ENSC 835: COMMUNICATION NETWORKS
Implementation of an IEEE 802.15.4 and ZigBee Protocol using the OPNET simulator

Spring 2009

FINAL REPORT

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Table of Contents

List of Figures

Index of Tables

1. ABSTRACT

The IEEE 802.15.4 and ZigBee protocol stack offers a practical application solution for low cost, low data rate, and low energy consumption characteristics for Wireless Sensor Networks (WSN). The ZigBee networks facilitate many applications, such as Commercial Building and Home Automation, Security, Healthcare Medical Monitoring, Vehicle Monitoring, Agriculture and Environmental Monitoring and so on. Energy consumption, latency and reliability are critical performance measurements in most monitoring systems. This project focuses on simulation an IEEE 802.15.4 and ZigBee protocol using the OPNET simulator.

2. INTRODUCTION

2.1. Overview

Philips, Motorola, Honeywell, Invensys and Mitsubishi Electric started promoting ZigBee when they formed the ZigBee Alliance in October 2002. This was once they had secured the physical layer (PHY) and media access control (MAC) under the IEEE 802.15.4 WPAN (Wireless Personal Area Network) standard [10]. The technology has been living under various guises at Philips for four years. It started life as HomeRF Lite (a sub-spec of the defunct HomeRF, which has now been ousted by Wi-Fi). Since then, it's had name changes to RF Lite, Firefly, RF EasyLink and finally, it became ZigBee [10]. The name comes from the zig-zag dancing of bees to tell the other bees in the colony of the location of a new food source.

ZigBee is a worldwide open standard for wireless radio networks in the monitoring and control fields. The standard was developed by the ZigBee Alliance to meet the following principal needs [9]:

- Low cost
- Ultra-low power consumption
- Low data rate (less than 250 Kbps)
- Use of unlicensed radio bands
- Cheap and easy installation
- Flexible and easy installation
- Integrated intelligence for network set-up and message routing

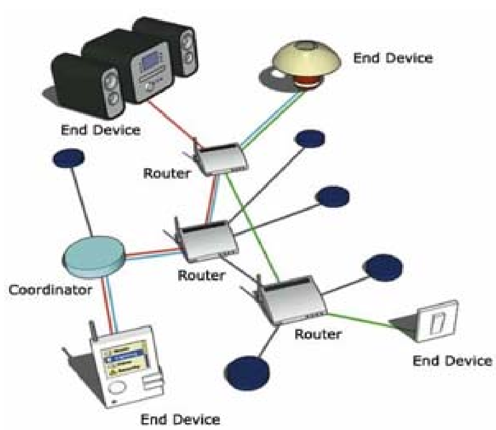

Figure 1: A typical example of ZigBee in Home Automation [9]

The ZigBee standard can operate in the 2.4GHz band or the 868MHz and 915MHz ISM (industrial, scientific, and medical) bands used in Europe and the US respectively [10].

2.2. Architecture

ZigBee has three layers. The top layer is called the application layer (APL). This layer gives the device its functionality. Basically, this layer converts the input into digital data, and/or converts digital data into output. A single device may run multiple applications to perform different tasks (i.e. reading temperature and humidity). The application layer is on top of another layer called the network layer (NWK). The network layer provides ZigBee functionality and acts as a buffer between application layer and data link layer (DLL). The network layer is responsible for network structure, routing, and security such as encryption, key management, and authentication. The data link layer is provided by IEEE 802.15.4 standard. This layer consists of two sub-layers – medium access control layer (MAC) and the physical layer (PHY).

Application layer (APL)
Network layer (NWK)
Medium access control layer (MAC)
Physical layer (PHY)

Table 1: ZigBee protocol layers

2.3. Device types

There are three different types of ZigBee devices:

- *ZigBee coordinator (ZC)*: The most capable device, the coordinator forms the root of the network tree and might bridge to other networks. There is exactly one ZigBee coordinator in each network since it is the device that started the network originally. It is able to store information about the network, including acting as the Trust Centre & repository for security keys.
- *ZigBee Router (ZR)*: As well as running an application function a router can act as an intermediate router, passing data from other devices.
- *ZigBee End Device (ZED)*: Contains just enough functionality to talk to the parent node (either the coordinator or a router); it cannot relay data from other devices. This relationship allows the node to be asleep a significant amount of the time thereby giving long battery life. A ZED requires the least amount of memory, and therefore can be less expensive to manufacture than a ZR or ZC [7].

2.4. Addressing

IEEE 802.15.4 uses two methods of addressing:

- 16-bit short addressing
- 64-bit extended addressing

A network can choose to use either 16-bit or 64-bit addressing. Using the short addressing mechanism reduces the packet length and thereafter the space to store the addresses. This mechanism allows addressing within a single network; however, the combination of a unique PAN ID (personal area network identifier) and 16-bit addressing can be used to address independent networks. Alternatively, 64-bit addressing in IEEE 802.15.4 has not limitation on the number of devices in a single network.

The network layer (NWK) of ZigBee protocol uses a 16-bit address in addition to the IEEE address. The network layer data transactions require an NWK address. A lookup table is used to map each IEEE 802.15.4 64-bit address to a unique network layer address [11].

2.5. ZigBee vs. Bluetooth

The ZigBee specification is defined to be simpler and less expensive than other WPAN (Wireless Personal Area Network) such as Bluetooth. ZigBee operates in radio-frequency bands; 868 MHz in Europe, 915 MHz in the US and Australia, and 2.4 GHz in the rest of the World. Bluetooth uses the microwave RF spectrum from 2.4 GHz to 2.4835 GHz range. ZigBee data rate is 20, 40, and 250 kbps for 868 MHz, 915 MHz, and 2.4 GHz respectively. On the other hand, Bluetooth can achieve a gross data rate of 1 Mbps.

ZigBee operational range is from 10 to 75 metres (up to 1500 metres for ZigBee Pro[1]). The operational range of Bluetooth is 1, 10, and 100 metres depending on the maximum permitted power of the device (see table 2).

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[1] *ZigBee 2007*, now the current stack release, contains 2 stack profiles, stack profile 1 (simply called ZigBee), for home and light commercial use, and stack profile 2 (called ZigBee Pro). ZigBee Pro offers more features, such as multi-casting, many-to-one routing and high security with Symmetric-Key Key Exchange (SKKE), while ZigBee (stack profile 1) offers a smaller footprint in RAM and flash. Both offer full mesh networking and work with all ZigBee application profiles [7].

Class	Maximum permitted power mW (dBm)	Range (approximate)
Class 1	100 mW (20 dBm)	~ 100 metres
Class 2	2.5 mW (4 dBm)	~ 10 metres
Class 3	1 mW (0 dBm)	~ 1 metre

Table 2: Bluetooth operational range

ZigBee uses master-slave configuration in which ZigBee coordinator (ZC) acts as a master and other devices act as slave nodes. Bluetooth devices can work in two different configurations; peer-to-peer and master-slave. In master-slave configuration, one master can have up to seven slave nodes called piconet. Subsequently, two or more piconets can join and form a scatternet.

ZigBee devices can be powered down; meaning that all the circuitry switches off except a 32 kHz clock. The time elapsed from when the device is powered down until it becomes active and receives a packet is called wake up time. The wake up time of ZigBee and Bluetooth are significantly different. Unlike ZigBee that can wake up in 15 msec, Bluetooth takes 3 seconds to wake up [10].

ZigBee is designed to be simple and inexpensive. Therefore, the ZigBee protocol stack has a smaller footprint compared to Bluetooth. The smaller memory size of the protocol stack causes the unit price be cheaper that Bluetooth.

Table 3 shows a brief comparison of ZigBee and Bluetooth.

`	ZigBee	Bluetooth
Transmission band	868, 915, and 2459 MHz	2.4 GHz
Data rate	250 Kbps (at 2.4 GHz)	1 Mbps
Operational range	10 – 75 m (1500 m for ZigBee Pro)	1, 10, and 100 m
Configuration	Master-slave	Peer-to-peer, master-slave
Maximum child	254	7 (active) + 255 (inactive)
Maximum power	1 mW	1, 2.5, and 100 mW
Wake up delay	15 msec	3 sec
Protocol stack	30 kwords	256 kwords
Protocol complexity	Lower	Higher
Price	less expensive	more expensive

Table 3: ZigBee vs. Bluetooth

3. Simulation scenarios

There are two scenarios studied in this project. First, the three possible topologies (Star, Tree, and Mesh) are compared with each other. There is just one ZigBee coordinator in each topology, therefore it just forms a single personal area network (PAN). The comparison includes the statistics: end-to-end delay, number of hops, ZC throughput, and global throughput. Second, the Tree topology with a single ZC is chosen and compared with a similar network that has an additional ZC. The network with two ZCs forms two PANs. The comparison includes the statistics: end-to-end delay and ZC throughput.

End-to-end delay and global throughput use OPNET global statistic values. The method of gathering the global statistics in OPNET is described as: Global statistics provide information that relates to the overall system. Many separate objects may contribute to one global statistic during a simulation. For example, every node in a network model may use the same global statistic to record the end-to-end delay experienced by the packets it receives. The result is one statistic for the network's end-to-end delay performance. Global statistics are declared by process models and are supported by the global statistic probe object. Of course, no objects are referenced in a global statistic probe; only the name of the statistic is specified[2].

3.1.1. Star, Tree, and Mesh topologies

In this scenario, Star, Tree, and Mesh topologies in a ZigBee network are studied. The type and the number of ZigBee nodes in all three topologies are the same. There is just one ZigBee coordinator (ZC) in each setup. There are six ZigBee routers (ZR) and six ZigBee end devices (ZED). Except one mobile ZR and one mobile ZED, the rest of the devices are stationary. These are the parameters used in the simulation:

- 1,000 s simulated time
- Destination: random
- Packet inter-arrival time: constant, mean 1.0 s
- Packet size: 1024 bytes, constant
- Start time: uniform min 20 s, max 21 s

The ZigBee parameters for the three topologies are slightly different. Table 4 compares the parameters.

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[2] OPNET documentation, “Statistic Collection Mechanisms: Probes”

ZigBee Parameters	Value		
	Star	Tree	Mesh
Maximum children	255	3	3
Maximum routers	0	2	2
Maximum depth	1	5	5
Achieved depth	1	3	3
Mesh routing	Disabled	Disabled	Disabled
Transmit power	0.05	0.05	0.05
Transmit band	2450 MHz	2450 MHz	2450 MHz
PAN ID	Auto assigned	Auto assigned	Auto assigned

Table 4: ZigBee parameters

The network structure of Star, Tree, and Mesh topologies are as follows (see Figure 2, Figure 3, and Figure 4 respectively).

There are two trajectories for the two mobile devices defined which are shown by white arrows on the topology screen shots. The doted line between the two nodes shows the parent and child association. Note that the ZigBee coordinator has children but it is not a child itself.

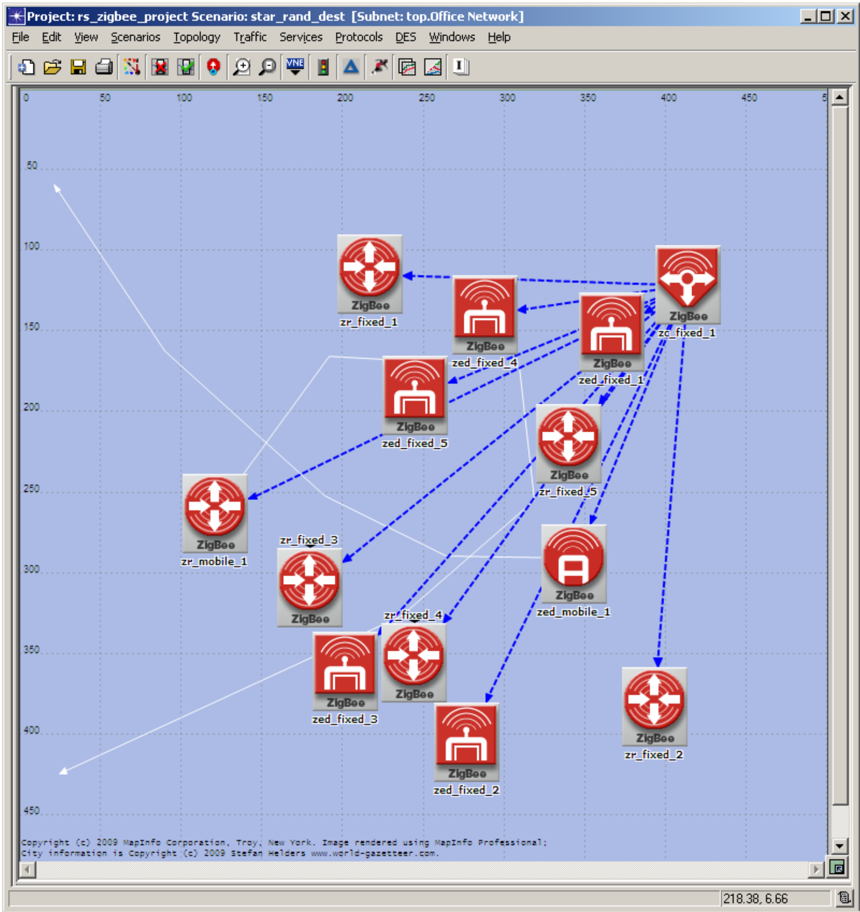

Figure 2: Start topology

In the Star topology, ZC allows up to 255 child nodes to connect to it. The maximum depth is set to one.

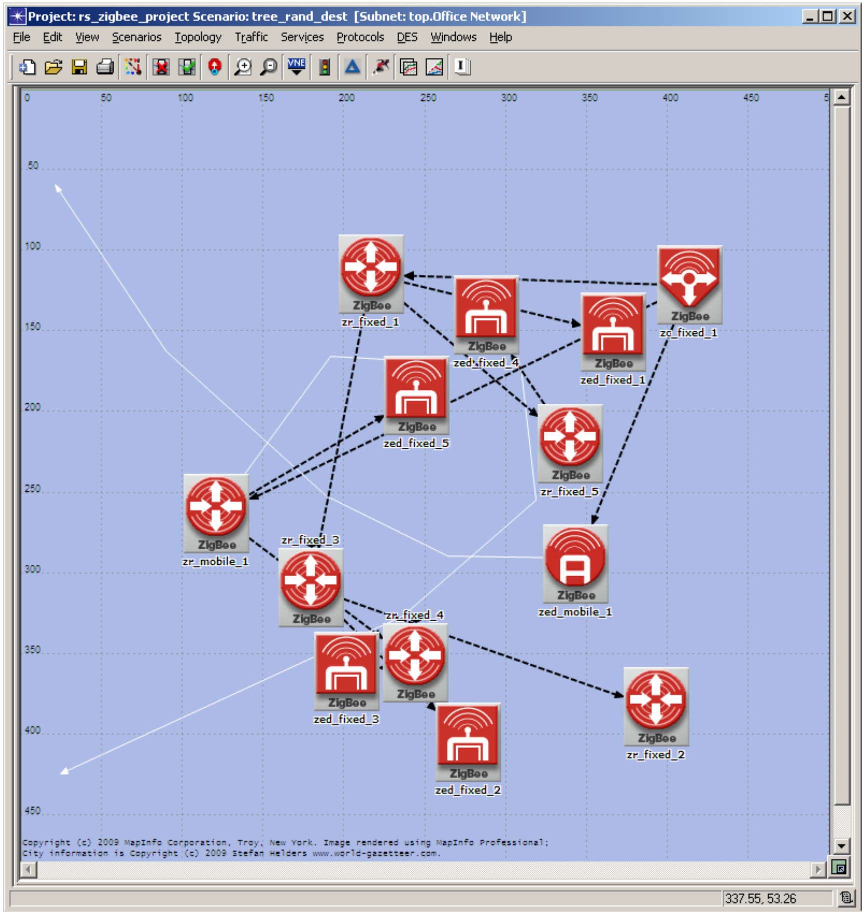

Figure 3: Tree topology

The Tree and the Mesh topologies form the same network structure with the similar seed. The significant difference of the Mesh topology compared to the Tree topology is that the Mesh calculates routing table.

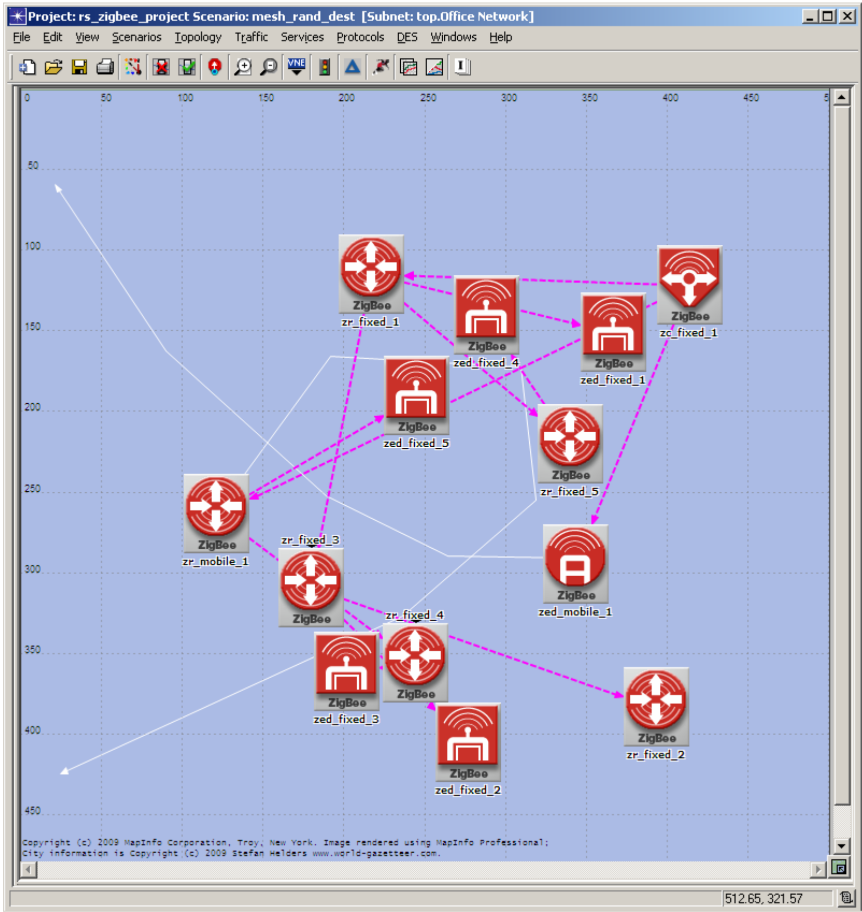

Figure 4: Mesh topology

3.1.2. Single and multiple ZC

The Tree topology of the previous scenario is used as a baseline. A new ZigBee coordinator is added to the network structure that causes the network to have two personal area network (PAN). Simulated time for all three setup is 1,000 seconds. Every device in the network sends packet of 1024 bytes to a random destination with the interval of 1 second. The maximum number of children is set to three.

4. Simulation Results

The results of "Star, Tree, and Mesh topologies scenario" and "single and multiple ZC scenario" are as follows:

4.1. Star, Tree, and Mesh topologies results

In this scenario, the number and type of the devices are identical. The difference is the topology of the network, which is imposed by ZC at start-up. Simulated time for all three setup is 1,000 seconds. Every device in the network sends packet of 1024 bytes to a random destination with the interval of 1 second. The Tree and the Mesh topologies both have maximum children of three nodes. Maximum depth for the Star topology is set to one and for the Tree and the Mesh topologies is set to five. In practice, the Tree and the Mesh topologies formed a network with the maximum depth of three (with the seed 128 in the simulation). The Mesh topology is the only setup that was allowed to generate and use a mesh routing table (see Figure 5).

Mesh Routes.PAN 0 at Simulation Time 60

File Edit View Help

	Source	Destination	Next Hop
1	Office Network.zc_fixed_1	Office Network.zr_fixed_4	Office Network.zr_fixed_4
2	Office Network.zc_fixed_1	Office Network.zr_fixed_3	Office Network.zr_fixed_3
3	Office Network.zc_fixed_1	Office Network.zr_fixed_2	Office Network.zr_fixed_2
4	Office Network.zc_fixed_1	Office Network.zr_fixed_5	Office Network.zr_fixed_5
5	Office Network.zc_fixed_1	Office Network.zr_mobile_1	Office Network.zr_mobile_1
6	Office Network.zc_fixed_1	Office Network.zr_fixed_1	Office Network.zr_fixed_1
7	Office Network.zc_fixed_1	Office Network.zed_mobile_1	Office Network.zed_mobile_1
8	Office Network.zc_fixed_1	Office Network.zr_fixed_1	Office Network.zr_fixed_1
9	Office Network.zc_fixed_1	Office Network.zr_mobile_1	Office Network.zr_mobile_1
10	Office Network.zed_fixed_1	Office Network.zr_fixed_1	Office Network.zr_fixed_1
11	Office Network.zed_fixed_2	Office Network.zr_fixed_3	Office Network.zr_fixed_3
12	Office Network.zed_fixed_3	Office Network.zr_fixed_4	Office Network.zr_fixed_4
13	Office Network.zed_fixed_4	Office Network.zr_fixed_5	Office Network.zr_fixed_5
14	Office Network.zed_fixed_5	Office Network.zr_mobile_1	Office Network.zr_mobile_1
15	Office Network.zr_fixed_5	Office Network.zr_fixed_4	Office Network.zr_fixed_4
16	Office Network.zr_fixed_5	Office Network.zed_fixed_1	Office Network.zr_fixed_1
17	Office Network.zr_fixed_5	Office Network.zr_fixed_3	Office Network.zr_fixed_3
18	Office Network.zr_fixed_5	Office Network.zr_fixed_2	Office Network.zr_fixed_2
19	Office Network.zr_fixed_5	Office Network.zr_mobile_1	Office Network.zr_mobile_1
20	Office Network.zr_fixed_5	Office Network.zr_fixed_1	Office Network.zr_fixed_1
21	Office Network.zr_fixed_5	Office Network.zed_fixed_4	Office Network.zed_fixed_4
22	Office Network.zr_fixed_5	Office Network.zr_fixed_1	Office Network.zr_fixed_1
23	Office Network.zr_fixed_4	Office Network.zed_fixed_5	Office Network.zr_mobile_1
24	Office Network.zr_fixed_4	Office Network.zr_fixed_3	Office Network.zr_fixed_3
25	Office Network.zr_fixed_4	Office Network.zr_fixed_2	Office Network.zr_fixed_2
26	Office Network.zr_fixed_4	Office Network.zr_fixed_5	Office Network.zr_fixed_5
27	Office Network.zr_fixed_4	Office Network.zr_mobile_1	Office Network.zr_mobile_1

Figure 5: Mesh routing table

The focus of the study of the scenario is the following values captured form global and object statistics:

- End-to-end delay
- Number of hops
- Throughput – ZC
- Throughput – global

4.1.1. End-to-end delay result

End-to-end delay is an OPNET global statistics. Global statistics provide information that relates to the overall system. Different object may contribute to the global statistics. Figure 6 shows the end-to-end delay result of the three topologies. The Star and the Mesh topologies have similar end-to-end delay in this simulation. The Tree topology has a higher end-to-end delay of 50% and increasing.

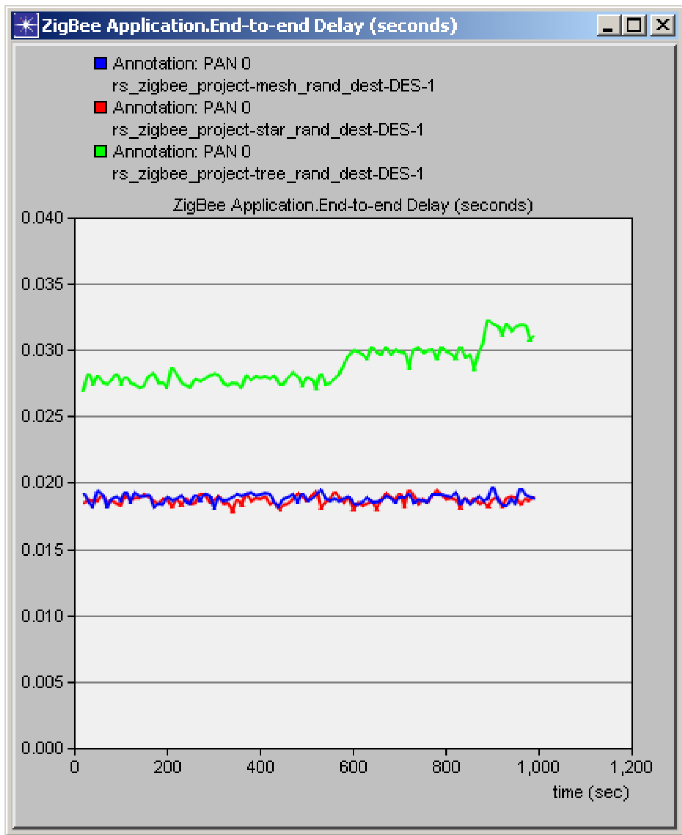

Figure 6: End-to-end delay (Star, Tree, and Mesh)

4.1.2. Number of hops result

The number of hops is the number of times a packet travels from the source through the intermediate nodes to reach the destination. The number of hops for the Star topology is two, meaning the source and the random destinations have another intermediate node, which relays the data. That node in this topology is the coordinator. The number of hops for the Tree topology varies from one to six. Since the maximum depth of the network structure for the simulation is three, it takes a maximum of six hops to deliver the packet to the furthest node. The Mesh topology uses a routing table and the average number of hops is two. Therefore, the average number of hops for the Mesh topology is the same as the Star topology. The Tree setup in this simulation has a higher average number of hops by 75% (see Figure 7).

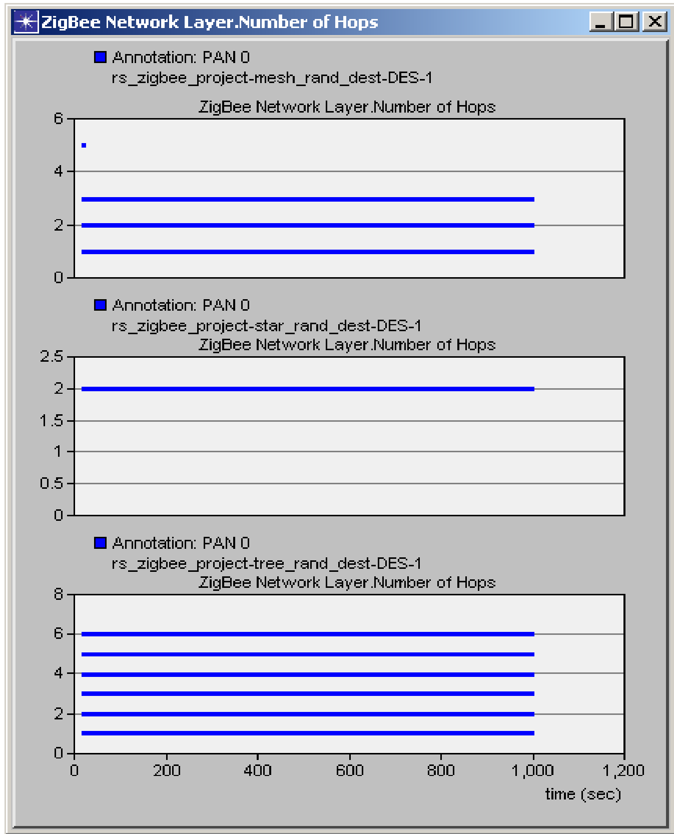

Figure 7: Number of hops

4.1.3. Throughput – ZC result

The throughput is the number bits per second a node can deliver. In this statistic, the ZigBee coordinator throughput is the focus. Unsurprisingly, the result shows that the ZC throughput of the Star topology is the highest, since all of the traffic funnels through the coordinator. The coordinator in the Tree topology has the second highest throughput because if the parent node does not recognize the address of the destination to be one of its children, it sends it to its parent node. The Mesh topology is not as reliant to the ZC traffic as the other two topologies. Some nodes can communicate with each other through routing table (see Figure 8).

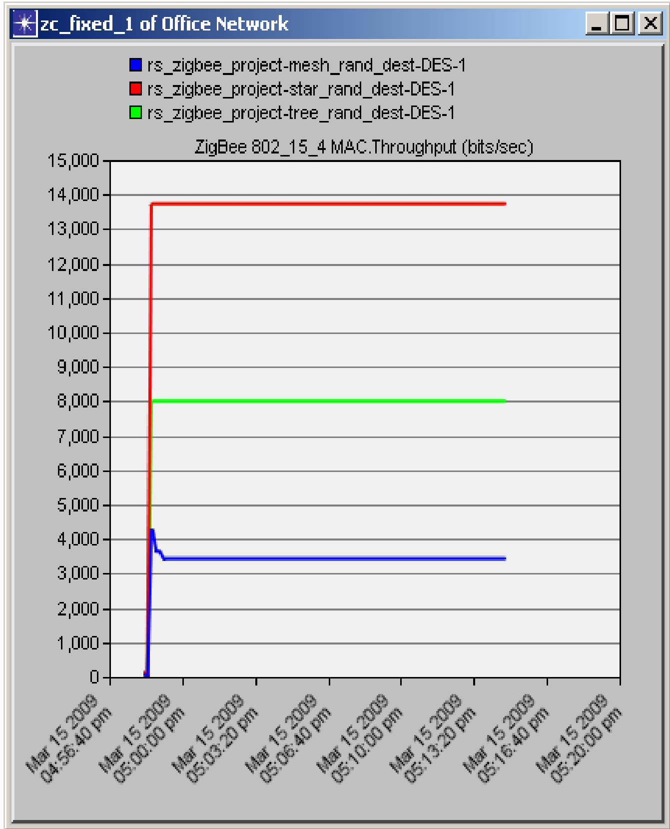

Figure 8: Throughput - ZC

4.1.4. Throughput – global result

The global throughput is a global statistics and any object could contribute to its value. It gives a general idea of the overall throughput of the system. In this simulation, the Tree topology has the highest global throughput (bits/second). The Mesh topology has the second highest global throughput. Finally, the Star topology has the lowest global throughput (see Figure 9).

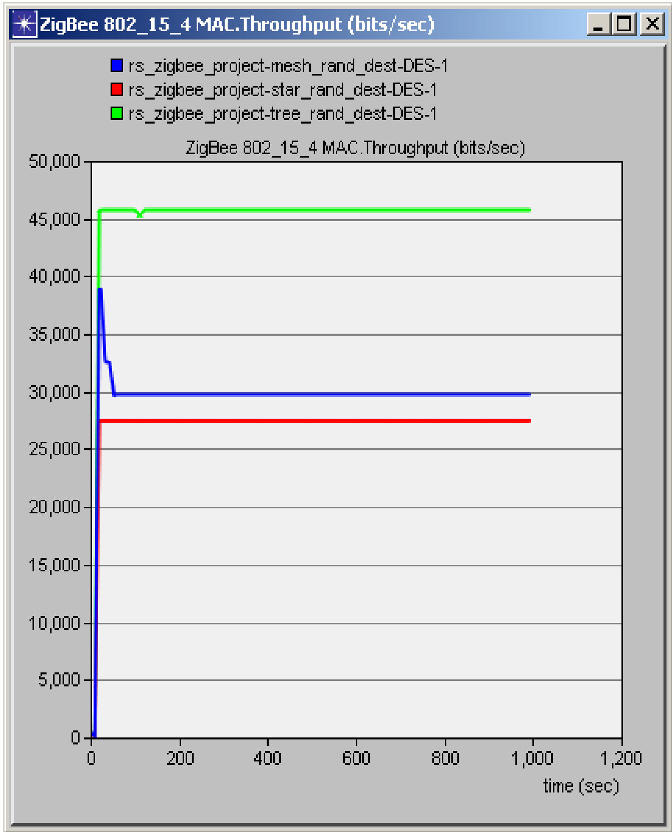

Figure 9: Throughput - global

4.2. Single and multiple ZC results

In this scenario, the Tree topology of the previous scenario is used as a baseline. A new ZigBee coordinator is added to the network structure that causes the network to have two personal area network (PAN). Simulated time for all three setup is 1,000 seconds. Every device in the network sends a packet of 1024 bytes to a random destination with the interval of 1 second. The maximum number of children is set to three (see Figure 10).

The focus of the study of the scenario is the following values captured form global and object statistics:

- End-to-end delay
- Throughput – ZC

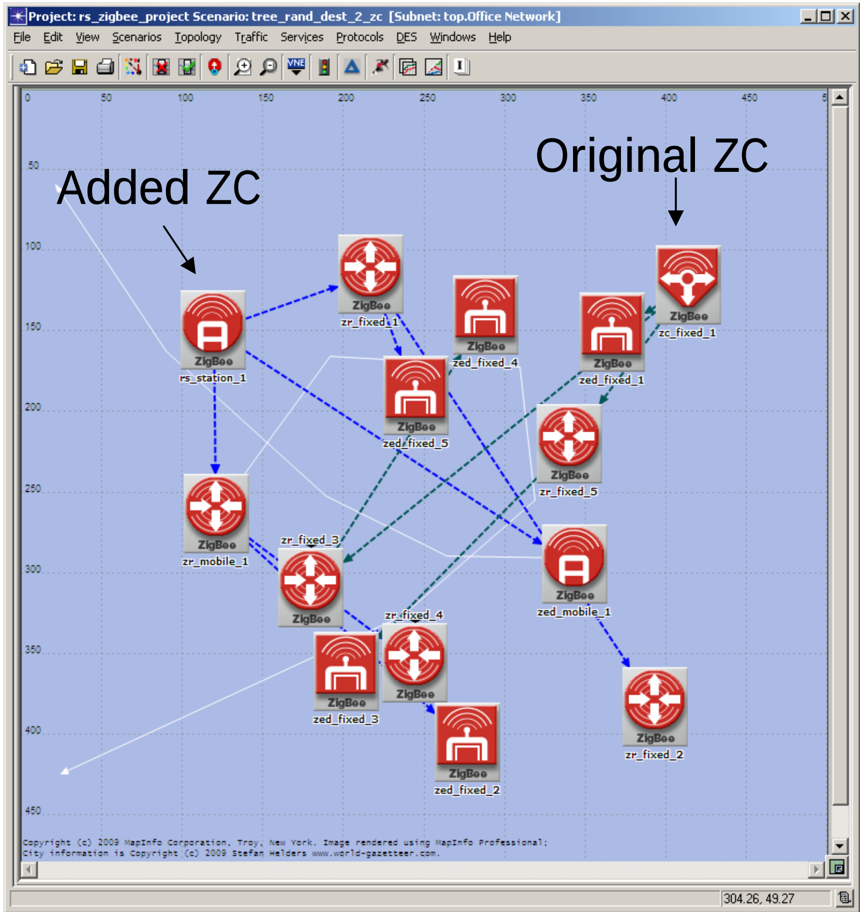

Figure 10: Multiple ZC - tree topology

4.2.1. End-to-end delay result

Figure 11 shows the end-to-end delay result of the Tree topology with a single PAN versus the Tree topology with two PANs. The following is the result of this global statistics.

- Ds_0: end-to-end delay of the network with a single PAN
- Dm_0: end-to-end delay of PAN_0 in the network with two PANs
- Dm_1: end-to-end delay of PAN_1 in the network with two PANs

- Ds_0 > Dm_0
- Ds_0 > Dm_1
- Ds_0 < Dm_0 + Dm_1

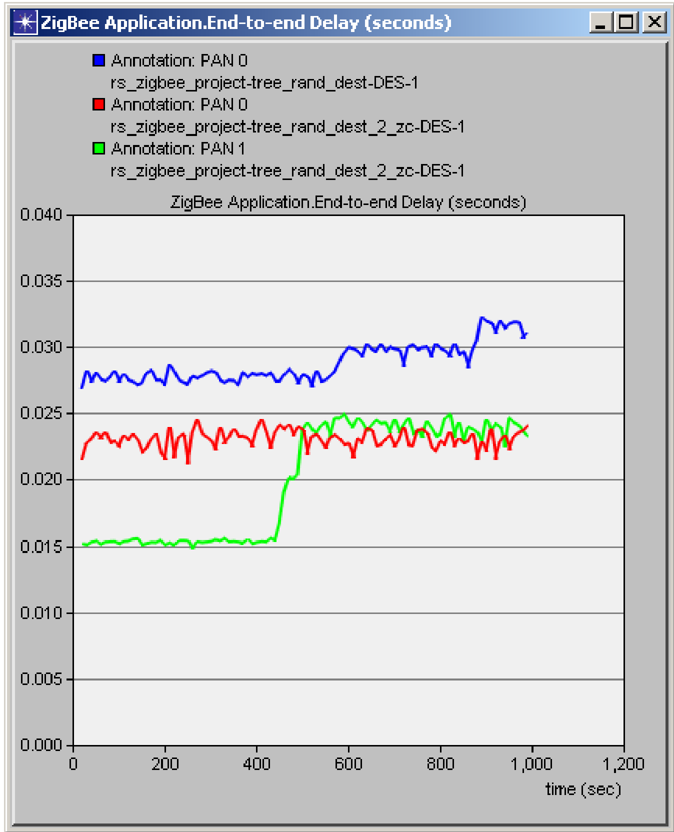

Figure 11: End-to-end delay - single vs. multiple ZC

4.2.2. Throughput - ZC result

The throughput is the number of bits per second a node can deliver. In this statistics, the ZigBee coordinator throughput is the focus. There are three ZigBee coordinators in this study. The first ZC belongs to the Tree topology with single PAN and the other two ZCs belong to the Tree topology with two PANs. The following is the result of this objects statistics:

- Ts_0: throughput of ZC in the network with a single PAN
- Tm_0: throughput of ZC in PAN_0 of the network with two PANs
- Tm_1: throughput of ZC in PAN_1 of the network with two PANs

- (Ts_0 * 1.25) = Tm_1 + Tm_2

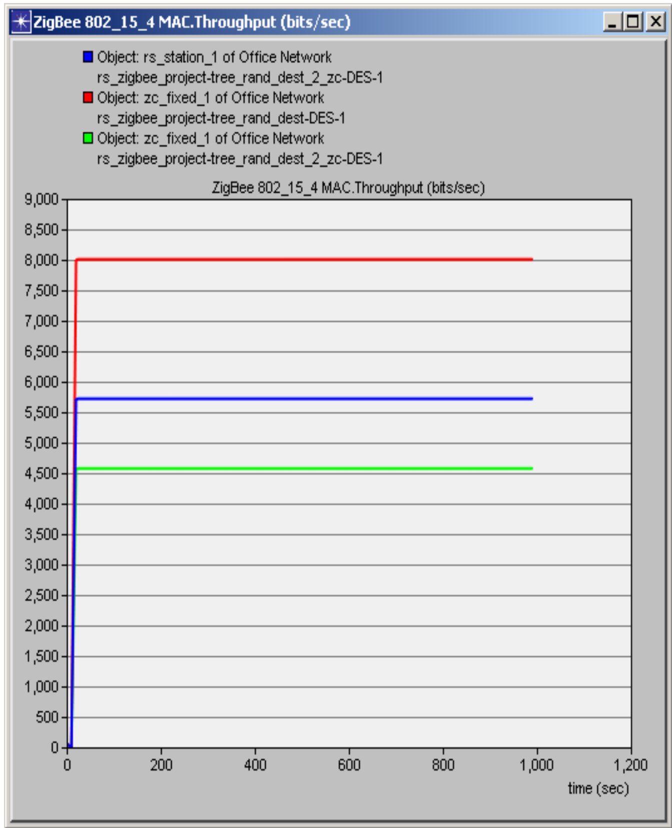

Figure 12: Throughput ZC - single vs. multiple ZC

5. DISCUSSION AND CONCLUSIONS

In this study, The Star, Tree, and Mesh topology with a single PAN were evaluated. The thirteen nodes (one ZC, six ZRs, and six ZEDs) in each topology were identical. Simulated time for all three setup was 1,000 seconds. Every node transmitted packets of 1024 bytes to a random destination with the interval of one second. It appeared that the end-to-end delay of the Star and the Mesh topology for this simulation is similar, but the Tree topology end-to-end delay is higher. The average number of hops for the Star topology and the Mesh topology are the same. However, the average number of hops for the Tree topology is higher by 75%. The coordinator throughput of the Star topology is the highest, and then second is the Tree topology and the third in the rank is the Mesh topology. The global throughput (bits/second) of the Tree topology is the highest. The Mesh topology has the second highest global throughput. Finally, the Star topology has the lowest global throughput.

The second part of the study was dedicated to the comparison of the Tree topology with a single PAN and similar Tree topology with two PANs (an extra ZC added). The study shows that the end-to-end delay of the network with a single PAN is higher than the end-to-end delay of PAN_0 or PAN_1 in the network with two PANs. However, the end-to-end delay of the network with a single PAN is lower than the end-to-end delay of PAN_0 and PAN_1 combined in the network with two PANs.

The throughput of the ZC in the network with a single PAN is almost 25% lower than the throughput of the ZC_0 and ZC_1 combined in the network with two PANs.

6. Unfinished work

ZigBee is a low bandwidth, cost effective, and secure protocol that can be used in many areas. Monitoring and control is a field to which this protocol is well suited. Reliability of the network in such an environment is always a key factor. Recently, ZigBee entered into the area of health monitoring. Patients, especially those with chronic illnesses do not have to leave their homes to get medical attention. ZigBee devices can be installed in the patient's home environment or can be carried by the patient in order to report his/her medical status to a remote centre. A ZigBee coordinator or gateway is required to carry ZigBee messages to the internet using a hybrid solution. Evidently, the reliability of the devices, particularly the coordinator, becomes very apparent.

ZCB is a supplementary device that monitors and mirrors the ZigBee coordinator data and in the case of a failure substitutes itself as the new ZigBee coordinator of the network. At start ZCB act as a router or maybe a ZED and passively or actively monitors the activities of the ZigBee coordinator. With the sense of a failure or reaching a no hear or no response timeout it changes its type to coordinator and takes over.

The issue with implementing the idea is that OPNET does not provide source code for ZigBee application layer and network layer. These two layers were intentionally provided without any source code and only object code is provided. Access to the source code appears to be essential to implement the concept of ZCB.

The following figures show the areas that were worked on to make the concept operational

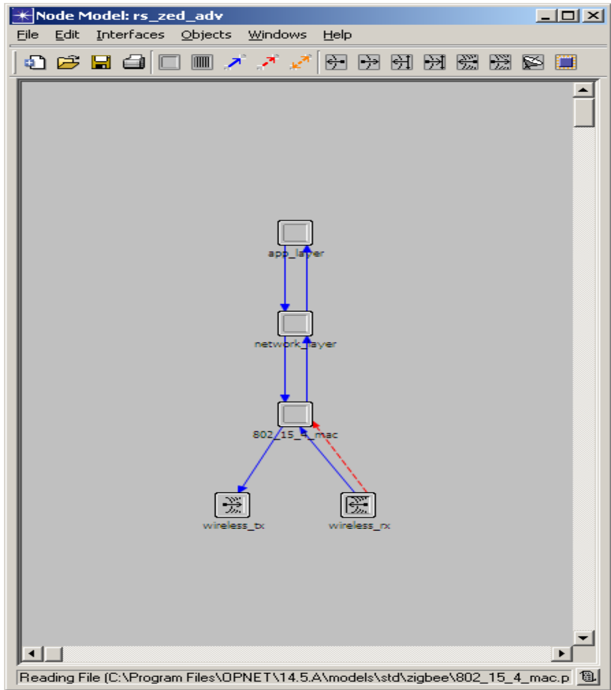

Figure 13: ZigBee node model

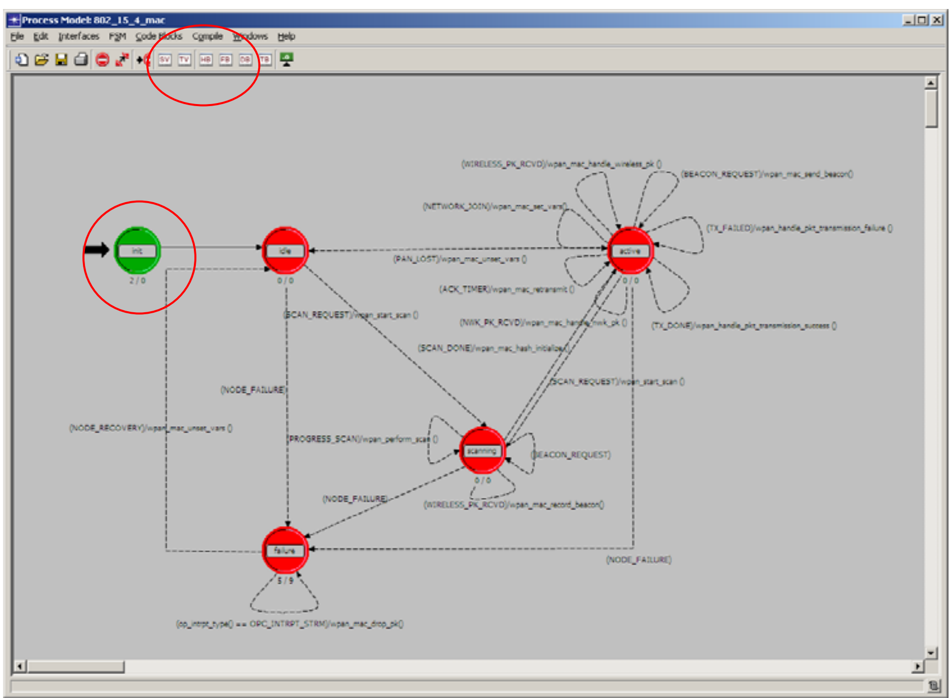

Figure 14: ZigBee process model

```
static void failNode(void * ptrVoid, int iCode);
void wpan_prj_init();
...
void wpan_prj_init() {

    double dInterruptTime = 100.0; // time is second that the interrupt is
    scheduled
    int iCode = 0; // verification code
    void * ptrVoid = 0; // data structure to send to the called function

    FIN (wpan_prj_init());
    dInterruptTime += op_sim_time();
    op_intrpt_schedule_call(dInterruptTime, iCode, failNode, ptrVoid);

    FOUT;
}
```

Figure 15: Sample code

7. Future work

This section describes the future work that could be done to improve this area of study. One of the difficulties during the study was the lack of OPNET source code for ZigBee application layer and network layer. These two layers were intentionally provided without any source code and only object code is provided. Access to the source code, especially the application layer will relieve the issue of implementing the ZC Backup (ZCB). ZCB is an auxiliary node that monitors and mirrors the ZigBee coordinator data and in the case of a failure replaces itself as the new ZC of the network. Finally, implementing the study in ns-2 would be advantageous, since the open source and free access to all layers of the protocol is possible. Also, the new contribution would benefit the research community.

Here is the future work that could be considered in a nutshell:

- Access to OPNET source code of the network and the application layers
- Complete ZC backup (ZCB) concept:
    - Monitor and mirror ZC data
    - Substitute ZC in case of failure
- Implement and analyze the concept in ns-2

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