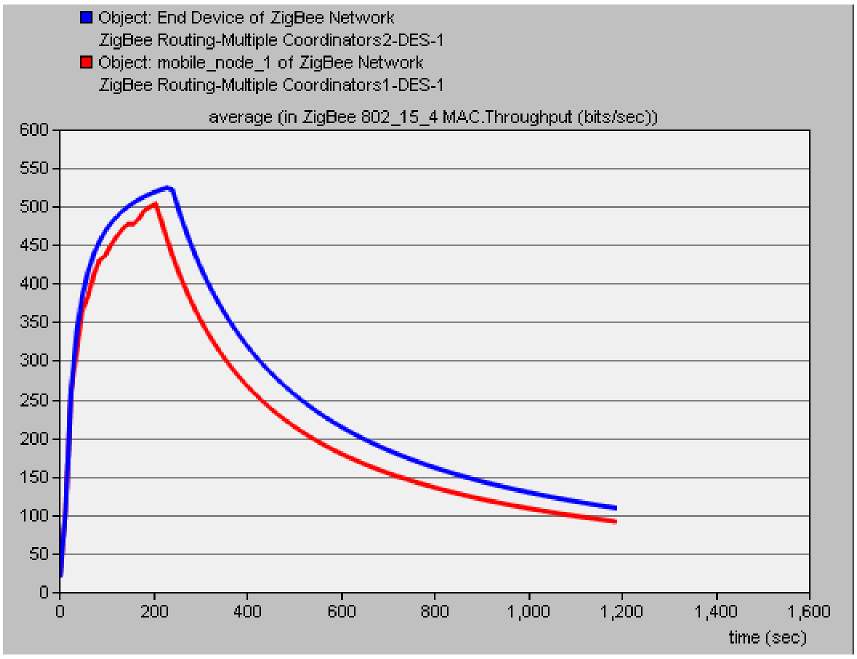

Figure 9. ZigBee 802.15.4 MAC throughput (bits/sec) for multiple coordinator

Delay: it is measured within a second. It is viewing of the delay between two parties. By which received packets from all nodes in the network are collected via Mac layer. Figure 10 shows the delay for both the mesh and tree routing.

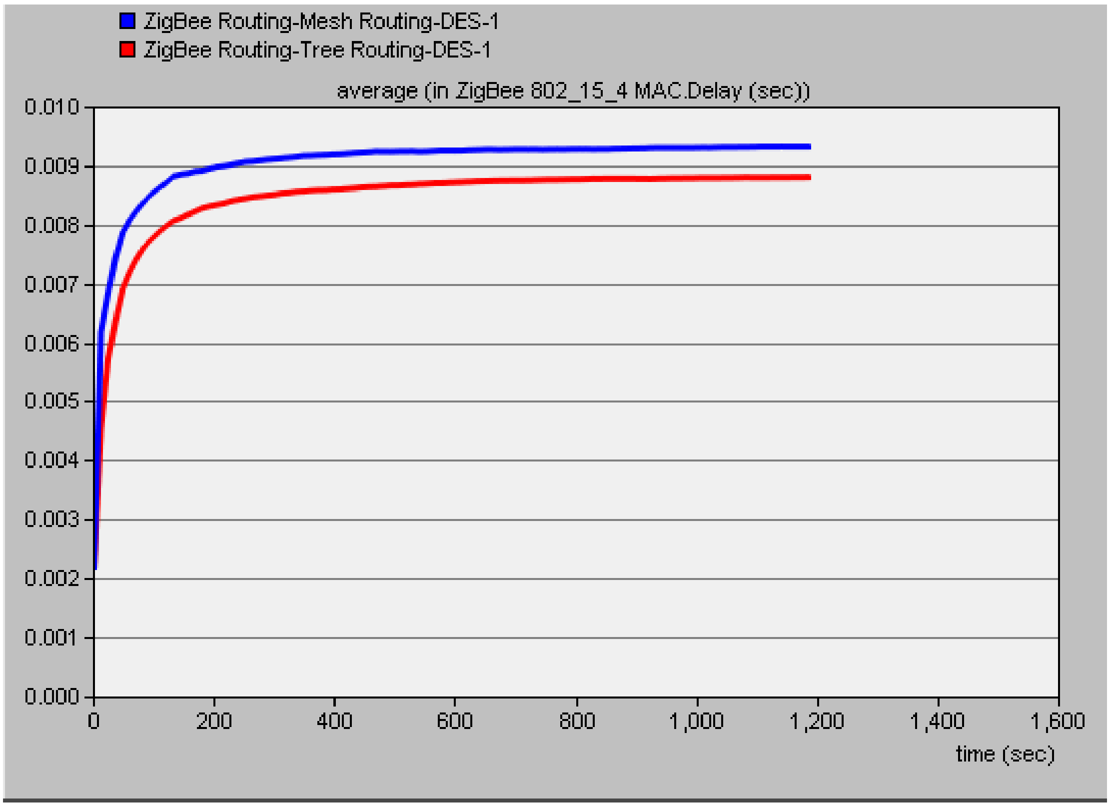

Figure 10. ZigBee 802.15.4 MAC Delay (sec).

End to end delay: the total delay consumed by the process of generating the packet and the transfer of the node. It is shown in figure 11.

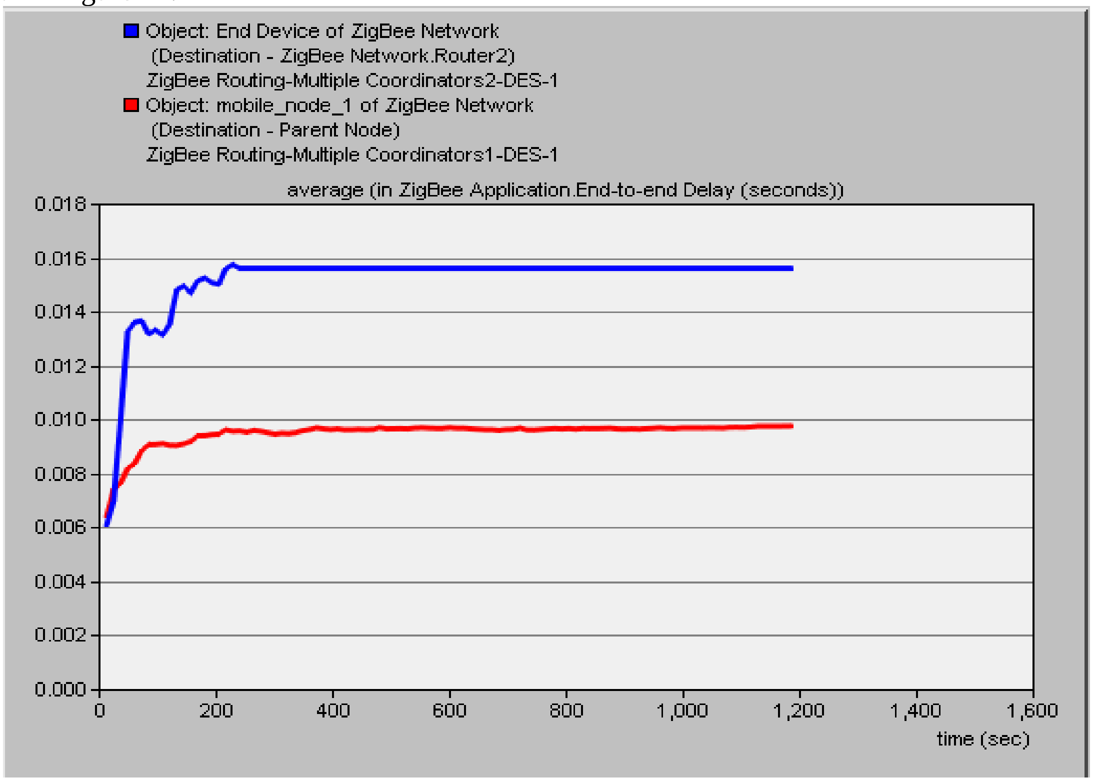

Figure 11. ZigBee application end to end delay (sec) for multiple coordinators

Load per PAN: measured by bits per second (bits/sec). It is a representation of the number of bits that are submitted to the MAC layer by the upper layer in a node per time unit. It is shown in figure 12.

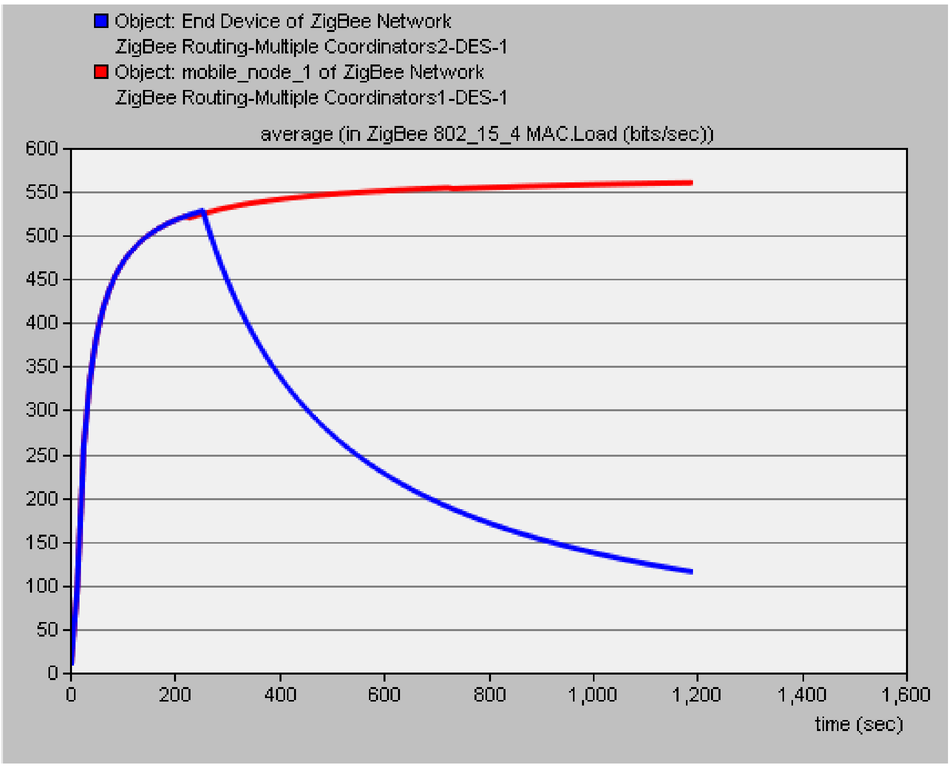

Figure 12. ZigBee 802.15.4 MAC Load (bits/sec) for multiple coordinators

Received data traffic: measured by bits per second (bits/sec). It is a representation of the number of bits that are positivelyreceived from the MAC layer in a time unit including the transmissions. The received data traffic for the five scenarios is shown in figure 13.

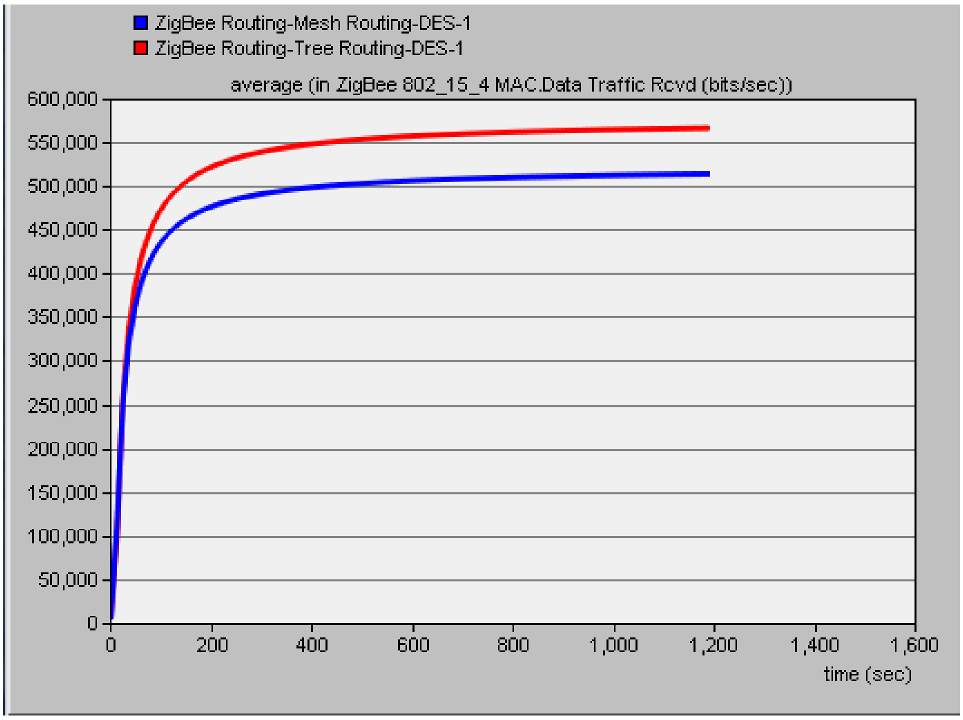

Figure 13. ZigBee 802_15_4 MAC data traffic received (bits/sec)

The global received data traffic for each PAN is also analyzed as shown in figure 14. Figure 15 shows the global received data traffic for each pan in case of multiple coordinators model.

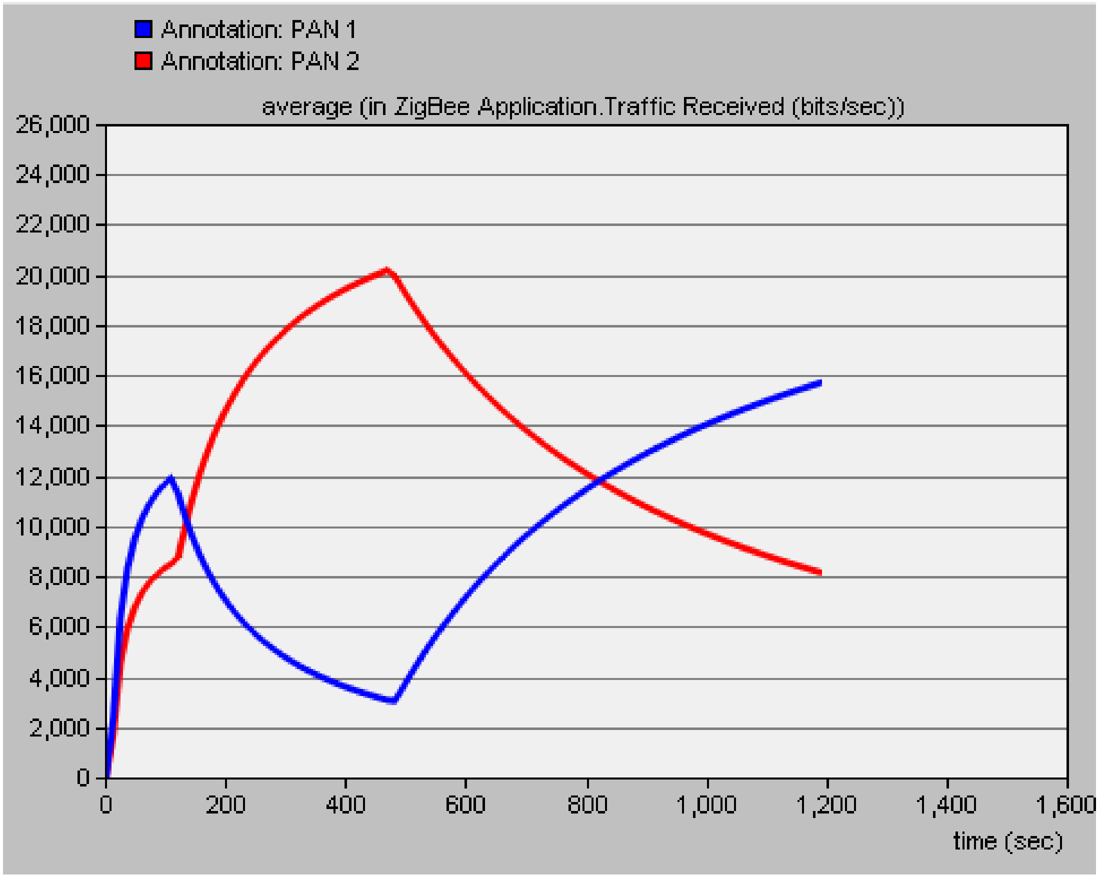

Figure 14. ZigBee application traffic received (bits/sec) for coordinator failure

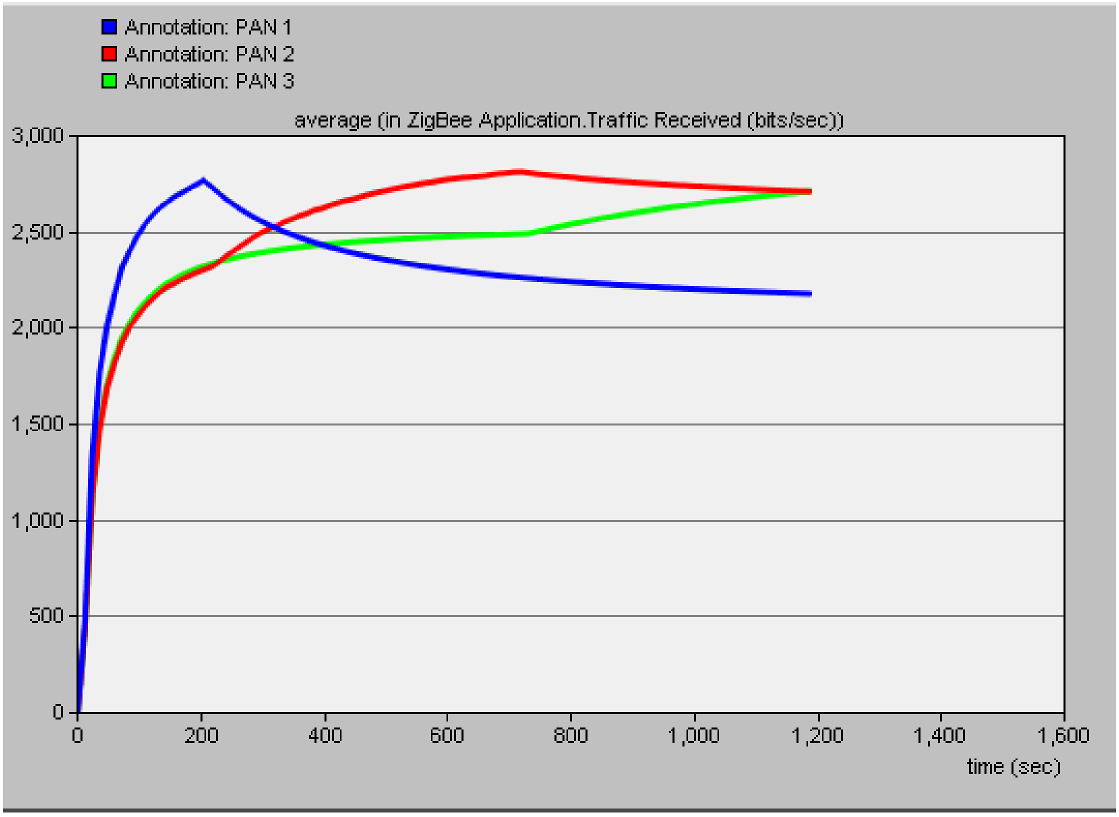

Figure 15. ZigBee application traffic received (bits/sec) for multiple coordinators

PAN affiliation: figure 16 shows the time needed for the node to join the ZigBee network.

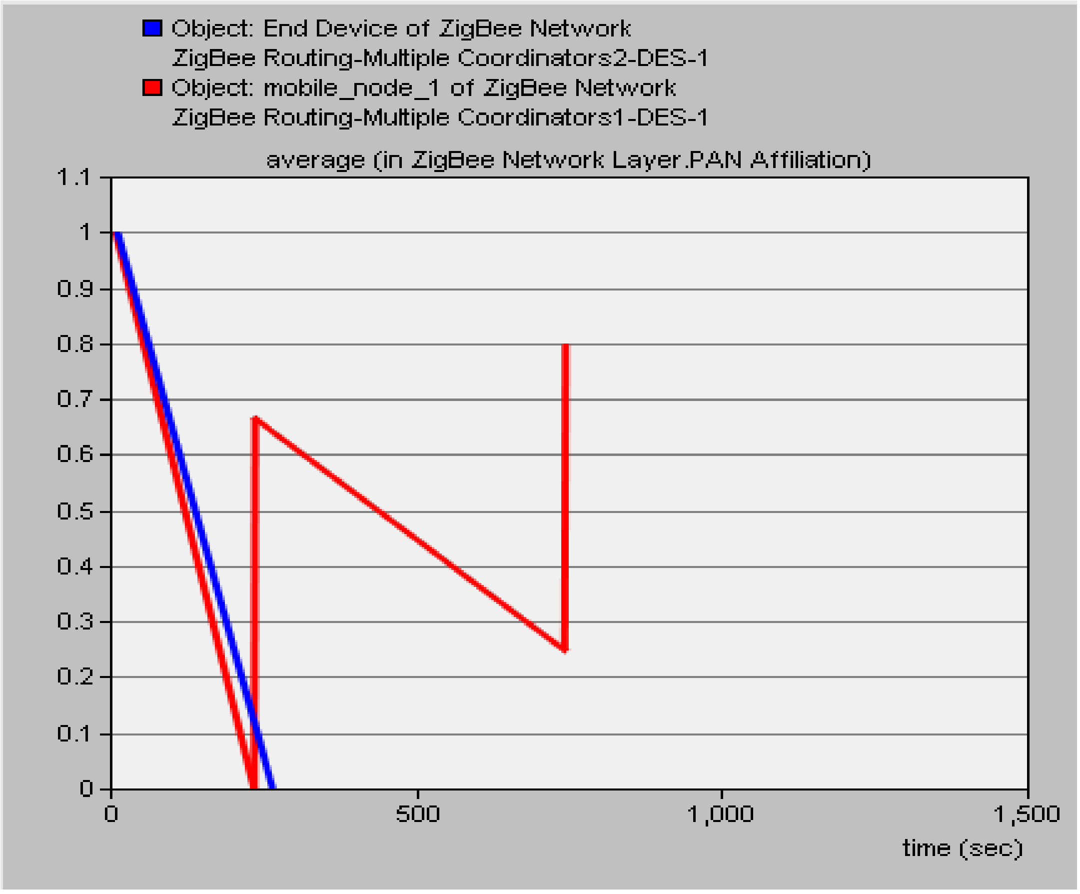

Figure 16. ZigBee network layer PAN affiliation

The results can be summarized as follows:
PAN affiliation: PAN affiliation is the time required to join the ZigBee network. If the path comes of moving nodes, this means the first node will be linked to PAN1 from the first four minutes before short time of switching process to PAN2. In the 12 minute it will be separated from PAN2 and combined to PAN3. If this path is caused by the terminator, final device is merged to PAN1.This is done in the first four minutes and is disconnected from all PANs.
Throughput: results show that the throughput is slightly higher in case of end device trajectory than the mobile node trajectory.
Delay: results show that the delay is higher in case of end device trajectory than the mobile node trajectory.
MAC Load: at the first, the load on the MAC is high on the both paths. The load remains high as the node transfers to PAN2. That is the path of the mobile node. Four seconds later the load decreases on the termination device.

4. Conclusion

In this work, five scenarios are performed using IEEE 802.15.4/ZigBee devices. The following is a conclusion about these five topologies:

Scenarios 1 and 2: each scenario has an identical network to the other one where the same tree network is implemented in both networks. Nodes are configured to serve random traffic, and router 1 is configured to direct its traffic to Router 3. Results shows that the tree network in scenario 1 has more throughput than the mesh network. This is can be attributed to the multiple paths that can be found in the mesh network. On the other hand, the found routes in the tree network is the best one of the available paths that are found by the mesh network and thus the tree network shows a lightly improvement in terms of delay.
Scenario 3: in this scenario the network consists of two coordinators and twenty four routers and end devices. Auto-assigned PAN ID is assigned for each router and end device while coordinators 1 and 2 are assigned the addresses of PAN ID 1 and 2 respectively.

Table 1 shows the timing processes for these two coordinators. As shown at the fourth minute Router 1 will recover and reestablish the network. At the second minute, the nodes that are joined to coordinator 1 will leave that PAN and join coordinator 2. At the eight minute, the opposite situation will be happen. Due to the coordinators failure, throughput will be increased.

Table 1. functionality timing of coordinators Sec

Sec Router	1	2	4	8	10
1	Works	Failed	Recover	Work	
2	Work			Fail	Work

As shown, coordinator 2 has more traffic due to the number of nodes that join it, which are more than coordinator traffic will decrease from and to the failed coordinator and vice versa at the next coordinator.

Scenario 4 and 5: as shown, the traffic from and to PAN 1 will be a plus for the first four minutes, until the node disconnect from it and join PAN 2. The node will be disconnected and not joined to any one of the PANs as long as the traffic around PAN 2 is high, which is extended to minute 12. At this minute, the node will disconnect from PAN 2 and joins PAN 3, where the traffic will increase at 20 minutes. As aforementioned, Node 1 is configured to join those coordinators along 20 minutes. It is first joins PAN 1 and then switches to PAN 2 and at last switches to PAN 3 for the remaining time simulation. In terms of traffic and transmission, all nodes are configures to send their data to random destination within their PAN except Node 1, which is configures to transmit to its parent.
As a results, it is concluded that the tree topology is more combatable for WSNs requirements than mesh networks in terms of throughput. In the multi-coordinator ZigBee network, the network behavior and performance will be improved if the trajectory comes from the mobile node instead of the end device.

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