A Study of ZigBee Network Topologies for Wireless Sensor Network with One Coordinator and Multiple Coordinators

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Abstract

Wireless Sensor Networks have become a cheap and viable solution for a variety of applications, including monitoring of critical infrastructure (water supplies, power grids, traffic networks, agriculture, telecommunications systems etc.), wildlife habitat monitoring, industrial quality control, disaster recovery situations, military applications and much more. The ZigBee network model is more suitable for battery capacity, bandwidth and computing power's limitations of WSN. In the present investigation, the modeled system was simulated using OPNET Modeler v14 to obtain the results in order to study the performance of the system in terms of tree routing, mesh routing, multiple coordinator system and if one of the coordinators was failed. The results showed that tree routing was more suitable for WSN than the mesh routing and mobility of end device was better in multiple coordinator system.

Keywords: WSN, OPNET, ZigBee, IEEE 802.15.4, MAC, PAN

دراسة توبولوجيات شبكة الزيجبي لشبكات الاستشعار اللاسلكية مع المنسق الواحد ومتعدد المنسق

الخلاصة

لقد أصبحت شبكات الاستشعار اللاسلكية حل رخيص وقابل للتطبيق لمجموعة متنوعة من التطبيقات ، بما في ذلك مراقبة البنية التحتية الحيوية (مجهزات المياه ، وشبكات الكهرباء وشبكات النقل، والزراعة، ونظم الاتصالات ، الخ)، ورصد موائل الحياة البرية والسيطرة على الجودة الصناعية، وحالات التعافي من الكوارث والتطبيقات العسكرية وأكثر من ذلك. نموذج شبكة زيجبي هو أكثر ملاءمة لمحدودية الـ WSN من حيث سعة البطارية وعرض الحزمة والقدرة. وتمت محاكاة النظام باستخدام برنامج الاوبنيتOPNET للحصول على النتائج من أجل دراسة أداء النظام من حيث شجرة التوجيه، شبكة التوجيه ، متعددة نظام المنسق، وفي حالة فشل واحد من المنسقين. وأظهرت النتائج ان التوجيه في حالة الشجرة أكثر ملاءمة لـWSN من التوجيه في حالة الشبكة والحركة من الجهاز كان أفضل في نظام النتعدد المنسق.

الكلمات الدالة: WSN, OPNET, ZigBee, IEEE 802.15.4, MAC, PAN

List of Abbreviations

WSN: Wireless Sensor Network
MAC: Medium Access Control
GTS: Guaranteed Time Slot
CSMA/CA : Carrier Sense Multiple Access with Collision Avoidance
BPSK: Binary Phase Shift Keying
ASK: Amplitude Shift Keying
O-QPSK: Offset Quadrature Phase Shift Keying
PAN: Personal Area Network
PHY: physical Layer
ZC: ZigBee Coordinator
ZR: ZigBee Router

ZED: ZigBee End Device
WiFi: Wireless Fidelity
MHz: Mega Hertz
GHz: Giga Hertz
ISM: The Institute for Supply Management
OSI: Open Systems Interconnection
SAP: Service Access Point
NLDE-SAP: Network Layer Data Entity-Service Access Point
NLME-SAP: Network Layer Management Entity- Service Access Point
ZDO: ZigBee Device Objects
AODV: Ad hoc On Demand Distance Vector
NS-2: Network Simulator – 2
TCP/IP: Transmission Control Protocol/ Internet Protocol
OPNET**:** Optimized Network Engineering Tools
IEEE: Institute of Electrical and Electronics Engineers
WPAN: Wireless Personal Area Network
PAN ID: Personal Area Network Identifier

Introduction

Due to the recent technological advances in wireless communications, processor, low power, highly integrated digital electronics, and micro electro mechanical systems; it have made possible the advent of tiny sensor nodes sometimes referred as "motes". These are mini, low-cost devices with limited coverage having low power, smaller memory sizes and low bandwidth. These nodes are capable of wireless communications, sensing and computation. WSN contain hundreds or thousands of these sensor nodes. These sensors have the ability to communicate either among each other or directly to an external base-station. A greater number of sensors allows for sensing over larger geographical regions with greater accuracy. Sensor nodes are usually scattered in a sensor field, which is an area where the sensor nodes are deployed. Sensor nodes coordinate among themselves to produce high-quality information about the physical environment. Each sensor node bases its decisions on its mission, the information it currently has, and its knowledge of its computing, communication, and energy resources. Each of these scattered sensor nodes has the capability to collect and route data either to other sensors or back to an external base station. A base-station may be a fixed node or a mobile node capable of connecting the sensor network to an existing communications infrastructure or to the Internet where a user can have access to the reported data [1]. These sensor nodes are able to collect and disseminate data in areas where ordinary networks are unsuitable for environmental or strategic reasons. As such, they have a promising future in many applications, such as smart houses, smart farms, smart parking, smart hospitals, habitat monitoring, and monitoring, distributed robotics, industry and manufacturing, national security etc. The sensors' low cost has made WSN more viable and has contributed to their increasing popularity as potential low-cost solutions to a variety of real life challenges[2]**.** The miniaturization of sensor nodes and the advances in Radio Frequency communications have allowed for such a technology to blossom. WSNs are the beginning of a "smart space" revolution, in which tiny devices will interface wireless information technology to our everyday living environments [3]. This paper introduced the WSN model using 802.15.4 ZigBee. ZigBee is a robust wireless communication standard managed by the ZigBee Alliance and based on the IEEE 802.15.4 physical and MAC layer standard. It defines a network layer, application framework as well as security services. ZigBee aims at handling low data rate, low cost devices and long-life batteries making it very suitable to WSN and can be .embedded in a wide range of products and applications [4]. The system was simulated using OPNET Modeler v14 to evaluate the performance of various topologies to show which of them was suitable for WSN and to study the mobility of end device.

Wireless Sensor Networks

A WSN can be defined as a group of independent nodes, communicating wirelessly over limited frequency and bandwidth. Wireless sensor networking remains one of the most exciting and challenging research domains of our time. As technology progresses, so do the capabilities of sensor networks. Limited only by what can be technologically sensed, it is envisaged that WSN will play an important part in our daily lives in the foreseeable future. Privy to many types of sensitive information, both sensed and disseminated, there is a critical need for security in a number of applications related to this technology. The novelty of WSNs in comparison to traditional sensor networks is that they depend on dense deployment and coordination to execute their tasks successfully. This method of distributed sensing allows for closer placement to the phenomena to be achieved, when the exact location of a particular event is unknown, than is possible using a single sensor [5].

WSNs belong to the Low-Rate Wireless Personal Area Network type. Here, the word “personal” means short range communication. Every device in the network is called a sensor node. It includes the processing unit (micro controller), the radio unit (low-power transceiver) and the sensing unit (a board with sensors). Nodes may communicate in ad-hoc way in order to extend the communication range and maintain network scalability. The main WSN limitations are battery capacity, bandwidth and computing power. Hence, packet routing techniques must be applied to provide long-range and large-scale communication in WSNs [6].

Communication Systems

The successful operation of WSN can be largely attributed to the role played by the communications protocol employed. Networking primitives include architecture, data rates, network size, span, power management and security protocols. Standardization has yet to occur for a communication system optimal for WSN. The choices have been considerably narrowed down with the specification of a number of low-power wireless communications protocols; including Bluetooth [7], the IEEE 802.15.4 standard [8] and ZigBee [9], TinyOS is included [5].

WSN Representation

A WSN has a number of exclusive characteristics when compared with conventional wireless networks. These include limited bandwidth, limited computation capability of individual nodes and limited energy supply. Self-organization, dynamic network topology, and multi-hop routing are additional key possible features of a WSN, which make them important for many applications. It is advantageous to perform precise simulations or to develop models before deploying WSNs in the field. Simulations help in the validation and evaluation of the performance of sensor networks within certain application environments, something which was not possible to achieve a number of years ago. Consequently, simulation of sensor networks is therefore gaining greater demand because of their capabilities, lower energy constraints and the use of a larger number of nodes compared to conventional wireless networks. ZigBee (a set of specifications built around the IEEE 802.15.4 wireless protocol) is a common platform for WSNs [10]. ZigBee technology has recently become one of important and significant options for Wireless Sensor Network (WSN) since it possesses many advantages such as low power consumption, low data rate, low cost and short-time delay characteristics. Therefore, ZigBee network applications are rapidly spread out to the many areas: the home automation, industrial control, and commercial fields, for example. However the dynamic structure of ZigBee network is changeable and configurable and lead to the ZigBee network management to be difficult and complex. Furthermore, the system reliability and efficiency of ZigBee network will play the key role and technology to achieve the requirement and stability of system performance [11]. Some published works exists on the evaluation of WSN simulation software [10].

ZigBee and IEEE 802.15.4

The ZigBee Alliance is an association of companies working together to enable reliable, cost-effective, low-power, wirelessly networked, monitoring, and control products based on open standards. It is composed of about 200 member companies including 14 promoters such as Motorola, Freescale, Philips, and Sarnsung. Since their release of the ZigBee Specification version 1.0 on December 2004, a new version was announced on September 2006 including multicast, end device mobility and routing mobility [12].

The IEEE 802.15.4

The IEEE 802.15.4 protocol has recently been adopted as a communication standard for low data rate, low power consumption and low cost Wireless Personal Area Networks. This protocol is quite flexible for a wide range of applications if appropriate tuning of its parameters is carried out. Importantly, the protocol also provides real-time guarantees by using the GTS mechanism. The GTS mechanism is quite attractive for time-sensitive WSN applications, particularly when supported by cluster-tree network topologies [13], such as defined in the ZigBee standard [9].

The IEEE 802.15.4 and the ZigBee network are tightly coupled to provide the consumer standardization for low power and low-rate wireless communication devices. IEEE 802.15.4 MAC uses the CSMA/CA mechanism for accessing the channel, like other wireless networks such as IEEE 802.11 and IEEE 802.15.3. There are two variations: Beacon Enabled Network which uses the Slotted CSMA-CA and Non Beacon Enabled Network which uses the Unslotted CSMA-CA. Moreover, it provides the GTS allocation method in order to provide real time data communication [12].

The IEEE 802.15.4 standard specifies the use of three f modulation types: BPSK, ASK and O-QPSK. For BPSK and O-QPSK the digital data modulates the phase of the signal. For ASK the data modulates the signal amplitude. The same standard specifies the use of Direct Sequence Spread Spectrum or of Parallel Sequence Spread Spectrum. These energy spreading techniques improve the performances of the system in a multipath environment. These specifications make ZigBee a robust and versatile technology [14]. The IEEE 802.15.4 Full Function Devices have three different operation modes [15]:

- PAN Coordinator: the principal controller of the PAN. This device identifies its own network as well as its configurations, to which other devices may be associated. In ZigBee, this device is referred to as ZC.
- The Coordinator: provides synchronization services through the transmission of beacons. This device should be associated to a PAN Coordinator and does not create its own network. In ZigBee, this device is referred to ZR.
- The End Device: a device which does not implement the previous functionalities and should associate with a ZC or ZR before interacting with the network. In ZigBee, this device is referred to as ZED.

The Reduced Function Device is an end device operating with the minimal implementation of the IEEE 802.15.4. It is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor; they do not have the need to send large amounts of data and may only associate with a single Full Function Devices at a time [10].

ZigBee

Based on IEEE 802.15.4 PHY/MAC, the ZigBee network layer provides functionality such as dynamic network formation, addressing, routing, and discovering I hop neighbors. The size of the network address is 16 bits, so ZigBee is capable to accept about 65535 devices in a network, and the network address is assigned in a hierarchical tree structure. ZigBee provides not only star topology, but also mesh topology. Since any device can communicate with other devices except the PAN Coordinator, the network has high scalability and flexibility. Besides, the self-formation and self--healing features makes ZigBee more attractive. The deployed ZigBee devices automatically construct the network, and then changes such as joining/leaving of devices are automatically reflected in the network configuration [12]. The transfer rate has a maximum of 250 kbit/s at 2.4 GHz band frequency. This transfer rate is quite small when compared with the 1 Mbps that Bluetooth can reach or the 54 Mbps that WiFi can reach [14].

The applications where ZigBee can be employed use mainly batteries and some of their main requirements concern small costs and long battery life. In order to maximize battery life in many ZigBee applications transceivers are active only for a short period and for the remaining time they enter a low energy consuming state (sleep). Because of this it is possible for ZigBee wireless nodes to be active for up to several years without maintenance and that is why this technology is preferred in many sensor networks [14].

ZigBee can operate in the following frequency bands:

- 868-868.6 MHz (the 868 MHz frequency band)
- 902-928 MHz (the 915 MHz frequency band)
- 2400-2483.5 MHz (the 2.4 GHz band frequency)

The 868 MHz band frequency is used mainly in Europe for wireless networks with low coverage radius. The 915 MHz and the 2.4 GHz bands are part of the so called industrial, scientific and medical frequency bands (ISM). The 915 MHz band is used mainly in North America while the 2.4 GHz is u sed worldwide [14].

The ZigBee Architecture

ZigBee defines two layers of the OSI model: the Application Layer and the Network Layer. Each layer performs a specific set of services for the layer above. The different layers communicate through SAP's. These SAPs enclose two types of entities: (1) a data entity NLDE-SAP to provide data transmission service and (2) a management entity NLME-SAP providing all the management services between layers. The ZDO is also responsible for communicating information about itself and its provided services.

The ZDO is located in EndPoint 0. The Application Objects are the manufacturer's applications running on top of the ZigBee protocol stack. These objects, located between Endpoints 1 to 240, adhere to a given profile approved by the ZigBee Alliance. The address of the device and the EndPoints available provide a uniform way of addressing individual application objects in the ZigBee network. The set of ZDOs, their configuration and functionalities form a ZigBee profile. The ZigBee profiles intent to be a uniform representation of common application scenarios. Currently, the ZigBee available profiles include the Network Specific (stack identifier 0); Home Controls (stack identifier 1); Building Automation (stack identifier 2) and Plant Control (stack identifier 3) [15].

The ZigBee Network Layer is responsible for Network management procedures (e.g. nodes joining and leaving the network), security and routing. It also encloses the neighbor tables and the storage of related information. The Network Layer provides one set of interfaces, NLDE-SAP used to exchange data with the APS. IEEE 802.15.4/ZigBee devices can be classified according to their functionalities [15]:

Full Function Devices implement the full IEEE 802.15.4/ZigBee protocol stack;

Reduced Function Devices implement a subset of the protocol stack [15].

Regarding the devices role in the network, ZigBee defines 3 types of devices:

- ZigBee Coordinator: The coordinator provides the initialization, maintenance, and control functions for the network [16]. It is one for each ZigBee Network; Initiates and Configure Network formation; Acts as an IEEE 802.15.4 Personal Area Network (PAN) Coordinator; Acts as ZigBee Router (ZR) once the network is formed; Is a Full Functional Device (FFD) – implements the full protocol stack; If the network is operating in beacon-enabled mode, the ZC will send periodic beacon frames that will serve to synchronize the rest of the nodes. In a Cluster-Tree network all ZR will receive beacon from their parents and send their own beacons to synchronize nodes belonging to their clusters [15].
- ZigBee Router: The router has a forwarding capability to route sensed data to a sink node [16]. It participates in multi-hop routing of messages in mesh and Cluster-Tree networks; Associates with ZC or with previously associated ZR in Cluster-Tree topologies; Acts as an IEEE 802.15.4 PAN Coordinator; Is a Full

Functional Device – implements the full protocol stack [15].

- ZigBee End Device**:** The end device lacks such a forwarding capability [16]. It does not allow other devices to associate with it; Does not participate in routing; It is just a sensor/actuator node; Can be a Reduced Function Device – implementing a reduced subset of the protocol stack [15].
- ZigBee/IEEE 802.15.4 enables three network topologies – star, mesh and cluster-tree as in Figure (1) [15].

In the star topology (Figure 1 a), it executes the centralized communication and management, it is radially connected as the star architecture based on one center node. The terminal nodes cannot directly transmit data each other, when needed they are linked together to communication with each other through the center node as medium [11]. The unique node operates as a ZC. The ZC chooses a PAN identifier, which must not be used by any other ZigBee network in the vicinity. The communication paradigm of the star topology is centralized, i.e. each device joining the network and willing to communicate with other devices must send its data to the ZC, which dispatches it to the adequate destination. The star topology may not be adequate for traditional Wireless Sensor Networks for two reasons. First, the sensor node selected as a ZC will get its battery resources rapidly ruined. Second, the coverage of an IEEE 802.15.4/ZigBee cluster is very limited while addressing a large scale WSN, leading to a scalability problem [15].

The mesh topology (Figure 1 b) also includes a ZC that identifies the entire network. However, the communication paradigm in this topology is decentralized, i.e. each node can directly communicate with any other node within its radio range. The mesh topology enables enhanced networking flexibility, but it induces additional complexity for providing end-to-end connectivity between all nodes in the network. Basically, the mesh topology operates in an ad-hoc fashion and allows multiple hops to route data from any node to any other node. In contrast with the star topology, the mesh topology may be more power-efficient and the battery resource usage is fairer, since the communication process does not rely on one particular node. Among the well-known ZigBee topologies, the cluster tree (Figure 1 c) is especially suitable for low-power and low-cost WSNs because it supports power saving operations and light-weight routing. In the ZigBee cluster-tree topology, the power saving operation is managed by the IEEE 802,15.4 MAC superframe structure; and a light-weight tree routing protocol is enabled under a distributed address assignment policy configured by several system parameters. Although the ZigBee cluster-tree network is effective for WSNs, the topology suffers from restricted routing and poor bandwidth utilization. In a tree structure, any link failure will suspend data delivery completely and the recovery operation will incur a considerable overhead. The topology also prevents the use of many potential routing paths, which means that a considerable amount of bandwidth cannot be utilized, In a constructed WSN, the information about some area of interest may require further investigation As a result, the sampling rate of the sensor nodes deployed in the area of interest will be increased, and more traffic will be generated suddenly in the network[16]. The cluster-tree network topology is a special case of a mesh network where there is a single routing path between any pair of nodes and there is a distributed synchronization mechanism (IEEE 802.15.4 beacon-enabled mode). There is only one ZC which identifies the entire network and one ZR per cluster. Any of the full function device can act as a ZR providing synchronization services to other devices and ZRs. Regarding the routing protocols, the tree routing protocol in the cluster-tree is lighter that the mesh routing protocol (AODV) in terms of memory and processing requirements. The routing overhead, as compared with the AODV in the mesh topology, is reduced. Note that the tree routing protocol considers just one path from any source to any destination, thus it does not consider redundant paths, in contrast to AODV. Therefore, the tree routing protocol is prone to the single point of failure problem, while that can be avoided in mesh networks if alternative routing paths are available (more than one ZigBee Router within radio coverage). Note that if there is a fault in a ZigBee Router, network inaccessibility times may be inadmissible for applications with critical timing and reliability requirements[15].

ZigBee Routing

ZigBee Coordinators and Routers must provide the following functionalities[15] :

- Relay data frames on behalf of higher layers;
- Relay data frames on behalf of other ZR;
- Participate in route discovery in order to establish routes for subsequent data frames;
- Participate in route discovery on behalf of end devices;
- Participate in end-to-end route repair;
- Participate in local route repair;
- Employ the ZigBee path cost metric as specified in route discovery and route repair.

Additionally, ZigBee Coordinators and Routers may provide the following functionalities [15]:

- Maintain routing tables in order to remember best available routes;
- Initiate route discovery on behalf of higher layers;
- Initiate route discovery on behalf of other ZR;
- Initiate end-to-end route repair;
- Initiate local route repair on behalf of other ZR.

Routing Schemes

ZigBee Coordinators and Routers support three types of routing [15]:

Neighbour Routing – based on a neighbor tables that contains the information of all the devices within radio coverage. If the target device is physically in range the message can be sent directly. Note that ZEDs cannot do this [10]. Each device in ZigBee maintains a neighbor table which has all the neighbor information in the I-hop transmission range. If users limit the size of the neighbor table, the selected numbers of neighbor entries are stored in the table. The contents for a neighbor entry are the network's PAN identifier, node's extended address, network address, device type and relationship. Optionally, additional information such as beacon order, depth or permit joining can be included [12].

Table Routing - AODV, based on routing and route discovery tables with the path cost metrics[10]; the AODV routing algorithm is on demand algorithm meaning that it builds routes between nodes only as desired by source nodes. It maintains these routes as long as they are needed by the sources. It is capable of unicast and multicast routing [1].

Tree-Routing- based on the address assignment schemes; messages are hierarchically routed upstream/downstream the tree[10]. Tree routing is based on the block address allocation mechanism, called Cskip, so each device has an address spaces to distribute to their children. When a device has no capability of routing table and route discovery table, it simply follows the hierarchical tree by comparing the destination address. The most significant benefit of tree routing is its simplicity and limited use of resources. Therefore, any device with low resources can participate in any ZigBee compliant network [12].

Simulation Model

A simulation of a system is the operation of a model of the system. The model can be reconfigured and experimented with; usually, this is impossible, too expensive or impractical to do in the system it represents. The operation of the model can be studied, and hence, properties concerning the behavior of the actual system or its subsystem can be inferred. In its broadest sense, simulation is a tool to evaluate the performance of a system, existing or proposed, under different configurations of interest and over long periods of real time. Simulation is used before an existing system is altered or a new system built, to reduce the chances of failure to meet specifications, to eliminate unforeseen bottlenecks, to prevent under or over-utilization of resources, and to optimize system performance [17].

WSN Simulators

There are number of simulation methods for WSN such as follows [18]:

NS-2 is a well-established discrete event simulator that provides extensive support for simulating TCP/IP, routing and multicast protocols over wired and wireless networks. Radio propagation model based on two ray ground reflection approximations and a shared media model in the physical layer, an IEEE 802.11 MAC protocol in the link layer and an implementation of dynamic source routing for the network layer were developed in the Monarch project.

J-Sim is another object-oriented, component-based, discrete event, network simulation framework that is written in Java. Modules can be added and deleted in a plug-and-play manner. J-Sim is useful for network simulation and emulation by incorporating one or more real sensor devices. This framework provides support for target, sensor and sink nodes, sensor channels and wireless communication channels, physical media such as seismic channels, power models and energy models.

OPNET Modeler is a commercial platform for simulating communication networks Conceptually, OPNET model comprises processes that are based on finite state machines and these processes communicate as specified in the top-level model. The wireless model uses a 13-stage pipeline to determine connectivity and propagation among nodes. Users can specify frequency, bandwidth, and power among other characteristics including antenna gain patterns and terrain models.

Introduction to OPNET Modeler

OPNET is powerful computational software used to model and simulate data networks [13]. OPNET Modeler provides a comprehensive development environment supporting the modeling of communication networks and distributed systems. Both behaviour and performance of a model can be analyzed by performing discrete event simulations. A Graphical User Interface supports the configuration of the scenarios and the development of network models. Three hierarchical levels for configuration are differentiated [10]:

i) The network level creating the topology of the network under investigation,

ii) The node level defining the behaviour of the node and controlling the flow of data between different functional elements inside the node, and

iii) The process level, describing the underlying protocols, represented by finite state machines (FSMs) and are created with states and transitions between states. The source code is based on C/C++. The analysis of simulated data is supported by a variety of built-in functions.

Different graphical presentations for the simulation results are available and node mobility can be easily implemented in different kinds of nodes i.e. ZigBee coordinator, end device and router nodes [10].

The OPNET simulation environment facilitates the simulation of ZigBee based networks by providing several components of a ZigBee network (ZigBee coordinator, ZigBee router, ZigBee end device, these components can be fixed or mobile). The objects are defined according to the standard. The possibilities offered by OPNET for modeling ZigBee wireless networks were studied from different perspectives [14].

The OPNET ZigBee model uses four process models [10]:

- ZigBee MAC model which implements a model of the IEEE 802.15.4 MAC protocol. The model implements channel scanning, joining and failure/recovery process of the protocol in the un slotted operation mode.
- ZigBee Application model which represents a low fidelity version of the ZigBee Application Layer as specified in the ZigBee Specification. The process model initiates network joins and formations, generates and receives traffic and generates different simulation reports.
- ZigBee (CSMA/CA) model which implements the media access protocol of the MAC layer.

ZigBee Network model which implements the ZigBee Network Layer as specified in the ZigBee specification. This model is responsible for routing traffic, process network join, formation requests and generating beacons. Using these components the user can build a network that represents a close enough model of a real network and can analyze this network and configure component attributes. After these initial steps are performed (define the network topology, set the attributes, and choose the statistic that should be collected) the simulation can be run. After the simulation process is completed, the user can analyze the statistic collected. These statistics can be defined at a global or network level or at a local or node level [14].

Simulation of design

In this system, mesh routing and tree routing with number of routers and end devices would be taken and number of end devices and routers with one PAN coordinator and multiple PAN coordinators would be taken. This study included when one of the coordinators was failed in order to study the performance of system with the specified routing. The simulation design was consist of a number of scenarios for each case to study the performance of system. Each scenario had number of end devices named (End Device) and number of routers named (Router) and one or two or three coordinators named (coordinator) as follows:

Scenario 1 (Tree Routing)

The model had number of end devices and number of routers connected to one coordinator in tree routing as shown in Figure (2).

Scenario 2 (Mesh routing)

The model had number of end devices and number of routers connected to one coordinator in mesh routing as shown in Figure (3).

Scenario 3 (Coordinator Failure)

The model had number of end devices and number of routers connected to two coordinators and one of them was failed as shown in Fig.4.

Scenario 4 (a mobile ZigBee node passing through the radius of multiple PANs.:

The model had number of end devices and number of routers connected to multiple coordinators with a mobile node. In this scenario, the trajectory was from the mobile node as shown in Figure (5).

Scenario 5 (the trajectory was from end device node)

The same as scenario 4 but in this scenario, the trajectory was from end device node as shown in Figure (6).

After modeling the system, individual statistics could be chosen about many parameters in order to collect the results to study the performance of system, in the designed model, the statistics were collected about throughput, delay, end to end delay and load per PAN.

Results

The simulation was then run to collect the results as follows:

Throughput: Represents the total number of bits (in bits/sec) forwarded from 802.15.4 MAC to higher layers in all WPAN nodes of the network. The throughput (for the mesh routing, tree routing) was shown in the same graph in Figure (7).

Delay: Represents the end to end delay of all the packets received by the 802.15.4 MACs of all WPAN nodes in the network and forwarded to the higher layer. The delay (for the tree routing, mesh routing) was shown in Figure (8).

Data Traffic Received (bits/sec): Represents the total traffic successfully received by the MAC from the physical layer in bits/sec. This includes retransmissions. Data traffic was taken for all scenarios on the same graph for comparison as shown in Figure (9).

Global Application Traffic Received for each PAN: The traffic received for each PAN coordinator was studied on the same graph if one of the coordinators was failed as shown in Figure (10).

Global Application Traffic Received for each PAN: The traffic received for each PAN coordinator for the multiple coordinator ZigBee model was taken on the same graph for comparison as shown in Figure (11). Some results from scenario 4 and scenario 5 were obtained to study the behavior of mobile node in the multiple PAN coordinators. The following results showed the comparison when the trajectory was from the end device and when the trajectory was from mobile node as follows:

PAN Affiliation: Time that the node joins a ZigBee network as shown in Figure (12).

Throughput (bit/sec): Total data traffic in bits/sec successfully received and forwarded to the higher layer by 802.15.4 MAC. The throughput of the end device node when the trajectory was from this end device and throughput of the mobile node when the trajectory from the mobile node as shown in Figure (13).

End to End delay (sec): Total delay between creation and reception of application packets generated by this node as shown in Figure (14).

Load (in bits/sec) submitted to the 802.15.4 MAC by its higher layers in this node as shown in Figure (15).

Discussion and Conclusions

Scenarios 1 and 2: The two scenarios contain identical networks. The same network tree structure forms in each case. The majority of the nodes have been configured with random traffic; however Router 1 has been explicitly configured to send traffic to Router 3. The throughput and data traffic received for scenario 1 (Tree Routing) were larger than scenario 2 (Mesh Routing) due to the mesh routing process finding more efficient routes than tree based routing for some of the traffic. For some nodes, the tree based route will be the most efficient route, resulting in only a minor overall improvement in end to end Delay.

- In scenario 3, the network contains two coordinators and 24 routers and end devices. Each router and end device in the scenario has its PAN ID set to Auto-Assigned. The coordinator has their PAN ID's set to 1 and 2 respectively. The first coordinator failed into the simulation after two minutes. It will remain failed until four minutes, when it will recover and re-establish a network. At eight minutes, the second coordinator would fail. It will remain failed until ten minutes. When the first coordinator failed, the nodes joined to that PAN should leave and join the second coordinator. When the second coordinator failed, all the nodes should join the first coordinator. The throughput is decreased due to the coordinator failure.
- The results of scenario 3 (coordinator failure) showed that both PANs have more and less equivalent traffics (PAN 1's is greater due to a few more nodes joining that network). After 2 minutes, PAN 1's data traffic drops while PAN 2's traffic increases. Even after the first coordinator recovers at 4 minutes. When the second coordinator failed at eight minutes, PAN 1's traffic increased while PAN 2's traffic dropped.
- The results of scenario 4 (multiple coordinators) showed that the traffic of PAN 1 increased for the first four minutes, the mobile node unjoined PAN 1 and joined PAN2 when the traffic increases on PAN 2 until 12 minutes at which the mobile node unjoined PAN 2 and joined PAN 3 and the traffic increased at 20 minutes.
- In scenario 4, the trajectory of mobile node (1) is configured to take the node through the coverage area of each of the three PANs over the course of 20 minutes. Based on this trajectory, it is expected that mobile node (1) will initially join PAN 1, and then switch to PAN 2, and finally to PAN 3, which it should remain joined to. The traffic on each node except mobile node (1) is configured as random destination. When they join the network, they will choose a random node within their own PAN and send traffic to that node for the rest of the simulation. Mobile node

(1) is configured to send traffic to its parent node. The results showed:

PAN Affiliation: (Time that the node joins a ZigBee network) for mobile node (1): when the trajectory was from the mobile node, mobile node (1) joined to PAN 1 for the first 4 minutes of the simulation. The node then briefly unjoins from the PAN (PAN ID -1), then promptly joins PAN 2. At 12 minutes, the node unjoins from PAN 2 and promptly joins PAN 3. When the trajectory was from the end device, the end device joined to PAN 1 for the first 4 minutes, then unjoins from PAN 1 an d didn't join any PAN.

Throughput: the throughput when the trajectory was from the end device was slightly larger than when the trajectory was from the mobile node.

Delay: the delay when the trajectory was from the mobile node was less than when the trajectory was from the end device.

MAC Load: the load was higher initially. When the trajectory was from the mobile node and mobile node switches to PAN 2, the load remained high. When the trajectory was from the end device, the load drops after the first 4 minutes.

- From all these results, it can be concluded that the tree routing was more suited for WSN than mesh routing due to more throughput.
- The mobility of end device in the multiple coordinator ZigBee model shows that the behavior of network was better when the trajectory was from mobile node than when the trajectory was from the end device.

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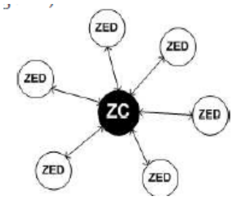
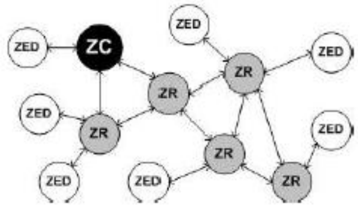
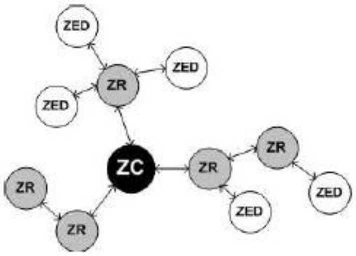


(a) Star topology



(b) Mesh topology



(c) Cluster – tree topology
Figure(1) ZigBee network topologies

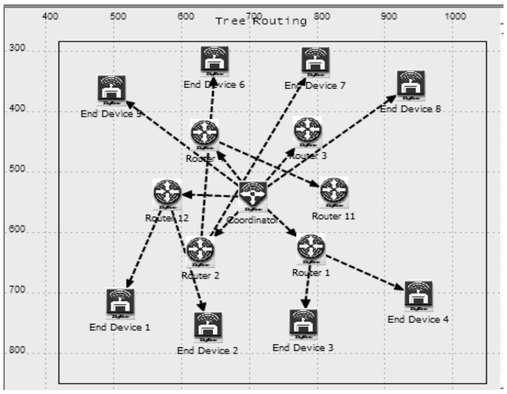


Figure (2) Tree Routing

Figure (3) Mesh Routing

Figure (4) Coordinator Failure

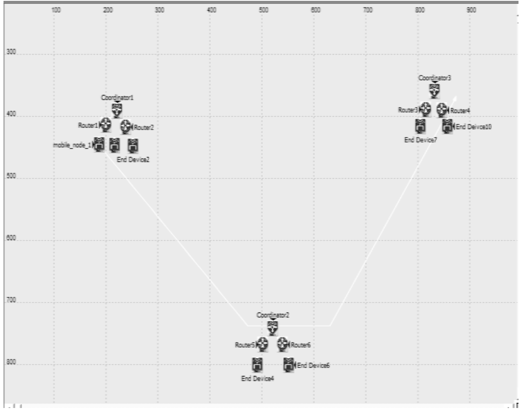


Figure (5) a mobile ZigBee node passing through the radius of multiple PANs

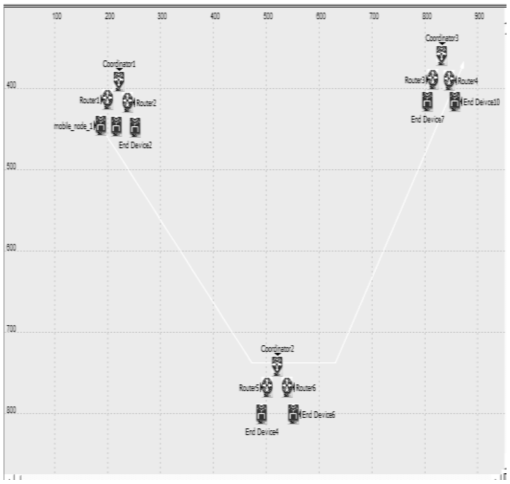


Figure (6) Multiple Coordinators with the trajectory was from end device node

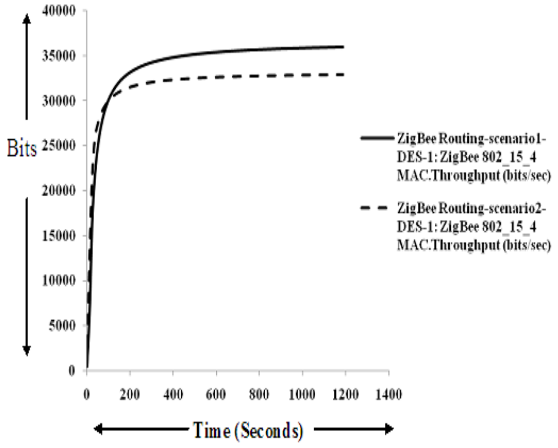


Figure (7) ZigBee 802_15_4 MAC Throughput (bits/sec)

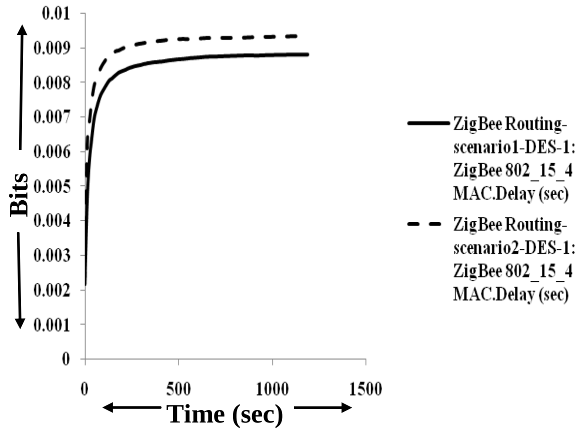


Figure (8) ZigBee 802.15.4 MAC Delay(sec)

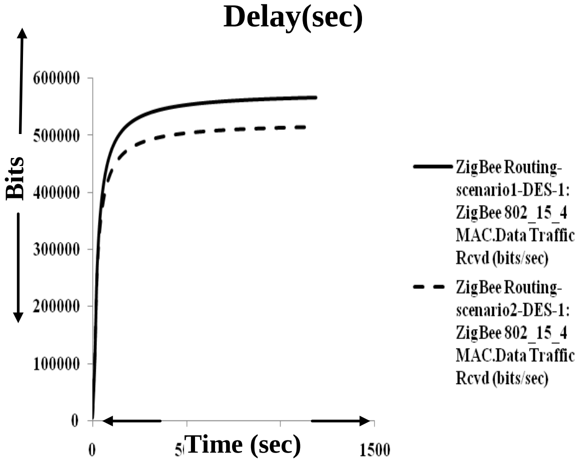


Figure (9) ZigBee 802_15_4 MAC Data Traffic Rcvd (bits/sec)

Scenario1 (Tree Routing)
Scenario2 (Mesh Routing)

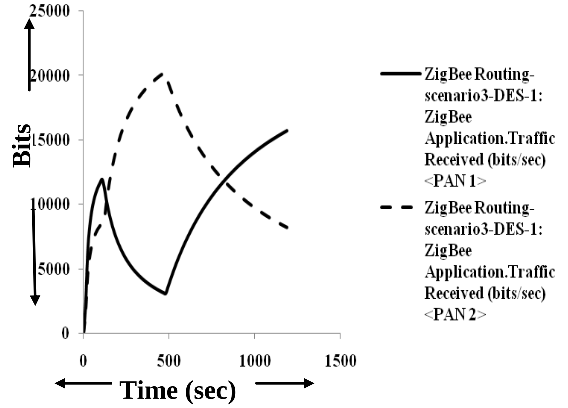


Figure (10) ZigBee Application Traffic Received (bits/sec) for coordinator failure

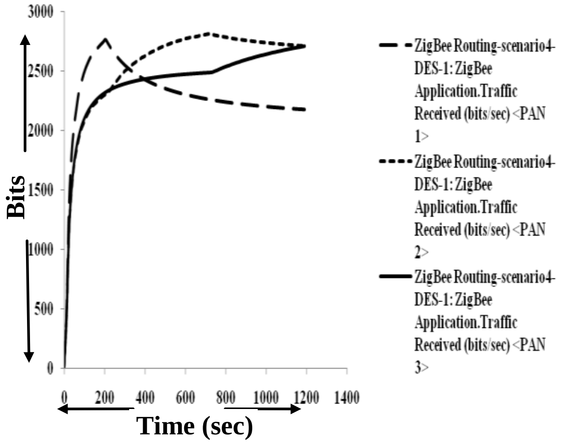


Figure (11) ZigBee Application Traffic Received (bits/sec) for multiple coordinators

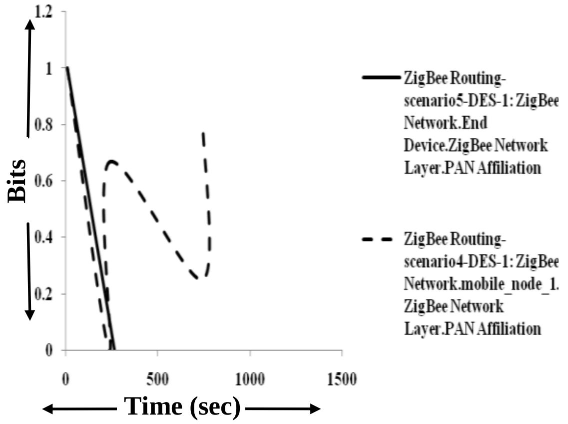


Figure (12) ZigBee Network Layer PAN Affiliation

Scenario 5 (the trajectory was from end device node)
Scenario 4 (mobile ZigBee node passing through the radius of multiple PANs)

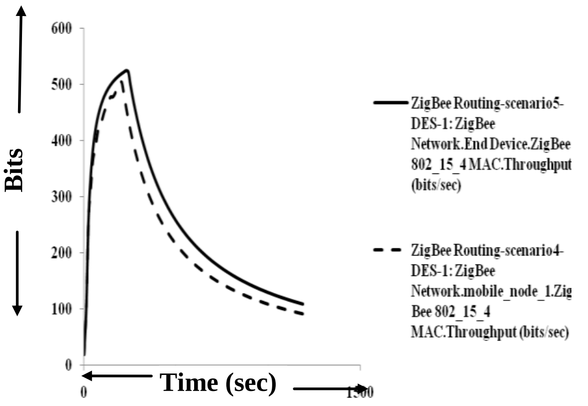


Figure (13) ZigBee 802.15.4 MAC Throughput (bits/sec) for multiple coordinators

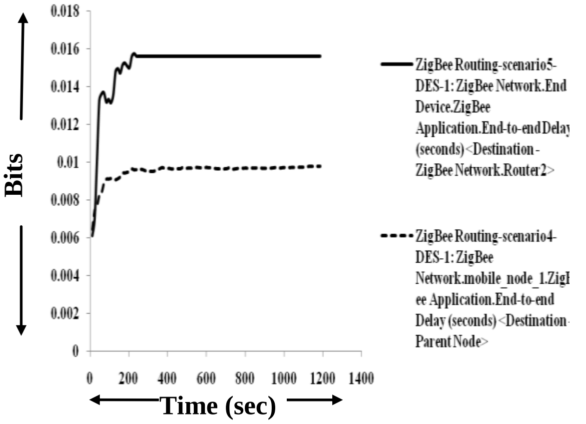


Figure (14) ZigBee Application End to end Delay (sec) for multiple coordinators

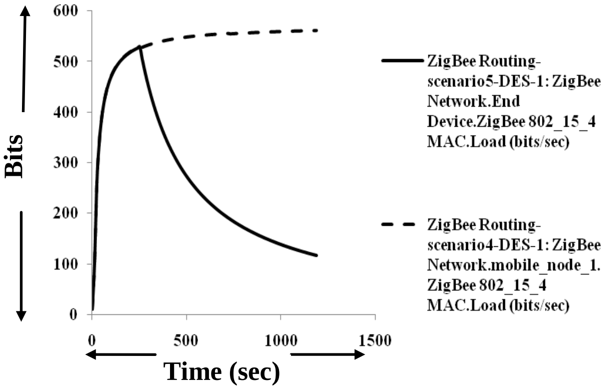


Figure (15) ZigBee 802.15.4 MAC Load (bits/sec) for multiple coordinators

Scenario 5 (the trajectory was from end device node), Scenario 4 (a mobile ZigBee node passing through the radius of multiple PANs.)