Chapter 5

IEEE 802.15.4 Structure

This chapter provides an overview of the most relevant aspects of the WSN IEEE 802.15.4 protocols. WSN includes various types of the topological structure with the different parameters. In this chapter, OPNET simulator is used to evaluate the performance of two topological structures of WSN.

The Institute of Electrical and Electronics Engineers (IEEE) finalized the IEEE 802.15.4 standard in October 2003 ([1] - [4]). The standard covers the physical layer and the Medium Access Control (MAC) sub-layer of a low-rate Wireless Personal Area Network (WPAN). Even though this standard was not specifically developed for wireless sensor networks, it is intended to be suitable for them since sensor networks can be built up from LRWPANs. Sometimes, people confuse IEEE 802.15.4 with ZigBee [5], an emerging standard from the ZigBee alliance. ZigBee uses the services offered by IEEE 802.15.4 and adds network construction (star networks, peer-to-peer/ mesh networks, and cluster-tree networks), security, application services, and more. In fact, the IEEE 802.15.4 protocol targets low data rate, low power consumption, low cost wireless networking, with typically fits the requirements of sensor networks. The ZigBee/IEEE 802.15.4 protocol architecture is presented in Figure 5.1.

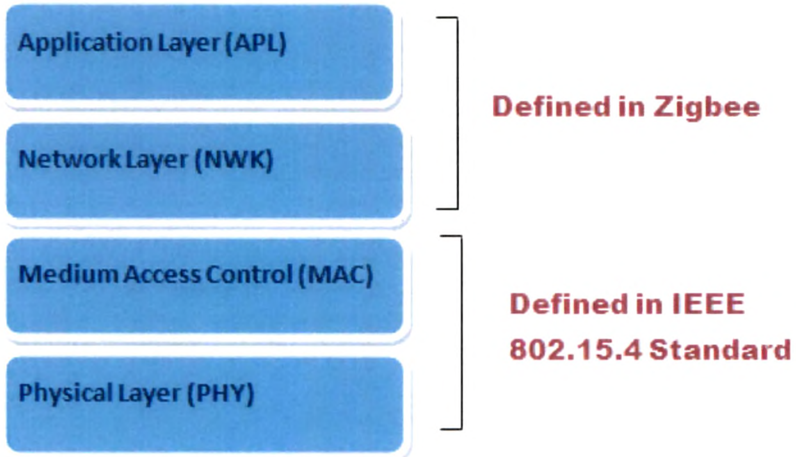


Figure 5.1: IEEE820.15.4/ZigBee protocol stack architecture

5.1 Network Devices

According to the IEEE 802.15.4 standard [6], a LR-WPAN distinguishes (on the MAC layer) two different types of devices: i) Full Function Device (FFD) and ii) Reduced Function Device (RFD).

i. **FFD**: It supports three different roles, attending as:

- **The Personal Area Network (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. This device is referred to as the Coordinator (C).
- **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. This device is referred to as the Router (R).
- **The End Device**: a device which does not implement the coordinator functionalities and should associate with a C or R before interacting with the network. This device is referred to as the End Device (ED).

ii. **RFD:** It can operate only as a device, operating with minimal implementation of the IEEE 802.15.4 protocol.

5.2 Network Topologies

The star and peer-to-peer topologies as shown in Figure 5.2 are two basic network topologies defined in the IEEE 802.15.4 standard [7].

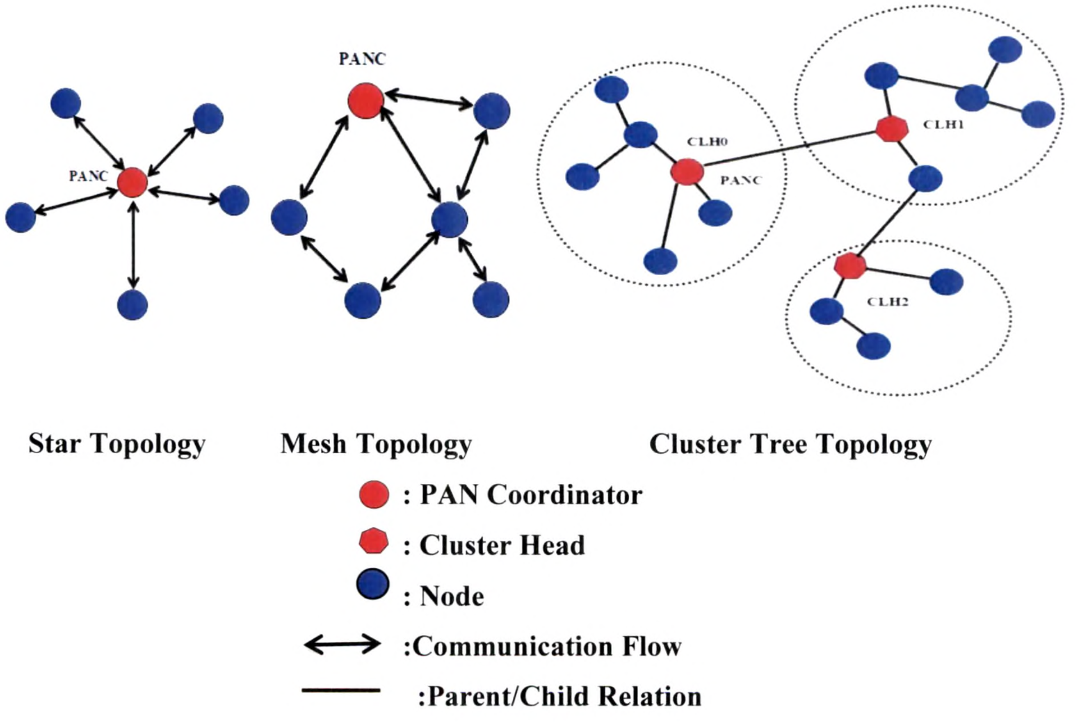


Figure 5.2: IEEE 802.15.4 Network Topologies

In the star topology, the communication is centralized and established between a PAN Coordinator and its associated devices. The main advantage of this topology is its simplicity. The peer-to-peer topology has also a PAN Coordinator; however, it differs from the star topology in that any device can communicate with any other device within its radio range. The cluster-tree topology is a special case of a peer-to-peer topology with a distributed synchronization mechanism. IEEE 802.15.4 standard in the beacon-enabled mode supports only the star topology.

5.3 IEEE 802.15.4 Physical Layer (PHY)

The PHY layer is responsible for the data service and the management of the data service using a certain radio channel according to a specific modulation and spreading techniques. The management part is the interface to the higher layers, and the data service part enables the transmission and reception of PHY protocol data units (PPDU) over the radio channel.

The IEEE 802.15.4 offers three operational (unlicensed) frequency bands: 2.4 GHz (worldwide, 16 channels), 915 MHz (North America and some Asian countries, 10 channels) and 866 MHz (Europe, 1 channel). The protocol also allows dynamic channel selection, a channel scan function in search of a beacon, receiver energy detection, link quality indication and channel switching. The data rate is 250 kbps at 2.4 GHz, 40 kbps at 915 MHz and 20 kbps at 868 MHz. In addition to these three frequency band patterns, two high data rate patterns have been added to the 868/915 MHz bands in the last revision of the standard IEEE 802.15.4REVb-2006. The higher data rates are achieved by using of the different modulation formats. This revision of the standard is backward-compatible to the IEEE 802.15.4-2003, meaning that devices conforming to IEEE 802.15.4REVb-2006 are capable of joining and functioning in a PAN composed of devices conforming to IEEE 802.15.4-2003. All of these frequency bands are based on the Direct Sequence Spread Spectrum (DSSS) spreading technique.

This thesis only considers the 2.4 GHz band with 250 kbps data rate, which is supported by the MICAz motes [8] used in the experimental test-beds.

5.4 IEEE 802.15.4 Medium Access Control (MAC)

The MAC sub-layer of the IEEE 802.15.4 protocol provides an interface between the physical layer and the higher layer protocols of LR-WPANs.

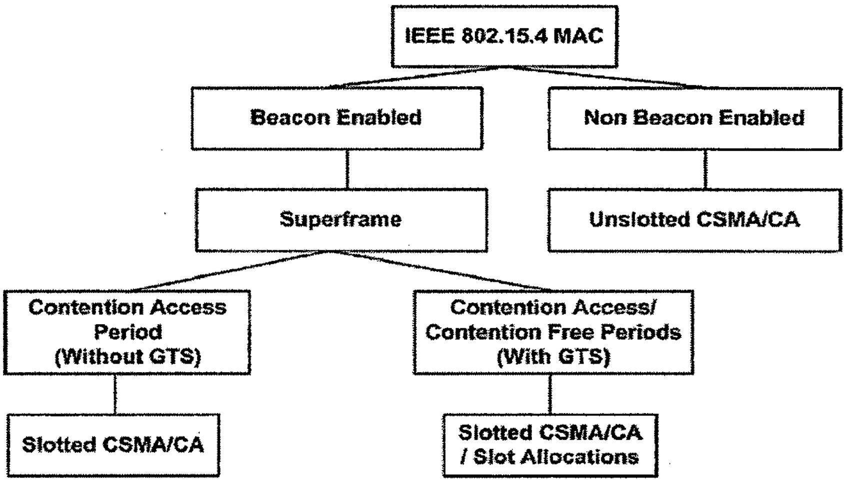


Figure 5.3: IEEE 802.15.4 Operational Modes

The MAC sub-layer of the IEEE 802.15.4 protocol has many common features with the MAC sub-layer of the IEEE 802.11 protocol, such as the use of CSMA/CA (*Carrier Sense Multiple Access / Contention Avoidance*) as a channel access protocol, the support of contention-free and contention-based periods. However, the specification of the IEEE 802.15.4 MAC sub-layer is adapted to the requirements of LR-WPAN as, for instance, eliminating the RTS/CTS mechanism (used in IEEE 802.11) to reduce the probability of collisions, since collisions are more likely to occur in low rate networks.

Figure 5.3 presents a structure of the IEEE 802.15.4 operational modes.

5.5 IEEE 802.15.4 Operational Modes

Following are two Operational modes in IEEE 802.15.4.

- **Non Beacon-enabled mode**: In non beacon-enabled mode (Figure 5.4(a)), the devices can simply send their data by using unslotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). There is no use of a superframe structure in this mode. The advantages of this mode are a scalability and self-organization. However, the non beacon-enabled mode cannot provide any time guarantees to deliver data frames. In fact, the "collision avoidance" mechanism is based on a random delay prior to transmission, which only reduces the probability of collisions. Thus, this mode cannot ensure collision-free and predictable access to the shared wireless medium and, consequently, it cannot provide any time and resource guarantees.

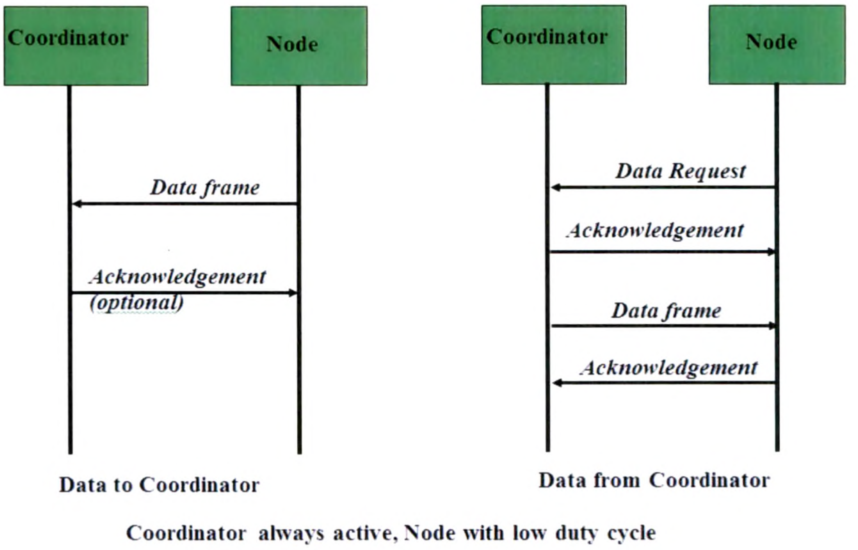


Figure 5.4 (a): Non Beacon mode

ℵ **Beacon-enabled mode**: In beacon-enabled mode (Figure 5.4(b)), the beacon frames are periodically generated by the PAN Coordinator to identify its PAN, to synchronize nodes (i.e. coordinators or/and end devices) that are associated to it and to describe the structure of the superframe (Figure 5.5). It provides the energy conservation using low duty cycles, and the provision of collision-free and predictable access to the wireless medium through the Guaranteed Time Slot (GTS) mechanism. Thus, when the timeliness and energy efficiency are the main concerns, the beacon enabled mode should be employed. [9]

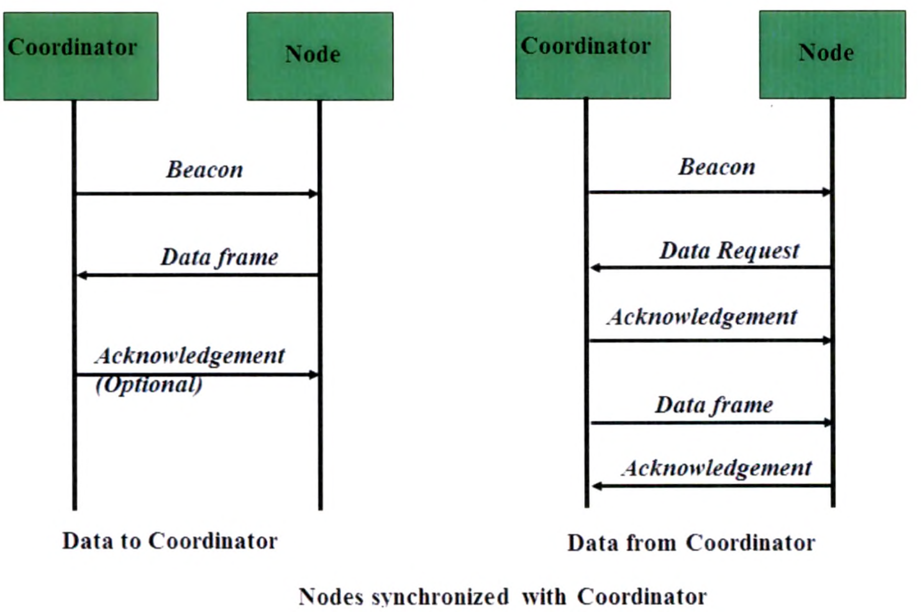


Figure 5.4 (b): Beacon mode

When the coordinator selects the beacon-enabled mode, it forces the use of a superframe structure to manage communication between devices (that are associated to that PAN). The format of the superframe is defined by the PAN coordinator and transmitted to other devices inside every beacon frame, which is broadcasted periodically by the PAN coordinator. The superframe is divided into 16 equally sized slots and is followed by a predefined inactive period. The superframe structure is discussed in section 5.6.

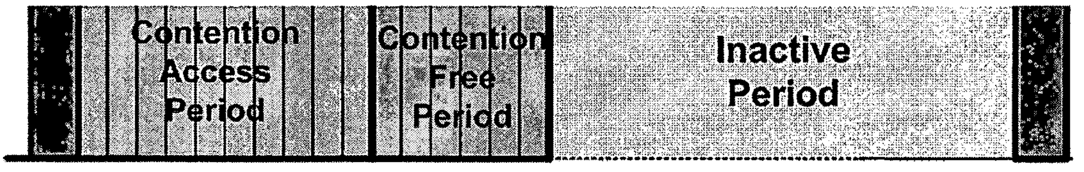


Figure 5.5: the Superframe Structure

As shown in Figure 5.5, the superframe is contained in a Beacon Interval, which is bounded by two consecutive beacon frames, and includes one *Contention- Access Period* (CAP) and may include also a *Contention-Free Period* (CFP), as outlined next:

- If communications are restricted to the CAP (defined in the beacon, issued by the PAN Coordinator) a device wishing to communicate must compete with other devices using a slotted CSMA/CA mechanism. All transmissions must be finished before the end of the superframe, i.e., before the beginning of the inactive period (if exists).

- If some guaranteed QoS is to be supported, then a *Contention-Free Period* (CFP) is defined. The CFP consists in *Guaranteed Time Slots* (GTSs) that may be allocated by the PAN coordinator to applications requiring low-latency or specific data bandwidth requirements. The CFP is a part of the superframe and starts at a slot boundary immediately following the CAP. The PAN coordinator may allocate up to seven GTSs and each GTS may occupy more than one time slot. With this superframe configuration, all contention-based communication must be finished before the start of the CFP, and a node transmitting a GTS must ensure that its transmission will be complete before the start of the next GTS (or the end of the CFP). According to the standard, the GTS is used only for communications between a PAN coordinator and a device. The GTS management are discussed in Section 6.7 in Chapter 6.

In both configurations (CAP only or CAP/CFP), the superframe structure can have an *inactive period* during which the PAN coordinator does not interact with its PAN and may enter in a low power mode. Switching the network between activity/inactivity periods is very suitable for devices where reduced energy consumption is a main concern. In fact, the inactive periods enable the devices to save energy and thus extend network lifetime.

5.6 The Superframe Structure

The superframe is contained in a Beacon Interval bounded by two beacon frames, and has an active period and an inactive period (see Figure 5.6).

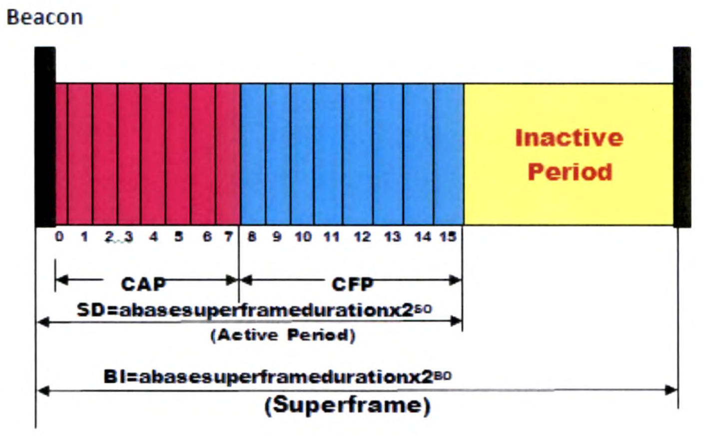


Figure 5.6: Example of the structure of a Superframe

The coordinator interacts with its PAN during the active period, and enters in a low power mode (sleep) during the inactive period. The structure of a superframe is defined by two parameters [7]:

- *macBeaconOrder* (BO): this attribute describes the interval at which the coordinator must transmit beacon frames. The value of the *macBeaconOrder* and the *Beacon Interval* (BI) are related as follows:

  For $0 \leq BO \leq 14$,

  $$BI = aBaseSuperframeDuration * 2^{BO} \text{ symbols}$$

- *macSuperframeOrder* (SO): this attributes describes the length of the active portion of the superframe, which includes the beacon frame. The value of the *macSuperframeOrder* and the *Superframe Duration* (SD) are related as follows:

  For $0 \leq SO \leq BO \leq 14$

  $$SD = aBaseSuperframeDuration * 2^{SO} \text{ symbols}$$

If $SO = BO \Rightarrow SD = BI$ and then the superframe is always active. According to the standard, if SO =15 , the superframe will not be active following the beacon. Moreover, if BO =15, then the superframe shall not exist and the network will operate in the non beacon-enabled mode. In this case, the value of SO is ignored. As a result, a PAN that wishes to use the superframe structure must set *macBeaconOrder* to a value between 0 and 14 and *macSuperframeOrder* to a value between 0 and the value of *macBeaconOrder*. Otherwise, the PAN will operate in a non beacon-enabled mode with a value of *macBeaconOrder* and *macSuperframeOrder* equal to 15. The active portion of each superframe is divided into *aNumSupeframeSlots*=16 equally spaced slots of duration 2^{SO} *$*$aBaseSlotDuration*. The attribute *aBaseSlotDuration* represents the number of symbols forming a superframe slot when the superframe order is equal to zero. The value of *aBaseSlotDuration* is equal to 60 symbols.

The active portion of the superframe structure is composed of three parts:

- ***Beacon***: the beacon is transmitted without the use of CSMA at the start of slot 0. It contains the information on the addressing fields, the superframe specification, the GTS fields, the pending address fields, etc.
- ***CAP***: the CAP starts immediately after the beacon frame and ends before the beginning of the CFP (if it exists). Otherwise, the CAP ends at the end of the active part of the superframe. The minimum length of the CAP is fixed at *aMinCAPLength* = 440 *Symbols* . This minimum length ensures that MAC commands can still be transferred to devices when GTSs are being used. A temporary violation of this minimum may be allowed if additional space is needed to temporarily accommodate the increase in the beacon frame length needed to perform GTS management. All the transmissions during the CAP are made using a slotted CSMA/CA mechanism to access the channel. However, the acknowledgement frames and any data that immediately follows the acknowledgement of a data request command are transmitted without contention. A device that cannot complete its transmission one *Inter Frame Spacing* period before the end of the CAP, must defer its transmission until the CAP of the next superframe.
- ***CFP***: The CFP starts immediately after the end of the CAP and must complete before the start of the next beacon frame. All the GTSs that may be allocated by the PAN coordinator are located in the CFP and must occupy contiguous slots.

The CFP may therefore grow or shrink depending on the total length of all GTSs. The transmissions in the CFP are contention-free and therefore do not use a CSMA/CA mechanism to access the channel. Additionally, a frame may only be transmitted if the transmission ends one IFS before the end of the correspondent GTS.

The IFS period defines the amount of time that separates the transmission of two consecutive frames. In fact, the MAC sub-layer needs a finite amount of time to process data received by the physical layer. In an acknowledged transmission the IFS follows the acknowledgement frame, otherwise the IFS follows the frame itself. The length of an IFS frame depends on the frame size. The transmission of short frames, whose sizes are lower than $aMaxSIFSFrameSize = 18\ Bytes$, is followed by a *SIFS* period of a duration of at least $aMinSIFSPeriod = 12\ symbols$. On the other hand, the transmissions of long frame, whose lengths are greater than *aMaxSIFSFrameSize* is followed by a LIFS of duration of at least $aMinLIFSPeriod = 40\ symbols$.

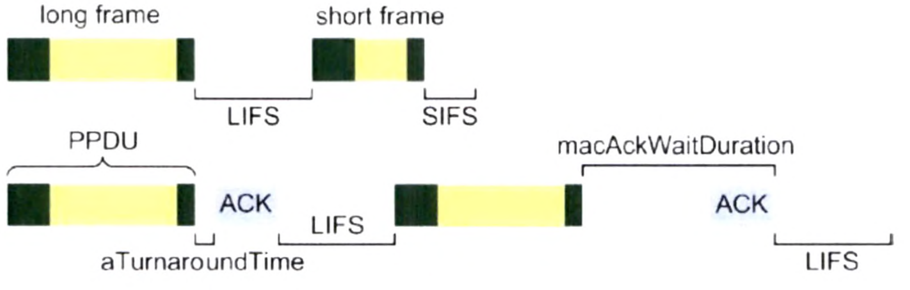


Figure 5.7: The Inter Framing Spacing

Figure 5.7 illustrates these concepts. The CSMA/CA must take this requirement into account for transmissions in the CAP.

5.7 Simulation Setup & Results[1]

In this section, an accurate simulation model is provided with respect to the specifications of IEEE 802.15.4 standard in non-beacon mode as discussed in previous section. Two different scenarios viz. tree and mesh are simulated and analysed, where the topological features and performance of the IEEE 802.15.4 standard using OPNET simulator are examined. The comparative results have been reported for the performance metrics viz. Number of hopes, End to End Delay, and Load of network [10].

[1] **Published a paper: Ms. Sonal J. Rane, Prof. Satish K. Shah, Ms. Dharmistha D Vishwakarma, "Analytical Approach for Performance of Wireless Sensor Networks",** ***International Journal of Electronics and Computer Science Engineering,*** **1877,** ***Available Online at www.ijecse.org*** **ISSN- 2277-1956.**

- **Number of hopes:** The number of hops is the number of times a packet travels from the source through the intermediate nodes to reach the destination.
- **End to End Delay (ETE):** This statistics represents the total delay (in seconds) occurs for the transmitted packet from source to the destination.
- **Throughput:** Throughput (bits/sec) is the average number of bits or packets successfully received or transmitted by the receiver or transmitter channel per second.
- **Load per PAN**: This statistics represents the total load (in bits/sec) for a particular PAN submitted to 802.15.4 MAC by all higher layers in all WPAN nodes of the network.
- **PAN Affiliation for Coordinator**: This represents time that the node joins a network.

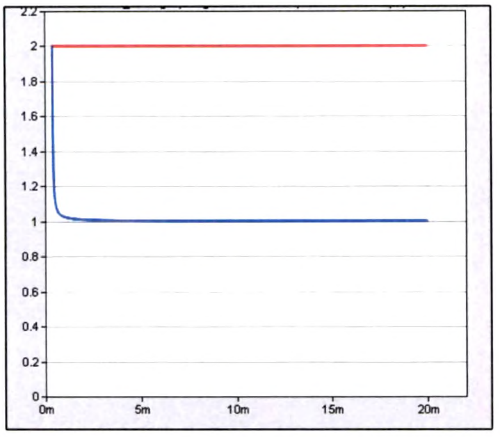
ℵ SCENARIO - 1

Tree Routing and Mesh Routing networks are designed and both are identical networks only difference is to configure PAN of Tree Routing with Default tree Network and PAN in Mesh Routing with Default Mesh Network. 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 PAN in the Tree Routing scenario has been configured as a Default Tree Network. Application traffic will be routed to the destination along the parent-child links of the network tree. The PAN in the Mesh Routing scenario has been configured as a Default Mesh Network. After mesh routes have been established (a few seconds after network formation), application traffic will be routed through the shortest possible route using any of the router or coordinator presents in the network. End devices do not participate in mesh routing, therefore they must still route traffic through their parent node.

Figure 5.8 shows that the number of hops taken by Router 1 to reaches its destination. This statistic for Tree Routing is of red line and for Mesh Routing is of blue line. Note that both lines begin at two hops, but the Mesh Routing line quickly changes to one hop for the remainder of the simulation.

In Figure 5.9, the red line indicates ETE Delay for the Tree Routing scenario while the blue line indicates ETE Delay for Mesh Routing. The ETE Delay for Mesh Routing is lower 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 ETE Delay.



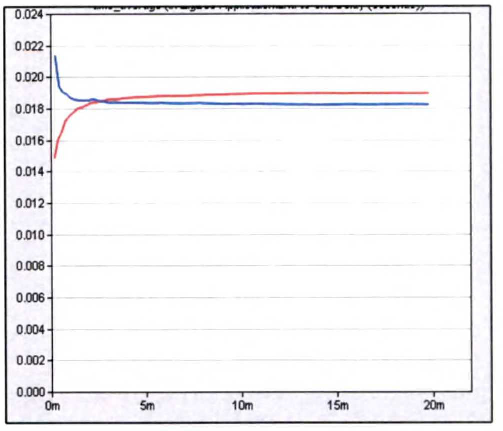
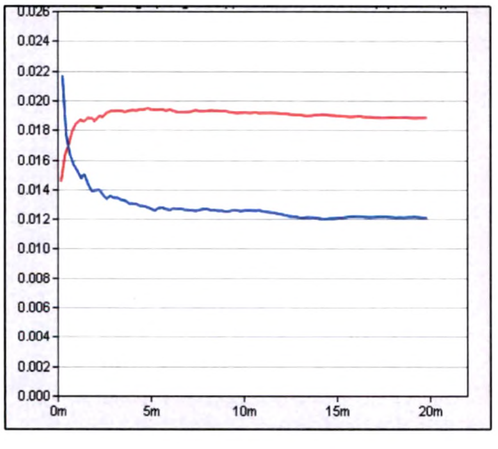


Figure 5.8: Number of Hopes

Figure 5.9: End to end delay(seconds)

In Figure 5.10 the red line indicates ETE Delay for Router 1 in the Tree Routing scenario while the blue line indicates ETE Delay for Router 1 in Mesh Routing. The ETE Delay in Mesh Routing is lower due to the mesh routing process finding more efficient route than tree based routing (1 hop vs. 2 hops).

The red line in Figure 5.11 is the total load for the Tree Routing scenario while the blue line is total load for Mesh Routing. The load for Mesh Routing is lower due to fewer hops for application traffic resulting in less overall traffic seen at the MAC layer. Also note that there is a very small spike in load for Mesh Routing near the beginning of the simulation that is not seen for Tree Routing. This is due to the routing messages being broadcast at that time.



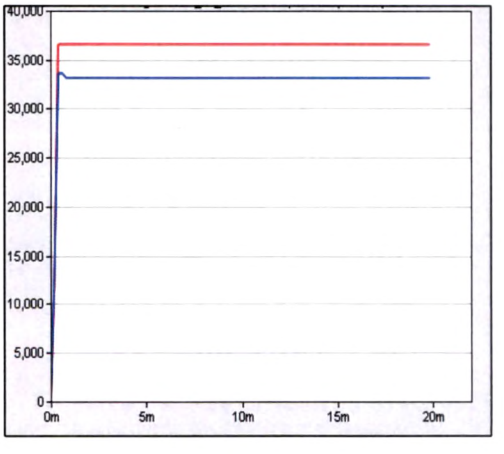


Figure 5.10: End to end delay(sec) for Router 1

Figure 5.11: Load per PAN (bits/sec)

Figure 5.12 shows the throughput for the tree and mesh topologies respectively. It shows that the maximum throughput is achieved in Tree topology and Mesh topology has the low throughput. The reason for this is because Tree topology is communicating on the basis of the PAN coordinators and R 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 Rs (Routers) 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.

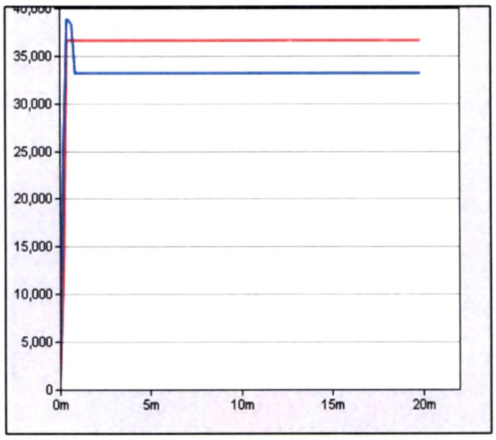


Figure 5.12 Throughput (bits/sec)

Figure 5.13(a) and (b) shows the tree structure and mesh route from Router 1. The tree structure in this scenario is identical to the previous one. Also note that the tree path from Router 1 to Router 3 passes through the Coordinator. In Mesh Network, the mesh route goes directly to Router 3.

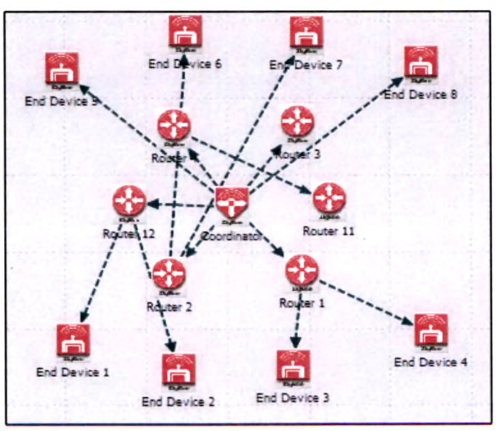


Figure 5.13(a) : Tree structure

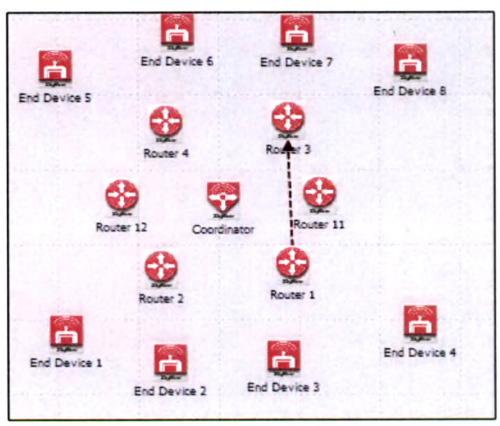


Figure 5.13(b) : Mesh Route

ℵ SCENARIO - 2

Figure 5.14 scenario studies the behavior of a network when the coordinator fails. 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 coordinators have their PAN ID's set to 1 and 2 respectively. A portion of the remaining nodes should join each of the two coordinators (any given node may join either coordinator).

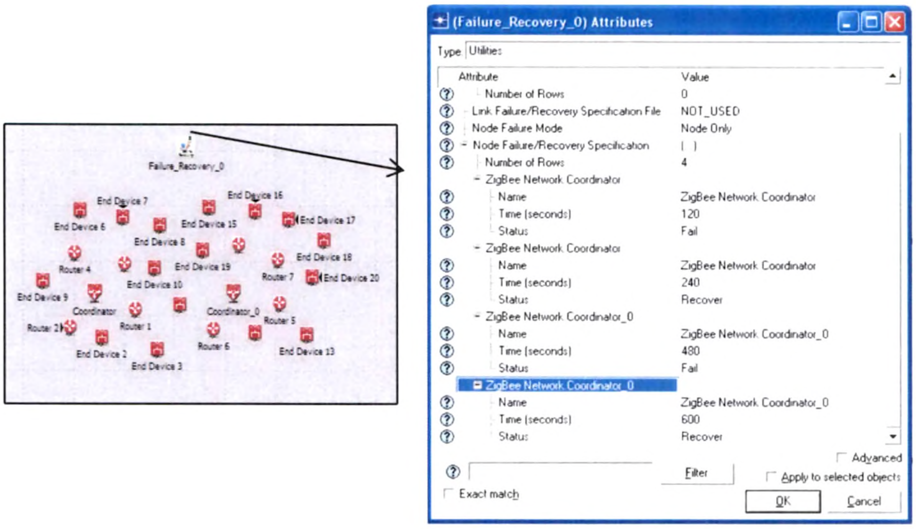
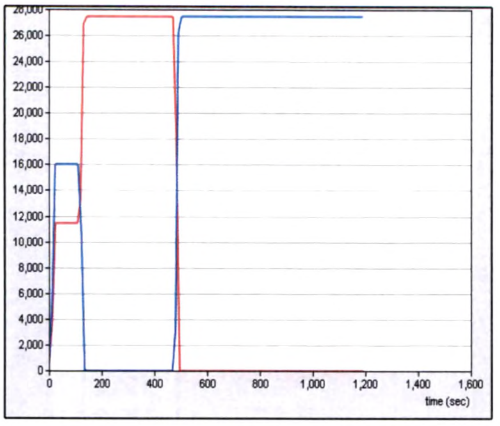


Figure 5.14 : Snapshot of the Network when Coordinator Fails

Two minutes into the simulation, the first coordinator fails. It will remain failed until four minutes, when it will recover and re-establish a network. At eight minutes, the second coordinator will fail. It will remain failed until ten minutes. The expected behavior is approximately half the nodes to join each of the two coordinators at initialization. When the first coordinator fails, the nodes joined to that PAN should leave and join the second coordinator. When the second coordinator fails, all the nodes should join the first coordinator.

Figure 5.15 shows Global MAC load for PAN. The blue line indicates the first coordinator (PAN 1) while the red is the second coordinator (PAN 2). Initially, both PANs have more or less equivalent loads (PAN 1's is greater due to a few more nodes joining that network). After 2 minutes, PAN 1's load drops to zero while PAN 2's load increases. Note that these numbers remain constant even after the first coordinator recovers at 4 minutes. When the second coordinator fails after eight minutes, PAN1's load increases and PAN 2's falls to zero at that time.



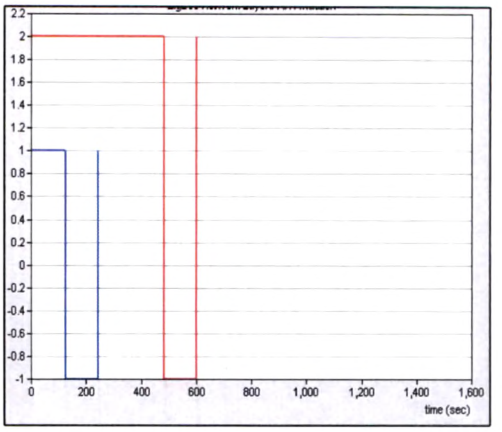


Figure 5.15: Load per PAN (bits/sec)

Figure 5.16 : PAN Affiliation

Figure 5.16 shows the PAN affiliation for coordinator and coordinator_0 in the network. From these two graphs you can see that during the their failed periods the coordinators have a PAN ID of -1, which is the code indicating they are not currently joined to the network.

	PAN ID	Number of Nodes	Tree Depth
1	1	15	2
2	2	11	2

	PAN ID	Number of Nodes	Tree Depth
1	2	25	3
2	1	1	0

	PAN ID	Number of Nodes	Tree Depth
1	1	25	3
2	2	1	0

Figure 5.17: Global Output Report at simulation time 360, 60,720

Figure 5.17 shows the global Output report derived from the simulation. From the Number of Nodes column in the three tables presented here, initially 15 nodes are joined to PAN 1 while 11 are joined to PAN 2 (roughly half each, with an acceptable variation due to randomness). After the first failure, 25 nodes are joined to PAN 2 while only one (the coordinator itself) is joined to PAN 1. After the second failure, the reverse is true.

Summary

In this chapter, the structure IEEE 802.15.4, widely used for WSN is discussed in terms of its operational modes. The Superframe Structure has been elaborated to manage communication between the devices of the WSN. Parametric evaluation for Topological structure of IEEE 802.15.4 has been carried out and analyzed.