Performance Analysis of IEEE 802.15.4 / ZIGBEE Networks

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DECLARATION

We, hereby declare that this thesis is based on the results found by ourselves. Materials of work found by other researcher are mentioned by reference. This Thesis, neither in whole or in part, has been previously submitted for any degree.

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ABSTRACT

We analyze the performance of IEEE 802.15.4 / ZigBee networks. In order to evaluate the performance, we design various sceneries varying number of nodes and network area. We research on self-healing mechanism in ZigBee, the technology is a self-organized and self-healing wireless communication technology with low power-consumption, large network capacity and small time-delay. With ZigBee technology a wireless personal area network in low data rate could be constructed. We evaluate the performance of designed networks using multimedia traffics. In particular, we present findings on network performance when a node is constantly moving and changing routes. We evaluate for packet delivery ratio when the nodes are moving and when they are fixed and range was within 100 meters. Our evaluation results indicate that ZigBee router typically suffers less packet losses under mobile scenarios. Also survey the end to end delays and throughputs for different number of mobile nodes by using single router. As a simulator we use OPNET simulation tool. It will help people to know why anyone will choose ZIGBEE not others.

CHAPTER 01
INTRODUCTION

1.1 Motivations

Wireless Personal Area Network (WPAN) and Wireless Local Area Network (WLAN) technologies are very popular in today's digital world. With new emerging standards being developed these are growing very fast [1]. Using wireless signals in open areas such as home, education, business or office rather than having to lay out wires its popularity grows. WLAN standard defines high rate data throughputs; such as the IEEE 802.11b with a maximum throughput of 11Mbps and the IEEE 802.11g with maximum throughput of 54Mbps.WLAN devices operate within 100 meters of distance range depending on the surrounding environment.

ZigBee is a wireless sensor network. It is a mesh network specification for low-power wireless local area networks that cover a large area. ZigBee was designed to provide high data throughput in applications where the duty cycle is low and low power consumption is an important consideration. Connect dozens of different devices into single control network. Specifies a data rate of 250 kbps and has nearly worldwide availability. In home automation system ZigBee gives much better performance than the other network protocols [2].

Depending on the types of topologies used in the project it can support up to 65,000 nodes. The range of transmit the data is 10-100 meters. In a typical ZigBee network, the network addresses are organized in a hierarchical manner so that one node can easily identify addresses of its tree neighbours, including its parent and children [3].

1.2 Project Scopes

The primary goal of this project is to better understand the use of OPNET simulation tool as well as to study the protocol of interest, ZigBee. In order to achieve these goals this project will provide a brief overview of what ZigBee protocol contains, and simulate several simple ZigBee networks while altering certain parameters using OPNET.

1.3 Overview

In this thesis work we are going to examine the ZigBee performance in various scenarios. There are three scenarios in our work

- **Self-healing mechanism test:** In Chapter 4 (Topic 4.1), that scenario is briefly described. In this scenario we will verify self-healing mechanism of a ZigBee network. Self-healing is a mechanism of ZigBee network which keeps data flow uninterrupted during any router failure if there is any additional router left. For this scenario we used 1 coordinator, 1 fixed router, 1 mobile router, 2 fixed end devices. For this test we will enable router discovery on for end devices. We will set timer. After some time one router will blow away and will stop working. Then other router will keep data flow uninterrupted till the end of our simulation.
- **ZigBee moving nodes:** In Chapter 4 (Topic 4.2), that scenario is briefly described. In this scenario we will add 4 nodes. 1 coordinator, 1 router, 1 fixed end device, 1 mobile and device. We will set a trajectory for the mobile end device which allows the mobile end device traverse around the network. We will examine the impact of mobile node on our network by comparing data flow between coordinator and mobile node.
- **Node density**: In Chapter 4 (Topic 4.3), that scenario is briefly described. In this last test we will examine the performance of ZigBee network when the nodes are increasing. We will keep 1 one coordinator and 1 router and will increase the number of end devices in the network. We will add 3 end device then 6 end device and in the last scenario 12 end devices. We will check the end to end delay and throughput of the scenarios and will compare them. By comparing them we will make our decision about the impact of node density in a ZigBee network.

CHAPTER 02
BACKGROUND INFORMATION

2.1 ZigBee Specifications

Table 2.1 – General ZigBee Specifications

ZigBee / 802.15.4	
100-1000	Battery Life (days)
>64000	Network Size (No. of Nodes)
1-100	Transmission Range (meters)
20-250	Throughput (kb/s)

2.2 ZigBee Layers

There are four layers in ZigBee. The Application and Network layers specified by the ZigBee Alliance to provide manufacturing standards [2]. These are top two layers of ZigBee and bottom two are Medium Access Control and Physical layers. Bottoms two specified by the IEEE 802.15.4 - 2006 standard to ensure coexistence without interference with other wireless protocols such as Wi-Fi [4].

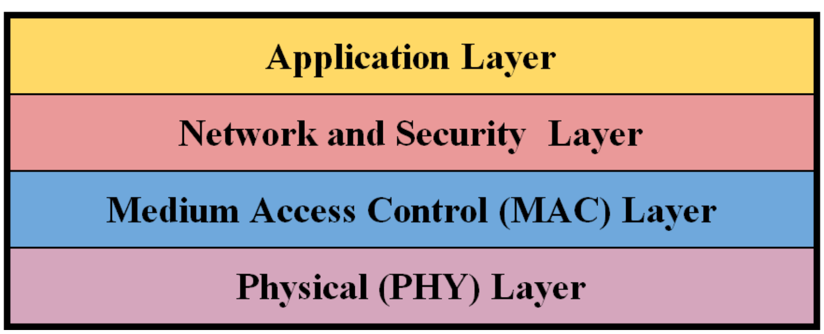

Fig 2.1 - ZigBee Layers

2.2.1 Application Layer

It is the highest-level layer defined by the specification and is the effective interface of the ZigBee system to its end users. Applications running on the ZigBee network are contained here. One node can run more than single application [1]. Up to 240 distinct application objects can be defined, each interfacing on an endpoint indexed from 1 to 240. Application object represents different application types (or profiles) that can be defined on a single ZigBee device [4]. Application support sub-layer (APS) provides an interface between the network layer (NWK) and the application layer (APL) through a general set of services. APSDE provides the data transmission service for the transport of application PDUs between two or more devices located on the same network. APSDE supports fragmentation and reassembly of packets and provides reliable data transport [11].

2.2.1.1 ZigBee Device Object (ZDO)

A special application is on every ZigBee device and this is the ZigBee Device Object, or ZDO [12]. This application provides key functions such as defining the type of ZigBee device (end device, router, and (coordinator) a particular node is, initializing the network, and to also participate in forming a network [4].

2.2.2 Network Layer and Security Plane

Self-healing mechanism is acquired through this network layer. There are some responsibilities of ZigBee Network layer. These are: Starting a network (NLME): The ability to successfully establish a new network. Joining and leaving a network (NLME): The ability to gain membership (join) or relinquish membership (leave) a network [4]. Configuring a new device (NLME): The ability to sufficiently configure the stack for operation as required. Addressing (NLME): The ability of a ZigBee coordinator to assign addresses to devices joining the network [16]. Topology specific routing (NLDE): The ability to transmit an NPDU to an appropriate device that is either the final destination of discovery (NLME): The ability to discover, record and report information pertaining to the one -hop neighbours of a device. Routing Discovery (NLME): routing frames to their intended destinations [9]. The security plane spans across both the network layer and the application layer. It is here, that security measures such as AFS-based encryption is implemented. Another security feature is message timeouts, which adds a frame counter onto each frame. Using this frame counter, the device can determine the age of the message it receives, and detect the possibility that an old message was recorded and is played back to the device (replay attack) [5].

2.2.3 Medium Access Control Sub-Layer

This layer extracted from the IEEE 802.15.4 standard provides services to the network layer above, which is part of the ZigBee stack level [9]. The MAC layer is responsible for the addressing of data to determine either where the frame is going, or coming from. It is also this layer that provides multiple access control such as CSMA/CA allowing for reliable transfer of data. Beaconing is another feature implemented through this layer. Finally, the MAC sub-layer can be exploited by higher layers to achieve secure communication (by measures such as an ACL) [5].

2.2.4 Physical Layer

The physical layer is provided by the IEEE 802.15.4 standard. This standard manages the physical transmission of radio waves in different unlicensed frequency bands around the world to provide communication between devices within a WPAN [9]. Low rate of the 816/915 MHz PHY can be translated into better sensitivity and larger coverage area, thus reduce the number of nodes in a given area. The bands are specified in the table below:

Table 2.2 - Frequency Bands used in 802.15.4 [6]

No. of Channels Available	Frequency Range (MHz)
1	868-868.6
10	902-928
16	2400-2483.5

2.3 Network Topologies

A mixture of three potential components contain by ZigBee networks. ZigBee coordinator, a ZigBee router, and a ZigBee end device are those three components [12]. In network layer, there are different types of nodes and they play different types of roles, but finally all these types can have same types of applications [3].

2.3.1 ZigBee Coordinator

For every ZigBee network, there can be only one coordinator. This node is responsible for initializing the network, selecting the appropriate channel, and permitting other devices to connect to its network. It can also be responsible for routing traffic in a ZigBee network [8]. In a star topology, the coordinator is at the center of the star, and all traffic from any end device must travel to this node. It is still possible for end devices to talk to another end device, but the message must be routed through the coordinator. In a tree topology, the coordinator is at the top of the tree, and in a mesh network, it is the root node of the mesh. A ZigBee coordinator can also take part in providing security services [10].

2.3.2 ZigBee Router

A router is able to pass on messages in a network, and is also able to have child nodes connect to it, whether it be another router, or an end device [14]. Router functions are only used in a tree or mesh topology, because in a star topology, all traffic is routed through the center node, which is the coordinator. Routers can take place of end devices, but the routing functions would be useless in such cases. If the network supports beaconing, then a router can sleep when inactive, periodically waking up to notify the network of its presence [15].

2.3.3 ZigBee End Device

The power saving features of a ZigBee network can be mainly credited to the end devices. Because these nodes are not used for routing traffic, they can be sleeping for the majority of the time, expanding battery life of such devices [12]. These nodes carry just enough function to talk to parent nodes, which can be either a router or a coordinator. An end device does not have the ability to have other nodes connect to its network through the end device, as it must be connected to the network through either a router, or directly to the coordinator [4].

2.3.4 Topology

The standard IEEE 802.15.4 envisages two topologies: star (star - all the nodes communicate with a central node called coordinator) or point-to-point (peer to peer - all the nodes with radio range can communicate together without hierarchy). The formed network is called PAN [7]. The network layer of ZigBee allows the creation of mesh topology thanks to an automatic routing: it is topology with a grid, or mesh topology [13]. Three topologies can be considered in the installation of a ZigBee network:

- ❑ Star Topology
- ❑ Tree Topology
- ❑ Mesh Topology

2.3.4.1 Star topology

In (Fig 2.2) is simplest and the most limited among all ZigBee topologies. It's made up of central equipment (coordinator) and the other equipment of the network (router, end device). Each equipment of the network can only communicate with the coordinator. Consequently, to send a packet from one equipment to the other, this one must pass through the coordinator who will send the packet towards the destination [7].

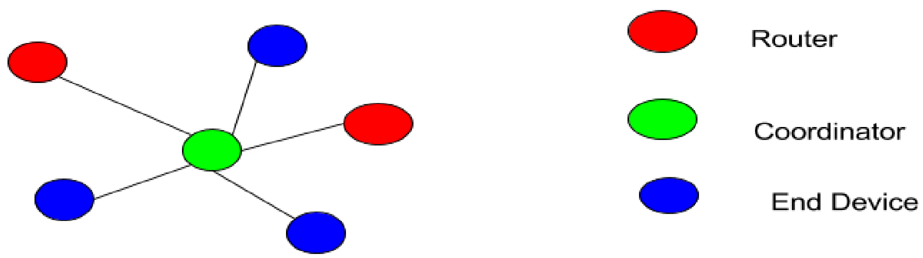

Fig 2.2 - Star Topology

The disadvantage of star topology is that there are no alternate routes if the link between the coordinator and the end device fails. The other disadvantage of this topology is that all the packets must pass through the coordinator, this last can be saturated with a great number of packets and like result, we have a congested network.

2.3.4.2 Tree topology

In (Fig 2.3) is made up of a coordinator to which other equipments are connected. The coordinator is related to the several routers and end devices (his/her children) [4]. A router can be also connected to several routers and end devices and that can continue until a certain number of levels. This hierarchy can be visualized like a structure of tree with the coordinator at the top.

The router can be used as an end device in the tree of the network, but in this case the functionality of diffusion of message is not used. In tree topology, the coordinator and the routers can have children, therefore they can be parents [10]. On the other hand, the end devices cannot

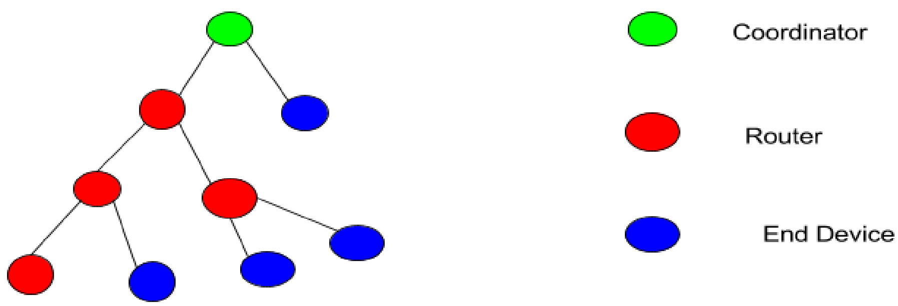

Fig 2.3 - Tree Topology

be parents and cannot have children either. The children can communicate only with their parents, while the parents can communicate with their children and their own parent. The disadvantage of this topology is that there is no alternate road if the bond necessary to reach the destination fails [7].

2.3.4.3 Mesh topology

The Mesh topology (Fig 2.4) has a structure similar to that out of tree with a coordinator at the top of the tree. In a mesh topology, the coordinator is related to his children (routers, end devices), it can also be related to several routers and end devices (his/her children). However, rules of communication are more flexible because the routers can communicate directly between them. A mesh topology is characterized with a more effective propagation of the packets [7], that means that alternate roads can be found if a bond breaks down or if there are congestions. A planned for makes it possible the network to find the best way available to convey the packet [8].

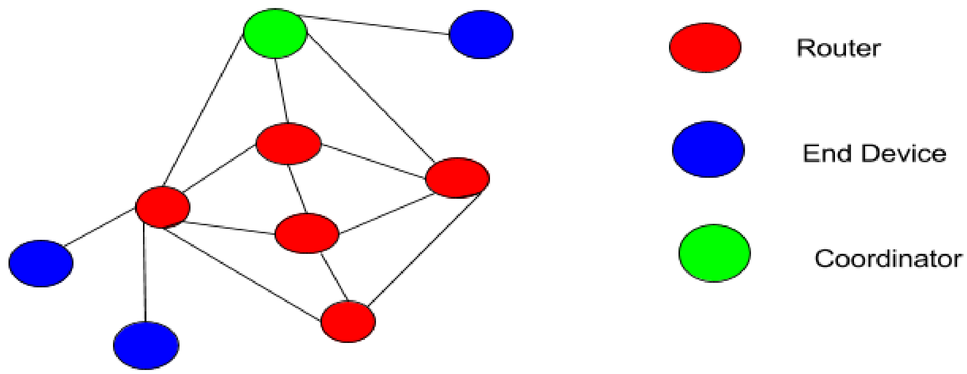

Fig 2.4 - Mesh Topology

CHAPTER 03
PROPOSED MODEL

Our proposed model is given bellow:

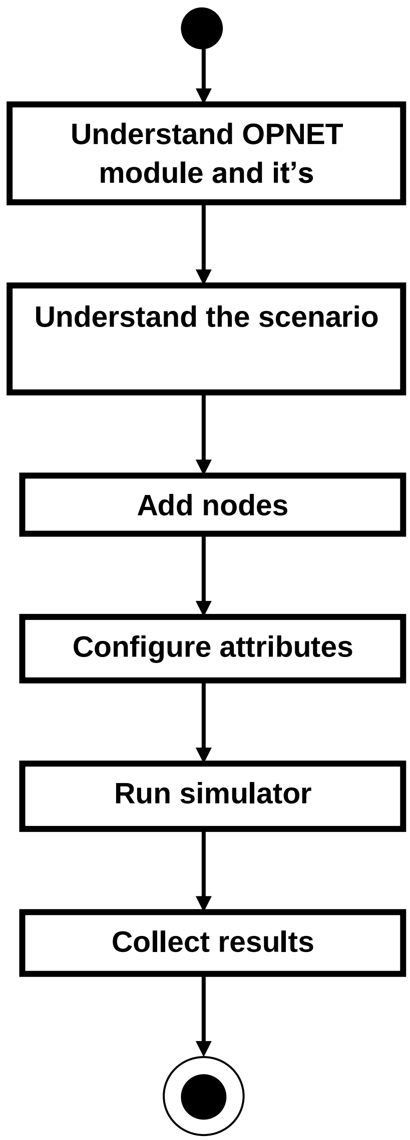

Fig 3.1 – Work Flow Diagram

3.1 Understanding OPNET Module and its Functionalities

Here we are going to examine the capabilities, functionalities and libraries of the OPNET Module. By examining we will know about the functionalities of the software and we will use these functionalities in our various scenarios.

3.2 Understanding the Scenario

In this phase we are going to determine what we are going to do in our next scenario. For this we will consider our software and hardware limitations. Then we will determine how we are going to create our scenario. We will measure the number of nodes and finally we will create the scenario.

3.3 Add Nodes

In this phase, we are going to add our nodes for specific scenario. We will drag and drop end devices, routers, coordinators from object palate from OPNET. Then we will configure them.

3.4 Configuring Attributes

In this phase, we are going to configure the nodes that we have already placed in our network area. From edit attributes option we can configure and edit any kind of attributes of a node. For example we can set a trajectory to a mobile device by simply adding a trajectory from edit attributes.

3.5 Run Simulations

After configuring all nodes we are going to run the simulations. Simulations can be run for different duration of times. For example a simulation can be run for 1 hour.

3.6 Collect Result

After done with all above procedures we will collect the result of specific scenarios. For example we can compute throughput from a scenario by simply adding throughput from DES statistics.

CHAPTER 04
EXPERIMENTAL ANALYSIS

4.1 Verification of ZigBee's Self-Healing Mechanism upon Router Failure

To handle a failure in the router, there is a method of simulation by adding modified code in a failure situation. However, an alternative method was used for deeming to be beyond scope of this project.

Besides, by providing a trajectory to the router to move it out of range to trigger self-healing is an alternate method. There might be any case of router being damaged or blown away in the providing area due to natural disaster or extreme winds respectively.

The ACK enable and understanding the range capability of ZigBee are the two key features required for this case scenario. To prevent observations for the self-healing feature we need to place the end devices too close to the destination coordinator; will result in traffic being sent directly, rather than through the router. To have no longer receiving and routing traffic; the ACK enable was required for the end devices to recognize that the failure in the router has occurred, in order to trigger route discovery.

Fig 4.1 - Router (mobile_node_0) Failure Situation

Fig 4.1 shows us that end device (node_1) has been failed to send and receive data from coordinator (node_0) due to select “move out and stop working” option in mobile router (mobile_node_0). As a result, end device (node_1) will start to find another router near to it as we activated router discovery earlier. Therefore, end device (node_1) will send data to router (node_3) without any data loss. Router (node_3) then receives data from both end devices (node_1 and node_2) at the same time. Moreover, end device (node_2) will find its nearer router and send data to coordinator through that router. In this topology router (node_3) is nearer. But if mobile router (mobile_node_0) comes nearer than router (node_3) when it is moving then end device (node_2) will send data to coordinator through mobile router (mobile_node_0).

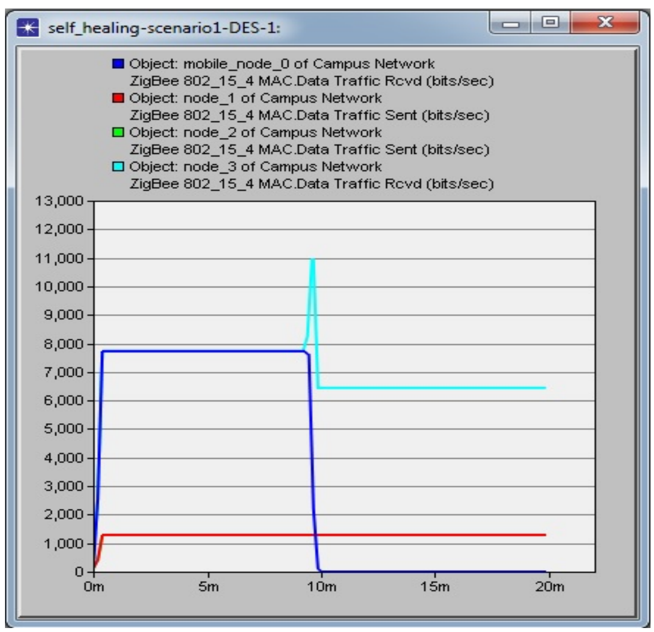

Fig 4.2 - ZigBee’s Self-Healing Mechanism upon Router Failure Graph

Fig 4.2 shows us when mobile_node_0 (indigo) is in failure condition, the statistics collected to observe the behaviour of self-healing. Here both end devices [node_1 (red) and node_2 (green)] have the same data sending rate that is why two lines are showing as one line. Mobile router and other router both have the same data receiving rate at the initial state. After 10 min mobile router (indigo) is moving out and stop working which will cause end device [node_1 (red)] to send its data to coordinator through other working router (blue) without any data loss.

That causes (indigo) to stop receiving data and (blue) to increase throughput as it receiving data of both end devices (red and green). Around 10 min (blue) goes to an unstable state for a while to manage high data rate. After a few seconds it comes in a stable state but throughput is decreasing than initial state for handling both end devices at the same time. After changing in topology all devices come in a stable data rate for rest of 10 min.

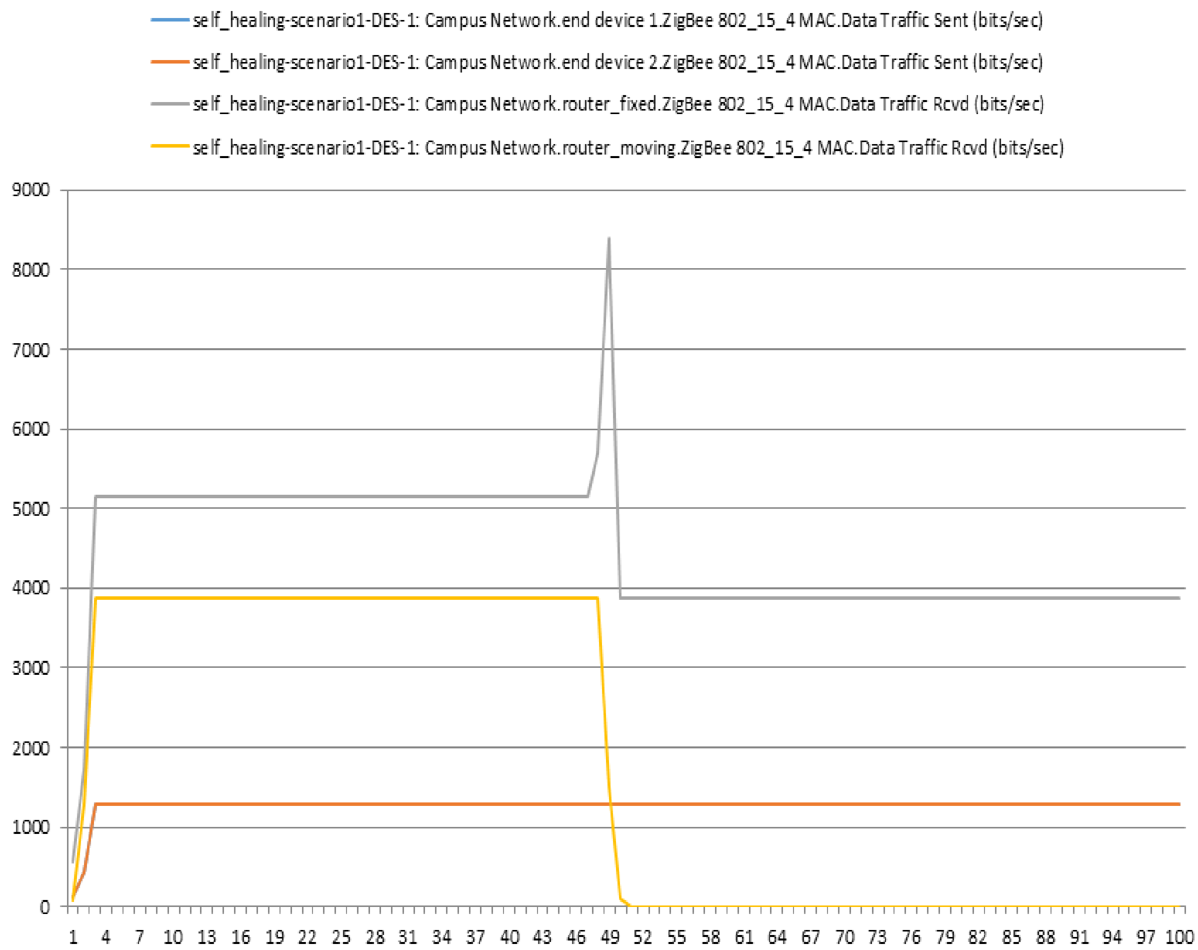

Fig 4.3 - Self-Healing Excel Graph

4.2 ZigBee's Mobile End Devices Scenario

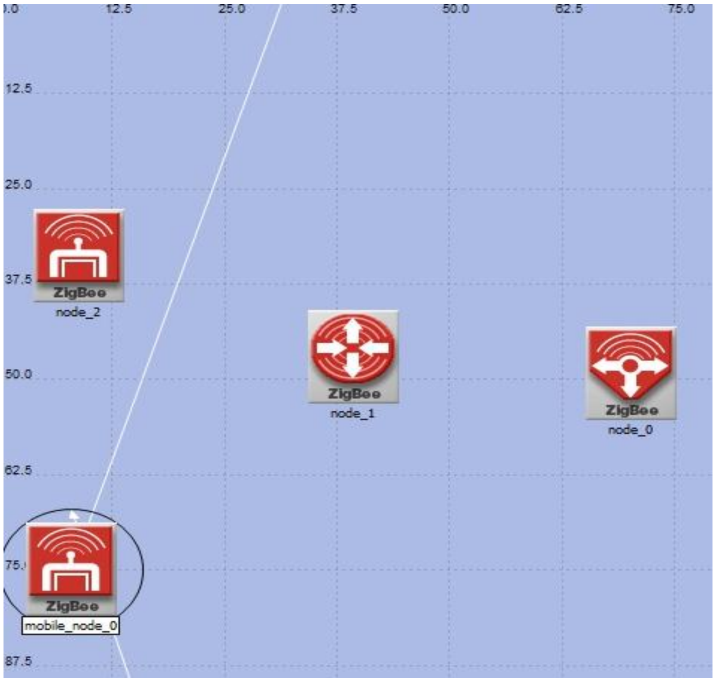

Fig 4.4 - Coordinator and End Devices Data Flow Topology

In Fig 4.4 and 4.5 we are showing that end device (mobile_node_0) is moving clockwise and goes out of range (100 metre), whereas other end device (node_2) is static, both are sending data to the coordinator (node_0) through router (node_1). When end device (mobile_node_0) is moving it makes fluctuation of sending data rate as it come closure or goes away from coordinator. As mobile_node_0 (indigo) is sending data to the coordinator [node_0 (red)], the receiving data rate increasing or decreasing accordingly for a certain period of time. From 3min to 30 min throughput remain constant for both devices (indigo and red).

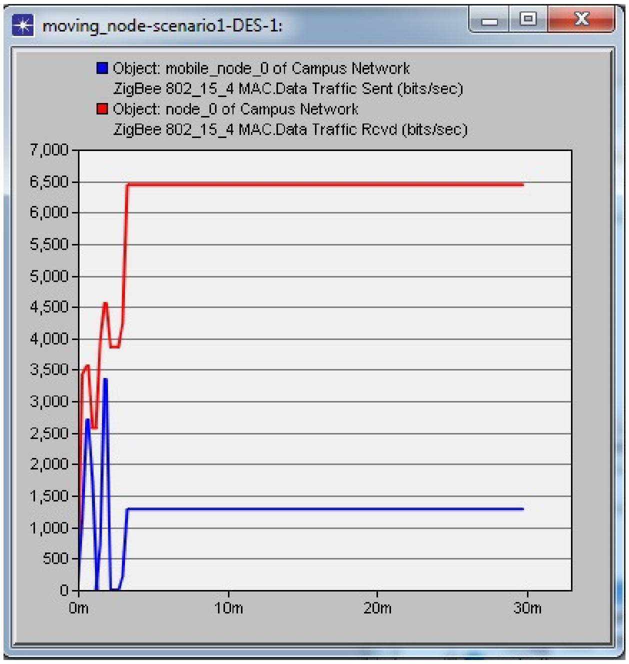

Fig 4.5 - Coordinator and End Devices Data Flow Graph

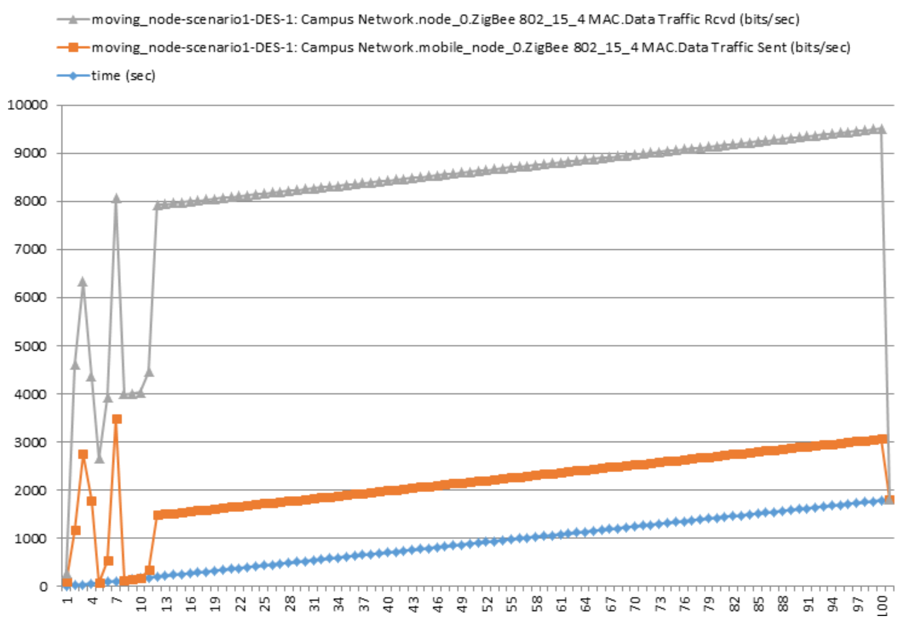

Fig 4.6 - Coordinator and End Devices Excel Data Flow Graph

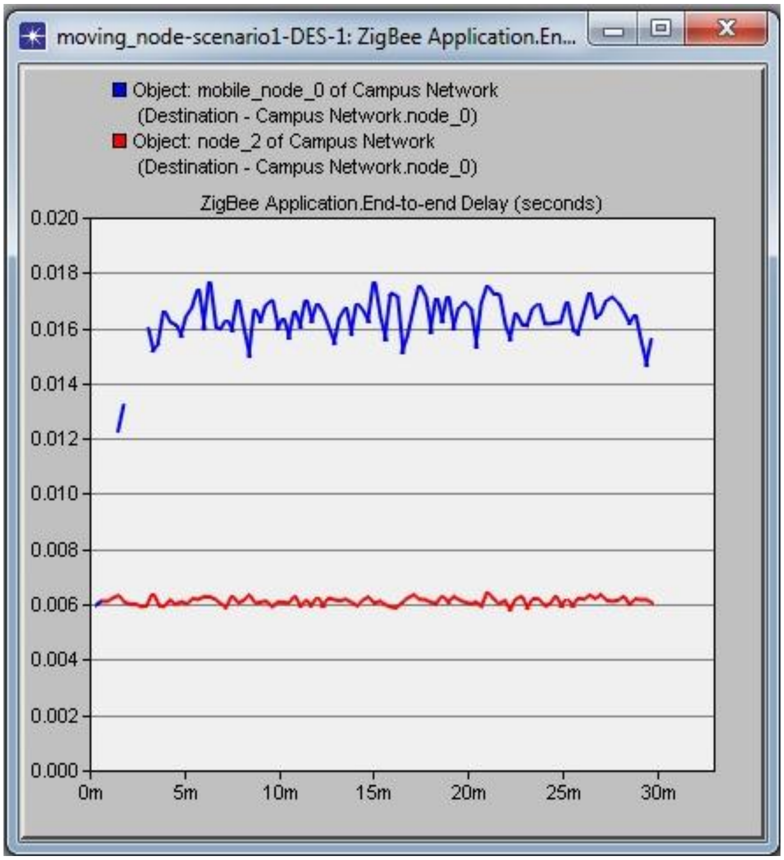

Fig 4.7 - End to End Delay for End Device Data Rate

In Fig 4.4 and 4.7 we are showing that end device [node_2 (red)] has a continuous end to end delay as it remains static always. Besides, mobile end device (indigo) is dynamic and goes out of range between (0.013-0.016). Therefore, there is no end to end delay among this range.

In Fig 4.4 and 4.8 we are showing that end device [node_2 (green)] gives a constant bit rate after boost up. Mobile_node_0 (indigo) initially fluctuate its bit rate because of its dynamic movement in that topology. Depending on both end devices sending data rate to router [node_1 (red)], receiving data rate act accordingly.

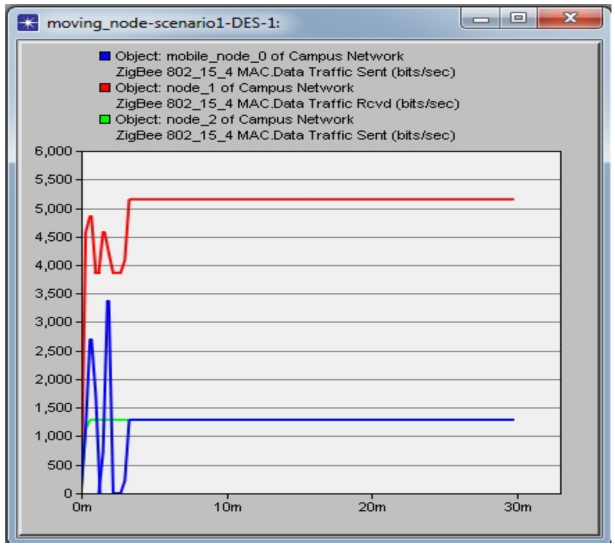

Fig 4.8 - Moving and Fixed End Device Data Rate

4.3 ZigBee's Node Density Scenario

In Node Density normally we check the performance of ZigBee network when we kept increasing nodes. We will keep 1 one coordinator and 1 router fixed and will keep increasing the number of end devices in the network.

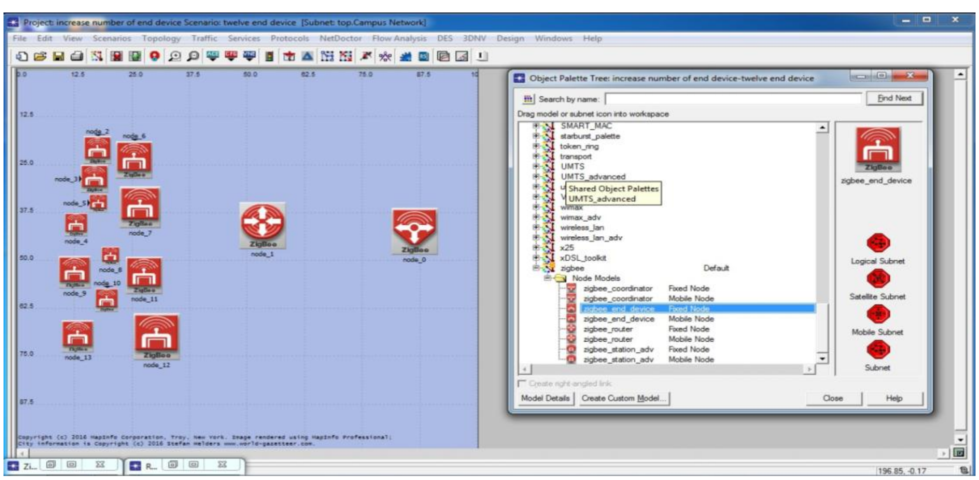

Fig 4.9 - Coordinator and End Devices Data Flow Topology

Initially we will add 3 end devices, then 6 end devices and at last scenario 12 end devices. We will check the end to end delay and throughput of the scenarios and will compare them. By comparing them we will make our decision about the impact of node density in a ZigBee network.

4.3.1 End to End Delay Case Study

End to end delay is total delay time between creation and reception of an application packet. When we have gone through the result of end to end delay of our project scenario where we have run the simulation for 1 hour long, we have found out that with increasing number of nodes, the end to end delay keeps increasing. We can see the actual scenario in the following graph:

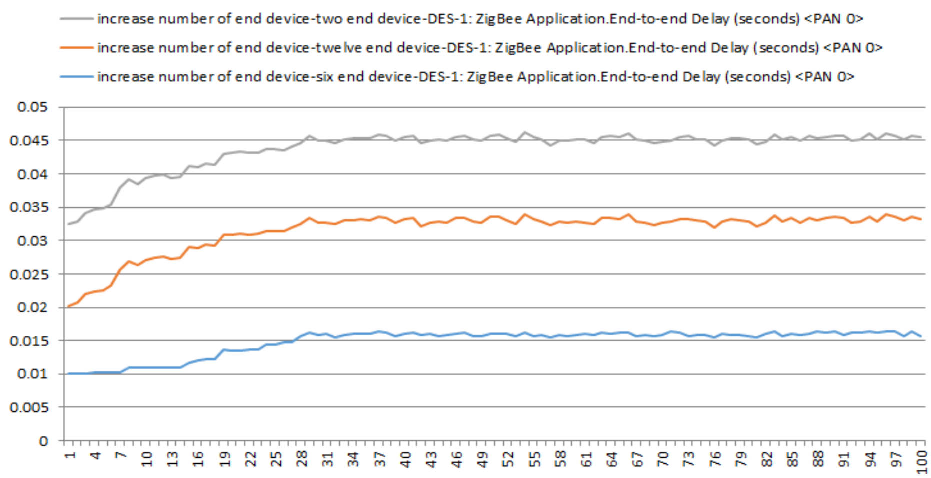

Fig 4.10 - End to End Delay Excel Graph

The reason behind increasing end to end delay is that, when we increase nodes, it takes much time than before to transmit a packet from source to destination node. At initial scenario the data packet was transmitted among 3 nodes but in next scenario, data transmit was happening among 6 nodes, so that time it was taking higher time than initial scenario as time required for packet transmit between one node to another node is kept increasing. So when we have twelve nodes, then we get more end to end delay.

4.3.2 Throughput Case Study

Throughput represents the total number of bits (in bits/sec) forwarded from one node to another node of the network. For this case, when we have gone through our project result, we have found out the same scenario like end to end delay. With increasing number of nodes, the throughput keeps increasing which show in following graph:

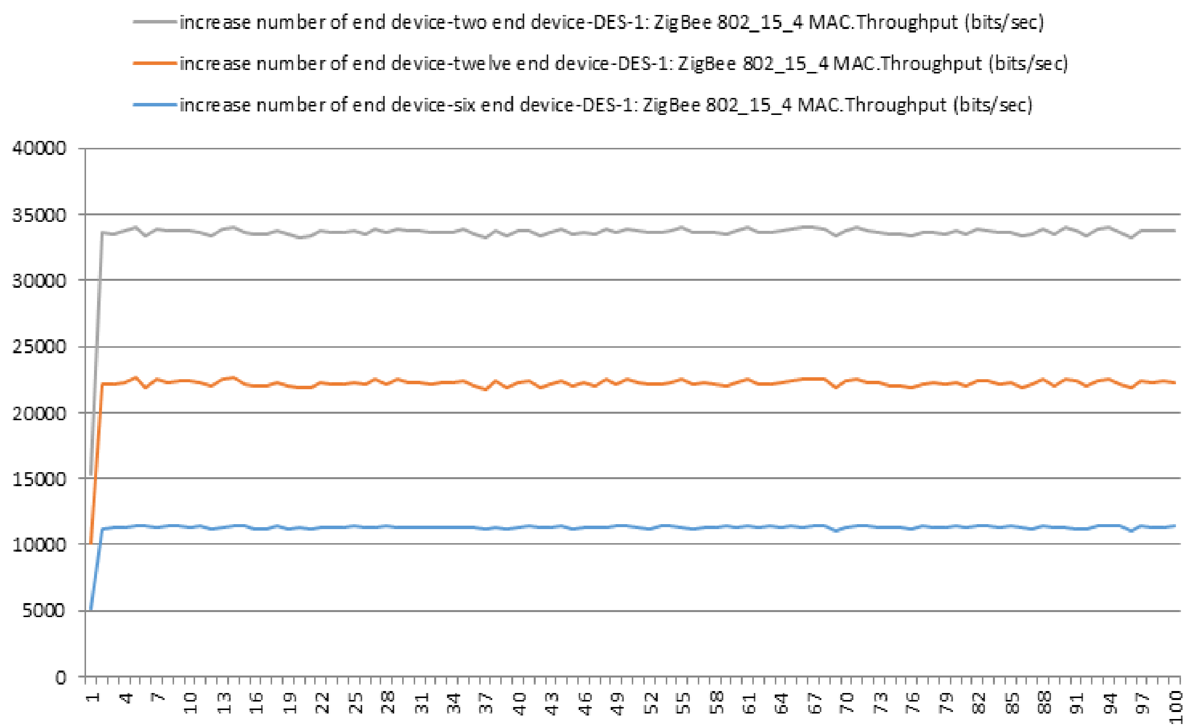

Fig 4.11 - Throughput Excel Graph

When we have assessed the result, we have found out that when we have started increasing nodes, then the total number of transferred data become higher than before.

CHAPTER 05
CONCLUSIONS AND FUTURE WORKS

5.1 CONCLUSIONS

ZigBee communications technology could form the basis of future wireless sensors by offering data reliability, long battery life, lower system costs, and good range through flexible networking.

This paper presents the overview of ZigBee protocol in terms of its network topologies and the functional overview. We can easily understand that ZigBee is going to be best solution of wireless technology and home automation industry.

5.2 FUTURE WORKS

In OPNET we could not find any customized map for ZigBee or Wi-fi implementation. In future we want to implement ZigBee on hilly tracks if we find any customized map in OPNET. As we discussed earlier that ZigBee has the cheapest implementation compared the other two network protocols so it can be a great source of internet for the poor people living in those hilly areas of our country. As it is a wireless sensor network so no wire should be needed for our implementation. That will reduce the complexity of network topology and network disconnection problem in those areas.

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APPENDIX

Chart 1 - Self-Healing Excel Data

1	time (se	self_hea	self_hea	self_hea	self_healing·
2	0	132	132	556	86
3	12	429.33	429.33	1717.3	1288
4	24	1288	1288	5152	3864
5	36	1288	1288	5152	3864
6	48	1288	1288	5152	3864
7	60	1288	1288	5152	3864
8	72	1288	1288	5152	3864
9	84	1288	1288	5152	3864
10	96	1288	1288	5152	3864
11	108	1288	1288	5152	3864
12	120	1288	1288	5152	3864
13	132	1288	1288	5152	3864
14	144	1288	1288	5152	3864
15	156	1288	1288	5152	3864
16	168	1288	1288	5152	3864
17	180	1288	1288	5152	3864
18	192	1288	1288	5152	3864
19	204	1288	1288	5152	3864
20	216	1288	1288	5152	3864
21	228	1288	1288	5152	3864
22	240	1288	1288	5152	3864
23	252	1288	1288	5152	3864
24	264	1288	1288	5152	3864
25	276	1288	1288	5152	3864
26	288	1288	1288	5152	3864
27	300	1288	1288	5152	3864
28	312	1288	1288	5152	3864
29	324	1288	1288	5152	3864
30	336	1288	1288	5152	3864
31	348	1288	1288	5152	3864
32	360	1288	1288	5152	3864
33	372	1288	1288	5152	3864
34	384	1288	1288	5152	3864
35	396	1288	1288	5152	3864
36	408	1288	1288	5152	3864
37	420	1288	1288	5152	3864
38	432	1288	1288	5152	3864
39	444	1288	1288	5152	3864
40	456	1288	1288	5152	3864
41	468	1288	1288	5152	3864
42	480	1288	1288	5152	3864
43	492	1288	1288	5152	3864
44	504	1288	1288	5152	3864
45	516	1288	1288	5152	3864

	A	B	C	D	E
45	516	1288	1288	5152	3864
46	528	1288	1288	5152	3864
47	540	1288	1288	5152	3864
48	552	1288	1288	5152	3864
49	564	1288	1288	5688.7	3864
50	576	1288	1288	8394	1502.7
51	588	1288	1288	3864	107.33
52	600	1288	1288	3864	0
53	612	1288	1288	3864	0
54	624	1288	1288	3864	0
55	636	1288	1288	3864	0
56	648	1288	1288	3864	0
57	660	1288	1288	3864	0
58	672	1288	1288	3864	0
59	684	1288	1288	3864	0
60	696	1288	1288	3864	0
61	708	1288	1288	3864	0
62	720	1288	1288	3864	0
63	732	1288	1288	3864	0
64	744	1288	1288	3864	0
65	756	1288	1288	3864	0
66	768	1288	1288	3864	0
67	780	1288	1288	3864	0
68	792	1288	1288	3864	0
69	804	1288	1288	3864	0
70	816	1288	1288	3864	0
71	828	1288	1288	3864	0
72	840	1288	1288	3864	0
73	852	1288	1288	3864	0
74	864	1288	1288	3864	0
75	876	1288	1288	3864	0
76	888	1288	1288	3864	0
77	900	1288	1288	3864	0
78	912	1288	1288	3864	0
79	924	1288	1288	3864	0
80	936	1288	1288	3864	0
81	948	1288	1288	3864	0
82	960	1288	1288	3864	0
83	972	1288	1288	3864	0
84	984	1288	1288	3864	0
85	996	1288	1288	3864	0
86	1008	1288	1288	3864	0
87	1020	1288	1288	3864	0

	A	B	C	D	E
87	1020	1288	1288	3864	0
88	1032	1288	1288	3864	0
89	1044	1288	1288	3864	0
90	1056	1288	1288	3864	0
91	1068	1288	1288	3864	0
92	1080	1288	1288	3864	0
93	1092	1288	1288	3864	0
94	1104	1288	1288	3864	0
95	1116	1288	1288	3864	0
96	1128	1288	1288	3864	0
97	1140	1288	1288	3864	0
98	1152	1288	1288	3864	0
99	1164	1288	1288	3864	0
100	1176	1288	1288	3864	0
101	1188	1288	1288	3864	0
102	1200	#N/A	#N/A	#N/A	#N/A

Chart 2 - Coordinator and End Devices Excel Data Flow

	A	B	C
1	time (sec	moving_r	moving_n
2	0	88	190.67
3	18	1144.9	3434.7
4	36	2719.1	3577.8
5	54	1732	2576
6	72	0	2576
7	90	445.78	3400.9
8	108	3377.8	4579.6
9	126	0	3864
10	144	0	3864
11	162	0	3864
12	180	159.56	4116.4
13	198	1288	6440
14	216	1288	6440
15	234	1288	6440
16	252	1288	6440
17	270	1288	6440
18	288	1288	6440
19	306	1288	6440
20	324	1288	6440
21	342	1288	6440
22	360	1288	6440
23	378	1288	6440
24	396	1288	6440
25	414	1288	6440
26	432	1288	6440
27	450	1288	6440
28	468	1288	6440
29	486	1288	6440
30	504	1288	6440
31	522	1288	6440
32	540	1288	6440
33	558	1288	6440
34	576	1288	6440
35	594	1288	6440
36	612	1288	6440
37	630	1288	6440
38	648	1288	6440
39	666	1288	6440
40	684	1288	6440
41	702	1288	6440
42	720	1288	6440
43	738	1288	6440
44	756	1288	6440
45	774	1288	6440
46	792	1288	6440
47	810	1288	6440
48	828	1288	6440
49	846	1288	6440
50	864	1288	6440
51	882	1288	6440
52	900	1288	6440
53	918	1288	6440
54	936	1288	6440
55	954	1288	6440
56	972	1288	6440
57	990	1288	6440
58	1008	1288	6440
59	1026	1288	6440
60	1044	1288	6440
61	1062	1288	6440
62	1080	1288	6440
63	1098	1288	6440
64	1116	1288	6440
65	1134	1288	6440
66	1152	1288	6440
67	1170	1288	6440
68	1188	1288	6440
69	1206	1288	6440
70	1224	1288	6440
71	1242	1288	6440
72	1260	1288	6440
73	1278	1288	6440
74	1296	1288	6440
75	1314	1288	6440
76	1332	1288	6440
77	1350	1288	6440
78	1368	1288	6440
79	1386	1288	6440
80	1404	1288	6440
81	1422	1288	6440
82	1440	1288	6440
83	1458	1288	6440
84	1476	1288	6440
85	1494	1288	6440
86	1512	1288	6440
87	1530	1288	6440
88	1548	1288	6440
89	1566	1288	6440
90	1584	1288	6440
91	1602	1288	6440
92	1620	1288	6440
93	1638	1288	6440
94	1656	1288	6440
95	1674	1288	6440
96	1692	1288	6440
97	1710	1288	6440
98	1728	1288	6440
99	1746	1288	6440
100	1764	1288	6440
101	1782	1288	6440
102	1800	#N/A	#N/A

Chart 3 - Moving and Fixed End Device Excel Data Rate

	A	B	C
1		moving_r	moving_nc
2	0	88	88
3	18	1144.9	1144.9
4	36	2719.1	1288
5	54	1732	1288
6	72	0	1288
7	90	445.78	1288
8	108	3377.8	1288
9	126	0	1288
10	144	0	1288
11	162	0	1288
12	180	159.56	1288
13	198	1288	1288
14	216	1288	1288
15	234	1288	1288
16	252	1288	1288
17	270	1288	1288
18	288	1288	1288
19	306	1288	1288
20	324	1288	1288
21	342	1288	1288
22	360	1288	1288
23	378	1288	1288
24	396	1288	1288
25	414	1288	1288
26	432	1288	1288
27	450	1288	1288
28	468	1288	1288
29	486	1288	1288
30	504	1288	1288
31	522	1288	1288
32	540	1288	1288
33	558	1288	1288
34	576	1288	1288
35	594	1288	1288
36	612	1288	1288
37	630	1288	1288
38	648	1288	1288

	A	B	C
39	666	1288	1288
40	684	1288	1288
41	702	1288	1288
42	720	1288	1288
43	738	1288	1288
44	756	1288	1288
45	774	1288	1288
46	792	1288	1288
47	810	1288	1288
48	828	1288	1288
49	846	1288	1288
50	864	1288	1288
51	882	1288	1288
52	900	1288	1288
53	918	1288	1288
54	936	1288	1288
55	954	1288	1288
56	972	1288	1288
57	990	1288	1288
58	1008	1288	1288
59	1026	1288	1288
60	1044	1288	1288
61	1062	1288	1288
62	1080	1288	1288
63	1098	1288	1288
64	1116	1288	1288
65	1134	1288	1288
66	1152	1288	1288
67	1170	1288	1288
68	1188	1288	1288
69	1206	1288	1288
70	1224	1288	1288
71	1242	1288	1288
72	1260	1288	1288
73	1278	1288	1288

	A	B	C
73	1278	1288	1288
74	1296	1288	1288
75	1314	1288	1288
76	1332	1288	1288
77	1350	1288	1288
78	1368	1288	1288
79	1386	1288	1288
80	1404	1288	1288
81	1422	1288	1288
82	1440	1288	1288
83	1458	1288	1288
84	1476	1288	1288
85	1494	1288	1288
86	1512	1288	1288
87	1530	1288	1288
88	1548	1288	1288
89	1566	1288	1288
90	1584	1288	1288
91	1602	1288	1288
92	1620	1288	1288
93	1638	1288	1288
94	1656	1288	1288
95	1674	1288	1288
96	1692	1288	1288
97	1710	1288	1288
98	1728	1288	1288
99	1746	1288	1288
100	1764	1288	1288
101	1782	1288	1288
102	1800	#N/A	#N/A

Chart 4 - End to End Delay Excel Data

1	time (sec)	increase n	increase n	increase number of end device-two end device-DES-1: ZigBee Application.End-to-end Delay (seconds) <PAN 0>
2	0	0.010077	0.010108	0.012324
3	36	0.010095	0.010609	0.012139
4	72	0.010141	0.011933	0.012123
5	108	0.010178	0.012225	0.012267
6	144	0.010237	0.012365	0.012272
7	180	0.010231	0.013056	0.012135
8	216	0.010184	0.015513	0.012128
9	252	0.010938	0.01602	0.012283
10	288	0.010871	0.015539	0.012114
11	324	0.011006	0.016073	0.01226
12	360	0.010914	0.016538	0.012267
13	396	0.010967	0.016605	0.012331
14	432	0.010942	0.016233	0.012137
15	468	0.010931	0.016402	0.012119
16	504	0.011677	0.017345	0.01216
17	540	0.012062	0.016815	0.01215
18	576	0.012314	0.017069	0.012143
19	612	0.012294	0.016971	0.012121
20	648	0.013677	0.017086	0.012244
21	684	0.013537	0.017256	0.012281
22	720	0.013577	0.017445	0.012288
23	756	0.013639	0.017257	0.012281
24	792	0.013604	0.017344	0.012221
25	828	0.014353	0.01707	0.012272
26	864	0.014359	0.017117	0.012255
27	900	0.014682	0.016692	0.012167
28	936	0.014714	0.017198	0.012141
29	972	0.015745	0.016683	0.012196
30	1008	0.016264	0.01712	0.012292
31	1044	0.015821	0.016812	0.012351
32	1080	0.016079	0.016619	0.012219
33	1116	0.015523	0.016887	0.012187
34	1152	0.015893	0.017152	0.012127

Chart 5 - Throughput Excel Data

1	time (sec)	increase n	increase n	increase number of end device-two end device-DES-1: ZigBee 802_15_4 MAC.Throughput (bits/sec)
2	0	5134.444	5049.111	5124.444
3	36	11154	11026.89	11440
4	72	11344.67	10740.89	11440
5	108	11312.89	10995.11	11440
6	144	11440	11154	11440
7	180	11376.44	10486.67	11440
8	216	11312.89	11154	11440
9	252	11376.44	10899.78	11440
10	288	11440	10931.56	11440
11	324	11344.67	11026.89	11440
12	360	11376.44	10868	11440
13	396	11185.78	10772.67	11440
14	432	11344.67	11122.22	11440
15	468	11440	11185.78	11440
16	504	11376.44	10772.67	11440
17	540	11154	10868	11440
18	576	11217.56	10836.22	11440
19	612	11376.44	10931.56	11440
20	648	11217.56	10836.22	11440
21	684	11249.33	10582	11440
22	720	11185.78	10709.11	11440
23	756	11312.89	10995.11	11440
24	792	11249.33	10899.78	11440
25	828	11312.89	10868	11440
26	864	11440	10868	11440
27	900	11312.89	10772.67	11440
28	936	11344.67	11154	11440
29	972	11376.44	10772.67	11440
30	1008	11344.67	11154	11440
31	1044	11344.67	10963.33	11440
32	1080	11312.89	10995.11	11440

increase_number_of_end_device-