Overview and Analysis of the Performances of ZigBee-based Wireless Sensor Networks

Boris Mihajlov[1] and Mitko Bogdanoski[2]

[1]Faculty of Informatics, European University, Skopje, Macedonia,

[2] Military Academy "General Mihailo Apostolski", Skopje, Macedonia

ABSTRACT
Wireless sensor networks (WSN) consists of light-weight, low-power and small size sensor nodes (SNs). They have ability to monitor, calculate and communicate wirelessly.

In this paper we present a performance evaluation of ZigBee which is IEEE 802.15.4 standard, including the Physical (PHY) layer and Media Access Control (MAC) sub-layer, which allow a simple interaction between the sensors.

We provide an accurate simulation model with respect to the specifications of IEEE 802.15.4 standard. We simulate and analyzed two different scenarios, where we examine the topological features and performance of the IEEE 802.15.4 standard using OPNET simulator. We compared the three possible topologies (Star, Mesh and Tree) to each other.

Keywords: Wireless Sensor Networks, ZigBee, routing protocols, OPNET.

1. INTRODUCTION
In 1999 it was named as one of "21 ideas for the 21st Century" [1], and in 2003 was presented as one of "10 new technologies that will change the world" [2]. This revolutionary technology is known as WSNs.

The development of this technology is supported by advancement in electronic miniaturization (including micro-electromechanical systems (MEMS) technologies), wireless communications and low cost manufacturing.

WSNs have not yet achieved widespread deployments, although they have been capable to meet the requirements of many applications categories. WSNs have some limitations as lower computing power, smaller storage devices, narrower bandwidth and very low battery power.

Routing protocols in WSNs vary depending on the application and network architecture. Used sensors are small, inexpensive, intelligent, and disposable, they can be deployed in large numbers in areas where there is no human access, disaster areas, battlefields etc.

The SNs are self-configurable and contain one or more sensors, embedded wireless communication and data components and limited sources of energy. Due to the large numbers of nodes and dangerous environment of deployment, their batteries cannot be replaced or recharged. The failure of one node in the network could cause network separation. The network lifecycle depends on the lifecycle of each node individually. Sensors are characterized with sensitivity capability, data processing and communication. During the movement, SNs make measurements of various parameters in the environment in which they operate and transforming them into electrical signals.

Scalability is another important issue in the design of such networks. Any protocol designed for such networks should be scalable, so that it can handle a larger network of thousands SNs.

Current and potential applications of the WSNs include: military sensing, physical security, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing automation, distributed robotics, environment monitoring, and building and structures monitoring [2].

The four possible models of WSNs are as follows [3]:

Model 1: Both the SNs as well as the Base Station (BS) are static.

Model 2: The SNs are mobile but the BS is static.

Model 3: The SNs are static but the BS is mobile.

Model 4: Both the SNs as well as BS are mobile.

It is unimportant to mention that all these models have applications in practical daily life.

The purpose of this research is performance analysis of the IEEE 802.15.4/ZigBee-based WSNs which are characterized with flexibility for a wide range of applications with easy adjustment of their parameters and also guaranteed transmission in real time using "Guaranteed Time Slot - GTS" mechanism.

In order these goals to be achieved, this paper will present a detailed overview of wireless sensor networks and content of ZigBee protocol. Doe to more realistic view of the performance of ZigBee protocol and its behavior in a realistic environment, this paper will conduct some simulations, and for this purpose OPNET Modeler simulation tool will be used.

2. WSNs
WSN consists of a large number of SNs wirelessly connected to each other, and BS, which connects the SNs with another network. WSNs are new field of research, which is currently growing rapidly.

2.1 Evolution of WSNs
The development of WSNs was initiated by the United States during the Cold War [4]. A system of acoustic sensors (hydrophones) was deployed at strategic locations on the ocean bottom, in order to detect and track quiet Soviet submarines. This system of acoustic sensors was called Sound Surveillance System-SOSUS.

In addition, during the Cold War, networks of air defense radars were developed and deployed to defend the continental United States and Canada. These sensor networks generally adopt a hierarchical processing structure where processing occurs at consecutive levels until the information about events of interest reaches the user. In many cases, human operators play a key role in the system [4].

Modern research on sensor networks started around 1980 with the Distributed Sensor Networks (DSN) program at the Defense Advanced Research Project Agency (DARPA).

One of the newest WSN projects is the Wireless Self-Sustaining Sensor Network-WSSN, project of Institute of Computer Technology at the Vienna University of Technology (Vienna University of Technology-TUV) [5].

The main research goal was to show that energy self-sufficient wireless SNs are feasible by using a very efficient overall system implementation with off-the-shelf components. This has been accomplished by an efficient MAC protocol, the CSMA-MPS optimized for high bit radio transceivers and the use of an efficient power management circuit [6]. One of the generated nodes is shown on Figure 1.

2.2 Factors influencing the WSN design

Different types of sensors can be incorporated in the WSNs, including: temperature, vibration (seismic), acoustics and infrared rays' sensors.
A WSN design is influenced by many factors, which include *reliability, scalability, production costs, network topology, operating environment, transmission media and power consumption* [7].

2.2.1 Reliability

Environmental interference, physical damage or exhaustive energy source can cause the SN to fail. However, it is important that the failure of a SN does not affect the overall efficiency of the network. Security in the WSN is the ability of the network to maintain its functionality, regardless of the nodes failure.

2.2.2 Scalability

The number of SNs deployed in studying a phenomenon may be in the order of hundreds or thousands. Depending on the application, the number may reach an extreme value of millions. The new schemes must be able to work with this number of nodes. They must also utilize the high-density nature of the WSNs. The density can range from few SNs to few hundred SNs in a region.

2.2.3 Production costs

Since the WSNs consist of a large number of SNs, the cost of a single node is very important to justify the overall cost of the networks. If the cost of the network is more expensive than deploying traditional sensors, then the WSNs is not cost-justified. As a result, the cost of each sensor node has to be kept low. The cost of a sensor node should be much less than $1 [7].

3. NETWORK TOPOLOGY

The topology changes and maintenance can be considered in three stages, i.e. *deployment phase, post-deployment phase and re-deployment phase* [7].

SNs can be either thrown in as a mass or placed one by one in the sensor field. They can be deployed by dropping from a plane, placing in factory, placing each one by one either by a human or by a robot etc.

Topology changes during the phase of post-deployment are due to node failures and nodes position changes because of the mobility. During the phase of re-deployment, additional nodes are deployed in the network. This can happen at any time.

3.1 Operating environment

SNs are densely deployed either very close or directly inside the phenomenon to be observed. Therefore, they usually work unattended in remote geographic areas. They may be working in busy intersections, interior of large machinery, bottom of an ocean, in a battlefield beyond the enemy lines, large building, attached to animals etc.

3.2 Transmission media

In a multihop sensor network, communicating nodes are linked by a wireless medium. These links can be formed by radio, infrared or optical media. To enable global operation of these networks, the chosen transmission medium must be available worldwide.
RF communication is used by WSNs developed by TUV for the WSSN project, and by the SNs developed by the University of California, Los Angeles (University of California, Los Angeles-UCLA) for Wireless Integrated Network Sensors (WINS) project [8].

3.3 Power consumption

The wireless SN can only be equipped with a limited power source. In some application scenarios, replenishment of power resources might be impossible. SN lifetime, therefore, shows a strong dependence on battery lifetime. In a multihop ad hoc sensor network, each node plays the dual role of data originator and data router. The dysfunctioning of few nodes can cause significant topological changes and might require packets re-routing and network re-organization. Hence, power conversation and power management take on additional importance.
The main task of a SN in a sensor field is to detect events, perform quick local data processing, and then transmit the data. Power consumption can hence be divided into three domains: *sensing, communication, and data processing*.

4. ROUTING PROTOCOLS

Even through, there are many routing protocols for WSN, there is still a great need for new protocols that can prolong the lifetime of the network and can be easily implemented in the nodes using the currently technology, and also can be used for networks with different size.

WSN routing protocols based on a network structure can be classified as *flat* and *hierarchical* protocols.

Flat routing protocols distribute information as needed to any router that can be reached or receive information. No effort is made to organize the network or its traffic, only to discover the best route hop by hop to a destination by any path [9].

Hierarchical routing protocols often group together by function into a hierarchy. A hierarchical protocol allows an administrator to make best use of his fast powerful routers as backbone routers, and the slower, lower powered routers may be used for access purposes.

Flat protocols are more effective for using than hierarchical WSN protocols, due to the fact that they are scalable and simple [9].

Scalability of flat protocols is because each node participates equally in routing tasks, and that the node requires only information about its neighbors. *The simplicity* is because flat routing networks provide simple routing, without much overhead, and no need for complex algorithms.

5. STANDARDS FOR WIRELESS CONNECTION

In March 1999, IEEE establishes the 802.15 working group as part of the IEEE Computer Society's 802 Local and Metropolitan Area Network Standards Committee. 802.15 working group was established with a specific goal of developing standards for short wireless networks, known as Wireless Personal Area Network-WPAN.

There are four target groups within the 802.15-working group. Target group number one (802.15.1) standard defines the WPAN based on the Physical (PHY) and Medium Access Control (MAC) level of Bluetooth version 1.1 [10].

Target group number two (802.15.2) develops a model for coexistence of WLAN (801.11) and WPAN (802.15).

The purpose of the target group three (802.15.3) is to develop standards for a data flow in WPAN (20Mbps and higher).

The target group four (802.15.4) is responsible for developing standards of PHY and MAC level for a small flow of data, very complex solutions that will extend battery lifetime to years.

5.1 IEEE 802.15.4/ZigBee overview

IEEE 802.15.4/ZigBee is a standard protocol for Low-Rate Wireless Personal Area Networks (LR-WPAN). Its main features are network flexibility, low data rate, low cost and very low power consumption, which make it suitable for an ad-hoc network between inexpensive fixed, portable and moving devices. The IEEE 802.15.4 protocol includes a PHY layer and MAC sub-layer for the LR-WPAN. The PHY layer offers three operational frequency bands; there are 27 channels allocated in the 802.15.4 range, with 16 channels in the 2.4 GHz band, 10 channels in the 915 MHz band, and 1 channel in 868 MHz band [11].

The MAC sub-layer handles all access to the physical radio channel. It provides an interface between the service specific convergence sub-layer (SSCS) and the PHY layer [11, 12].

5.2 ZigBee specifications

Table 1 presents the basic specifications of the ZigBee 802.15.4 standard.

Table 1. Basic ZigBee specifications

Parameters	ZigBee Value
Transmission range (meters)	**1 - 100**
Battery life (days)	**100 – 1.000**
Network size (# of nodes)	**> 64.000**
Throughput (kb/s)	**20 - 250**

5.2.1 *Network components*

IEEE 802.15.4 protocol generally defines three types of nodes:

1) *PAN (Personal Area Network) coordinator*. The main network coordinator identifies its PAN and can be connected to other nodes. In addition, it proposes global synchronization services to other nodes in the network through transmission of beacon frames that contained the identification of PAN and other relevant information.
2) *Coordinator*. It has the same functionality as PAN coordinator, except that it does not create its PAN. Coordinator is connected to the PAN coordinator and provides services for local synchronization of the nodes in its range with significant transfer beacon frames containing the identification of the PAN, which is connected.
3) *Simple (secondary) node.* It is a node with no coordinated functionalities. To be able to synchronize with the other nodes in the network, it is connected as a secondary node with the PAN Coordinator (or with the coordinator). In the IEEE 802.15.4 2003 standard, the first two types of nodes are defined as Full Function Devices – FFD, which means that they implement all the functionalities of the IEEE 802.15.4 protocol.

5.2.2 *ZigBee topologies*

IEEE 802.15.4 supports three types of topologies: Star, Mesh and Tree that can be considered as a special case of Mesh topology.

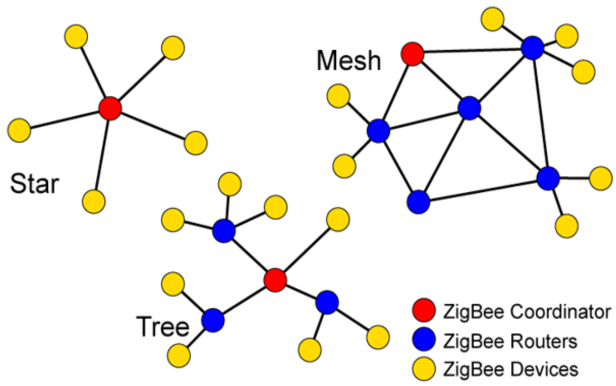

Figure 2. Network topologies

5.2.2.1 *Star topology*

In this simple topology, a coordinator is surrounded by a group of either end devices or routers. This type of topology is attractive because of its simplicity, but at the same time presents some key disadvantages. In the moment when the coordinator stops functioning, the entire network is functionless because all traffic must travel through the center of the star. For the same reason, the coordinator could easily be a bottleneck to traffic within the network, especially since a ZigBee network can have more than 60000 nodes.

5.2.2.2 *Tree topology*

In a Tree network, a coordinator initializes the network, and is the top (root) of the tree. The coordinator can now have either routers or end devices connected to it. For every router connected, there is a possibility for connection of more child nodes to each router. Child nodes cannot connect to end devices because it does not have the ability to relay messages.

This topology allows different levels of nodes, with the coordinator being at the highest level. In order the messages to be passed to other nodes in the same network, the source node must pass the messages to its parent, which is the node higher up by one level of the source node, and the message is continually relayed higher up in the tree until it is passed back down to the destination node. Because the number of potential paths a message can take is only one, this type of topology is not the most reliable topology. If a router fails, then all of that router's children are cut off from communicating with the rest of the network.

5.2.2.3 Mesh topology MHz

Mesh topology is the most flexible topology of the three. Flexibility is present because a message can take multiple paths from source to destination. If a particular router fails, then ZigBee's self-healing mechanism will allow the network to search for an alternate path for the message to be passed [13].

5.2.3 ZigBee layers

ZigBee consists of four layers. The top two (Application and Network) layers specifications are provided by the ZigBee Alliance to provide manufacturing standards. The bottom two (MAC and PHY) layers specifications are provided by the IEEE 802.15.4-2006 standard to ensure coexistence without interference with other wireless protocols, such as Wi-Fi.

5.2.3.1 Application Layer

Application layer is the top layer defined in the specifications and it is an effective interface of ZigBee system to its end users. This layer makes the device useful to the user. It contains most of the components added by the ZigBee specification: an integral part of this layer is also both ZDO (ZigBee Device Object) and its management procedures, along with application objects defined by the manufacturer [13].

5.2.3.2 Network Layer

A feature of ZigBee such as the self-healing mechanism is acquired through this layer. As Figure 3 shows, this layer provides network management, routing management, network message broker, and network security management. The ZigBee Alliance defines this layer, which is an association of companies working together to enable reliable, cost-effective, and low-power wirelessly networked monitoring and control products based on an open global standard [13].

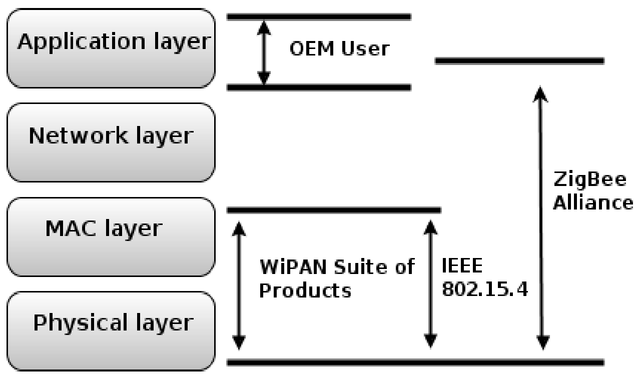

Figure 3. ZigBee layers

5.2.3.3 MAC sub-layer

The MAC layer is responsible for the data addressing in order to determine either where the frame is going, or coming from. This layer also provides multiple access control such as CSMA/CA allowing for reliable data transfer. Beaconing is another feature implemented through this layer. Finally, the MAC sub-layer can be exploited by higher layers to achieve secure communication [14].

5.2.3.4 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. Operates on 2.4 GHz frequency band with 250 kbps data rate and 16 available channels. This layer allows channel selection to avoid radio interference [14].

6. SIMULATION MODEL

Simulation and modeling are important approaches in the development and evaluation of the systems in terms of time and costs. The simulation shows the expected behavior of the system based on its simulation model under different conditions. Hence, the purpose of this simulation model is to determine the exact model and predict the behavior of the real system. For the purpose of simulation, we will use OPNET Modeler 14.5, which is a leading environment for modeling and simulations. This simulation tool provides a comprehensive development environment to support modeling of communication networks and distributed systems. This version of simulation supports three types of topologies: star, mesh and cluster-tree topology, where communication takes place between a central controller – PAN coordinator, routers and devices.

6.1 Simulation scenarios

In this project, we are considering two scenarios. First, we are comparing the three possible topologies (Star, Mesh and Tree) to each other. We are using only one ZigBee Coordinator (ZC) in each topology, six ZigBee routers (ZR) and six ZigBee End devices (ZED). One ZR and one ZED are mobile, while the others are fixed. The comparison includes the following statistics: end-to-end delay, number of hops and global throughput.

During the second scenario, we are using the Tree topology with a single ZC and compared with a similar network that has an additional ZC. The comparison includes the statistics for end-to-end delay and ZC throughput.

6.1.1 First scenario

In this scenario, Star, Mesh and Tree topologies in a ZigBee network are considered. The number and type of ZigBee nodes in all three topologies are the same. There is only one ZC, six ZR and six ZED. Only one ZR and ZED are mobile, while the others are stationary.

Table 2. ZigBee parameters

Parameters	Value		
	Star	Tree	Mesh
Max.childrens	255	3	3
Max.routers	0	2	2
Max.depth	1	5	5
Mesh routing	Disabled	Disabled	Disabled
Transmit power	0.05	0.05	0.05
Transmit band	2.4GHz	2.4GHz	2.4GHz
ACK mechanism	Enable	Enable	Enable

The other parameters used in simulation are:

- Destination: random
- Packet size: 1024 bytes
- Packet inter-arrival time: constant (1.0)
- Start Time: uniform (20, 21)
- Simulation time: 1.000 seconds

We define two trajectories where the mobile nodes will pass during the simulation progresses. If the mobile node is out of its parent transmission range, then it connects to the closer node and it continuing with the transmissions.

The network structure of Star topology is shown on Figure 4.

In the Star topology, ZC allows up to 255 child nodes to be connected, and the maximum depth is set to one. We set the Acknowledgment mechanism to "Enable" for every ZED, so every ZED can send an acknowledgment to its parent in order to confirm that it receives the packets.

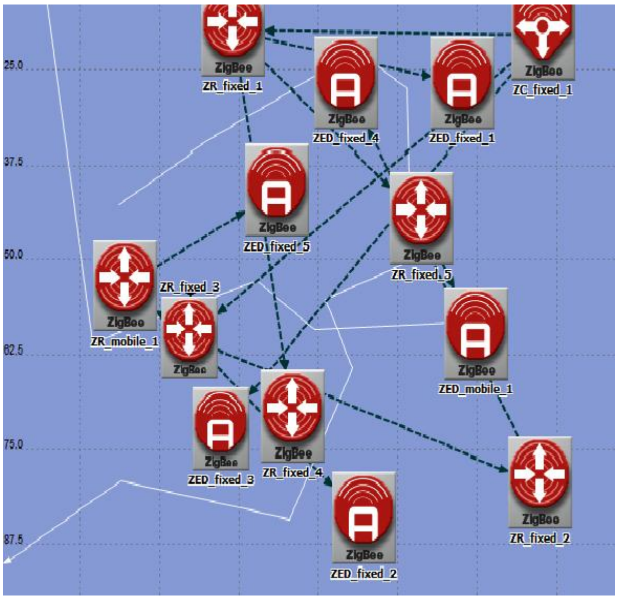

Figure 4. Star topology

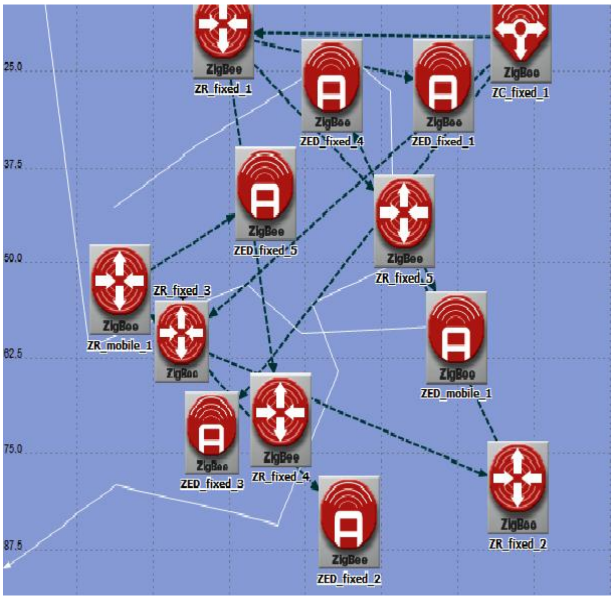

Figure 5. Tree topology

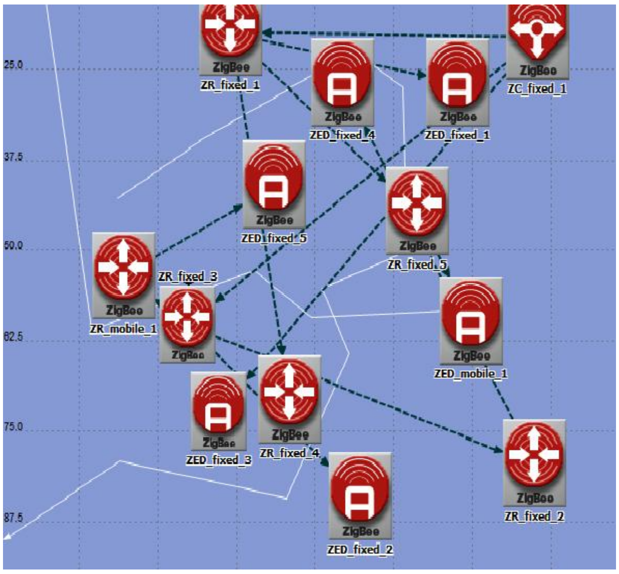

Figure 6. Mesh topology

The network structure of Tree and Mesh topologies are shown on Figure 5 and Figure 6 respectively.
The Mesh and the Tree topologies form the same network structure with the similar seed. The only difference between them is that the Mesh topology calculates routing table.

6.1.2 Second scenario

As we described above, this scenario uses the same ZigBee parameters as the first one, and the only difference is that in this scenario there are two ZigBee coordinators in the network structure. The first ZC belongs to the Tree topology with single PAN_0 and the other two ZCs to the Tree topology with two PANs (PAN_0 and PAN_1). In order to compare the simulation results we are using the Tree topology.

The simulation time is set to 1.000 seconds, and every device sends packet of 1024 bytes to a random destination with interval of 1 second. Maximum number of children is set to three, and every ZED has enabled ACK mechanism.

The network structure of this topology is shown on Figure 7.

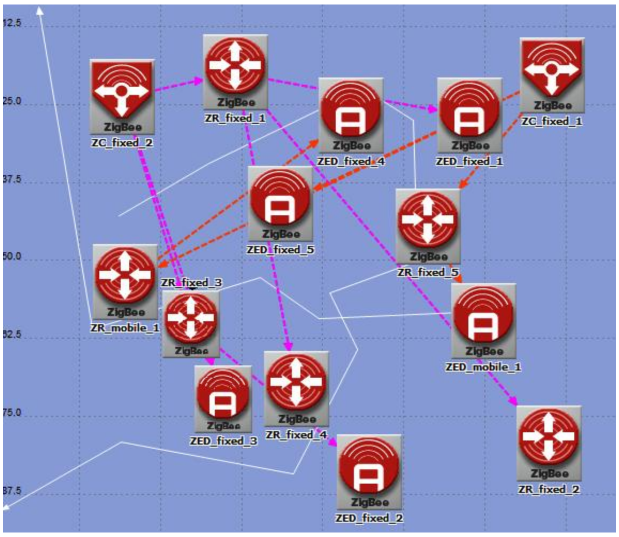

Figure 7. Tree topology with two ZigBee coordinators

6.2 Simulations results

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

6.2.1 *Star, Tree and Mesh topologies results*

The focus of the study of this scenario is on the following values captured from global and objects statistics:

- End-to-end delay,
- Number of hops,
- Throughput.

6.2.1.1 End-to-end delay

End-to-end delay is a measurement of the network delay on a packet and is measured by the time interval between when a message is queued for transmission at the physical layer until the last bit is received at the receiving node.

Figure 8 shows the end-to-end delay result of the three topologies. The Star and Mesh topologies have similar end-to-end delay in this simulation. The end-to-end delay of the Tree topology is higher for more than 50% compared with other two topologies.

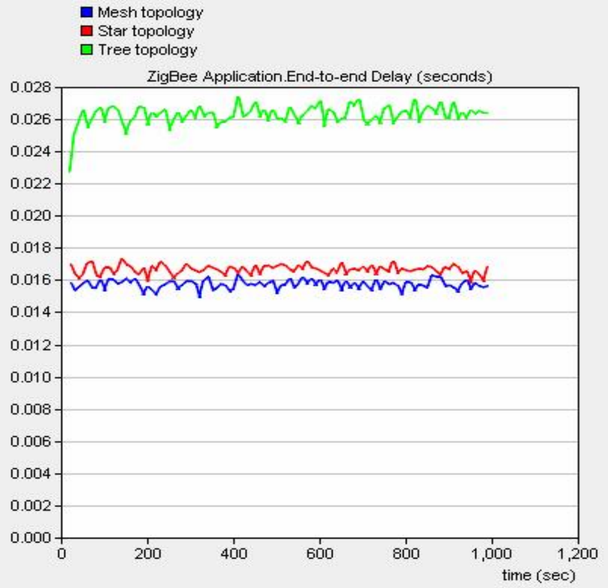

Figure 8. End-to-end delay (Star, Tree and Mesh)

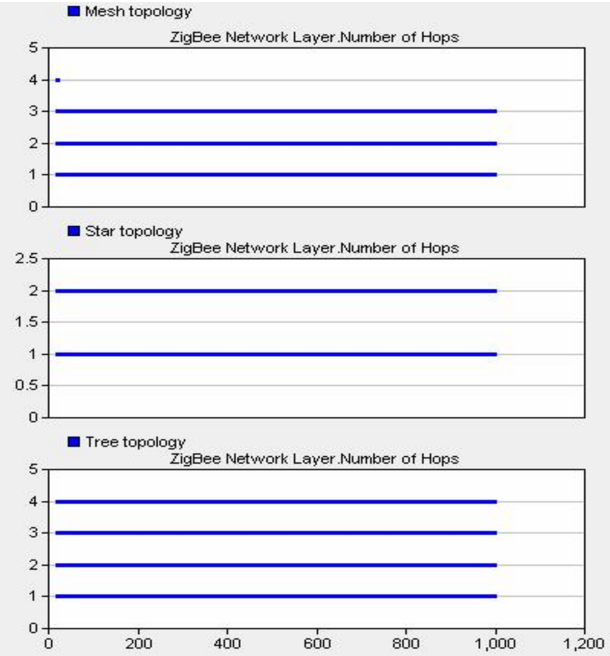

Figure 9. Number of hops

6.2.1.2 Number of hops

The number of hops is the number of times a packet travels from the source through the intermediate nodes to reach the destination. From Figure 9 it can be seen that the number of hops for Star topology is equal to 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 four. Since the maximum depth of the network structure for the simulation is three, it takes a maximum of four hops to deliver the packet to the further node. The Mesh topology uses a routing table and the average number of hops for simulated scenario is two.

6.2.1.3 Throughput

Throughput is the data quantity transmitted correctly starting from the source to the destination within a specified time (seconds). The importance of analyzing this QoS parameter is because the increased numbers of users of the wireless medium is the reason for increased possibility of interference. Throughput is quantified with varied factors including packet collisions, obstructions between nodes and the type of used topology. During the simulation throughput as a global statistics has been measured so any object could contribute to its value. It gives a general idea of the overall throughput of the system. Figure 10 shows that the maximum throughput is achieved in Tree topology, the Star topology has second highest throughput and the Mesh topology has the lowest throughput. The reason for this is because Tree topology is communicating on the basis of the PAN coordinators and ZR which are more efficient as compared to the end devices. Also in Tree topology total load of the network is divided among the local PAN and ZRs as a result of which lesser collisions and lesser packet drops takes place as a result of which the throughput is maximum in case of Tree topology.

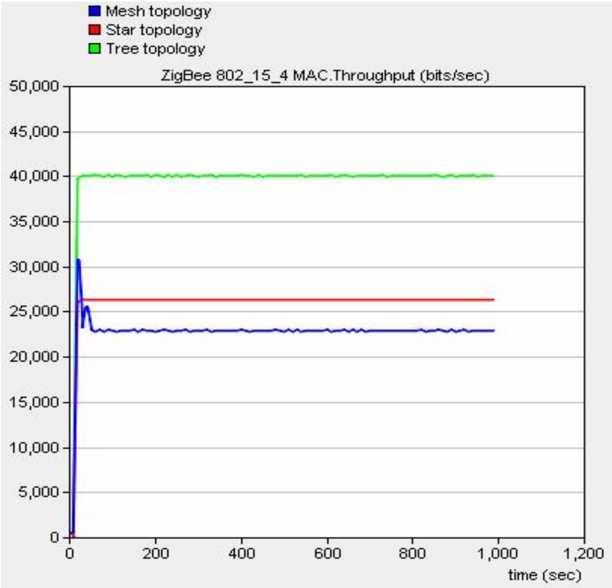

Figure 10. Throughput

6.2.2 Single and Multiple ZC results

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

- End-to-end delay
- Average throughput – ZC

6.2.2.1 End-to-end delay

In our second scenario, we analyzed the network behavior with one ZC and two ZCs. Figure 11 shows the end-to-end delay result of the Tree topology with one ZC versus Tree topology with two ZCs. As we it can be seen, the network with one ZC and two ZCs for PAN_0 have similar end-to-end delay results, while PAN_1 has lowest end-to-end delay. The reason for this is that in PAN_1 there is additional ZC which contributes for reducing the transmission time between the ZEDs and the ZCs (when one of the ZCs is busy, the other ZC take over the packets from other ZEDs, therefore, ZEDs does not have to wait).

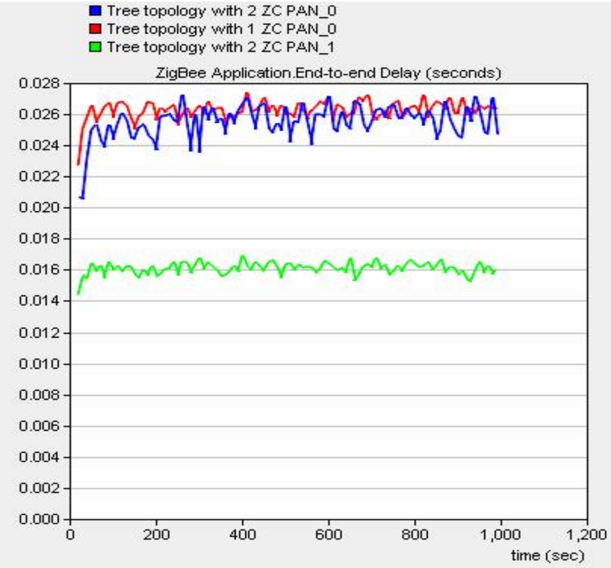

Figure 11. End-to-end delay

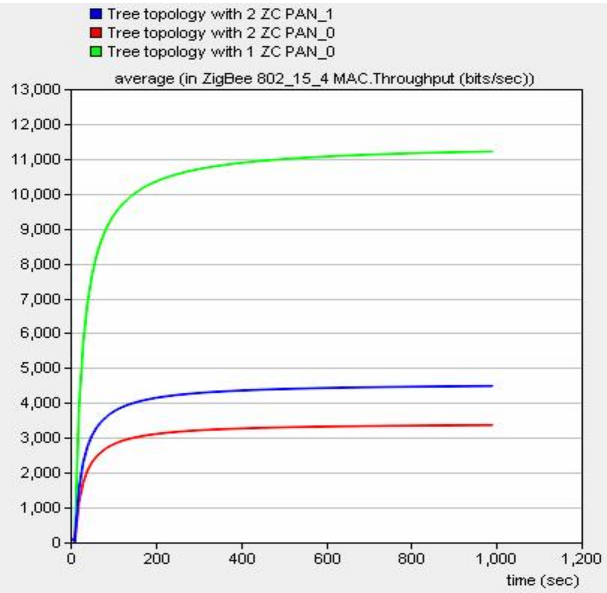

Figure 12. Average throughput – ZC

6.2.2.2 Throughput

In this statistics, the focus is on the ZigBee coordinator (ZC) average throughput. There are three ZCs used during this study. The first ZC belongs to the Tree topology with single PAN_0 and the other two ZCs to the Tree topology with two PANs (PAN_0 and PAN_1). Figure 12 shows the results.

The average throughput in a network with single PAN has highest throughput compared with the average throughput in a network with two PANs. The main reason for this is that in a network with one ZC, ZEDs communicate only with the ZC and they use only one path to reach the destination, thereby avoiding a collision between packets, and the ZC does not accept packets until the pending packets are not completely transmitted. On the other hand, the network with two PANs can use more than one path, so they do not have to wait until the pending packets are transmitted. The average throughput of PAN_0 is higher than the throughput of PAN_1 in a network with two PANs.

7. CONCLUSION

In this paper, we presented an overview of the wireless sensor networks with special emphasis on the some of the QoS performances of the ZigBee protocol. The IEEE 802.15.4/ZigBee protocol stack offers a practical application solution for low cost, low data rate, and low energy consumption characteristics WSNs. This project focuses on simulation an IEEE 802.15.4/ZigBee protocol using OPNET simulator.

To examine topological features of WSNs, we simulate and analyzed two scenarios. In first scenario, we compared the three possible topologies (Star, Mesh and Tree) to each other and considered the statistics for end-to-end delay, number of hops and global throughput.

In the second scenario, we used the Tree topology with a single ZC and compared with a similar network that has an additional ZC and considered the statistics for end-to-end delay and ZC throughput.

The thirteen nodes (one ZC, six ZRs and six ZEDs) in each topology were identical. From the simulation results we can conclude that the end-to-end delay of the Tree topology is higher for more than 50% compared with other two topologies. The throughput is highest in the Tree topology, and lowest in a Mesh topology. The second part of the simulation 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 results show that the end-to-end network delay with a single PAN is higher than the end-to-end delay of PAN_0 or PAN_1 in the network with two PANs.

Our future work will be associated with the study of energy-efficiency and reliability of all these topologies separately, i.e. emphasis will be placed on developing protocols that would continue the battery life, as well as access to the source code of the network and the application layers.

8. REFERENCES

[1] "21 ideas for the 21st century," Business Week, pp. 78–167, Aug. 30, 1999.

[2] Chong, C. and Kumar, P. "Sensor Networks: Evolution, Opportunities, and Challenges", *Proceedings of the IEEE*, vol.91, No.8, August 2003.

[3] Kumar, H., Sarma, D., Kar, A. and Mall, R. "Energy Efficient Communication Protocol for a Mobile Wireless

Sensor Network System" in International Journal of Computer Science and Network Security, Vol.9, No.2, February 2009.

[4] Chong, C. and Kumar, S. P. "Sensor Networks: Evolution, Opportunities, and Challenges," in Proceedings of the IEEE, vol. 91, no. 8, pp. 1247–1256, Aug. 2003.

[5] Mahlknecht, S. "WSSN (Wireless Self-sustaining Sensor Network) Project," 2005, http://www.ict.tuwien.ac.at/wireless/, last accessed on 15 July 2011.

[6] Mahlknecht, S. and Bock, M. "CSMA-MPS: a minimum preamble sampling MAC protocol for low power wireless sensor networks," in Proceedings of the IEEE International Workshop on Factory Communication Systems (IWFC), 22-24 Sept. 2004, Vienna, Austria, 2004, pp. 73–80 .

[7] Akyildiz, I. F., Su, Sankarasubramaniam, W. Y. and Cayirci, E. "Wireless sensor networks: A survey," Computer Networks (Elsevier), vol. 38, pp. 393-422, 2002.

[8] Pottie, G. J. and Kaiser, W. J. "Wireless Integrated Network Sensors," Communications of the ACM, vol. 43, no. 5, pp. 551–558, May 2000.

[9] Al-Karaki, J. N. and Kamal, A. E. "Routing techniques in Wireless Sensor Networks: A survey", Department of Electrical and Computer Engineering Iowa State University, Ames, Iowa 50011

[10] Bluetooth SIG, "Bluetooth Specification v1.1," 2001, http://www.bluetooth.org/spec/, Last accessed on 15 July 2011.

[11] IEEE 802.15 WPAN Task Group 4, "IEEE 802.15.4 Standard 2003," 2003, http://standards.ieee.org/getieee802/download/ 802.15.4-2003.pdf, last accessed on 15 July 2011.

[12] Shih, B., Chen, C., Chih, C. and Tseng, J. "The development of enhancing mechanisms for improving the performance of IEEE 802.15.4", International Journal of the Physical Sciences Vol.5 (6), pp.884-897, June 2010.

[13] Leung, S., Gomez, W. and Kim, J. J. "ZigBee Mesh Network Simulation using OPNET and Study of Routing Selection", spring 2009.

[14] Kinney, P. "ZigBee Technology: Wireless Control that Simply works", *Communication Design Conference*, 2 October 2003.

[15] García-Hernández, C. F., Ibargüengoytia-González, P. H., García-Hernández, J. and Perez Diaz, J. A. "Wireless Sensor Networks and Applications: a Survey", International Journal of Computer Science and Network Security, VOL.7 No.3, March 2007.

[16] Hoblos, G., Staroswiecki, M. and Aitouche, A. "Optimal Design of Fault Tolerant Sensor Networks," in Proceedings of the IEEE International Conference on Control Applications, Sept. 2000, Anchorage, USA, 2000, pp. 467–472.

[17] Bulusu, N., Estrin, D., Girod, L. and Heidemann, J. "Scalable Coordination for Wireless Sensor Networks: Self-Configuring Localization Systems," in Proceedings of the Sixth International Symposium on Communication Theory and Applications (ISCTA), Jul.2001, Ambleside, UK, 2001, pp. 1–6.

[18] Karayannis, G. "Emerging Wireless Standards: Understanding the Role of IEEE 802.15.4 & ZigBee in AMR & Submetering," 2003,

http://www.zigbee.org/imwp/idms/popups/pop_download.asp?contentID=820, last accessed on 15 July 2011.

[19] Shi, E. and Perrig, A. Designing Secure Sensor Networks"; *IEEE Wireless Communications*, pp. 38-43, December 2004.

[20] Perrig, A., Stankovic, J. and Wagner, D. "Security in Wireless Sensor Networks", *Communications of the ACM*, Vol.47, No.5, pp.53-57, June 24.

[21] Pathan, A.K., Lee, H. W. and Hong, C.S. "Security in Wireless Sensor Networks: Issues and Challenges", *ICACT2006*, Feb.20-22, 2006.

[22] Rehana, J. "Security of Wireless Sensor Networks", *Seminar on Internetworking*, April 27, 2009.

[23] Devineni, A. "Performance evaluation of body area network using ZigBee protocol", *Faculty of San Diego State University*, spring, 2011.