

COMPARATIVE EVALUATION AND ANALYSIS OF IEEE 802.15.4 AND IEEE 802.15.6 STANDARDS

*Thesis submitted in partial fulfillment of the requirements for the award
of degree of*

Master of Engineering
in
Computer Science and Engineering

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Certificate

I hereby certify that the work which is being presented in the thesis entitled, "**Comparative Evaluation and Analysis of IEEE 802.15.4 and IEEE 802.15.6 Standards**", in partial fulfillment of the requirements for the award of degree of Master of Engineering in Computer Science and Engineering submitted in Computer Science and Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. A.K. Verma and refers other researcher's work which are duly listed in the reference section.

The matter presented in the thesis has not been submitted for award of any other degree of this or any other University.

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

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Abstract

A Wireless Personal Area Network is a network of interconnecting devices centred around an individual's work space. Wireless Sensor Networks as well as Body Area Networks can be used in a Wireless Personal Area Network. The IEEE 802.15 group is specifically concentrated on the standardization of the Wireless Personal Area Networks and also categorizes Wireless Sensor Networks (low powered) in the IEEE 802.15.4 standard. Body Area Networks are defined by the IEEE 802.15.6 standard. Under normal conditions, both of these standards control the set of devices meant for their respective standards. However, the devices being architecturally similar (nodes being similar but with difference in power, area covered etc) must be able to work on their counterpart's standard.

In this thesis, both the IEEE 802.15.4 and IEEE 802.15.6 are used on a similar setup with same parameters in order to study the outcome which may arise due to this type of implementation. The existing techniques configure the devices to be used by a particular standard. However, it may be interesting to gauge the performance of a system of devices meant for a particular standard used with another standard. In this thesis, a similar exercise is performed by setting the nodes and implementing both the IEEE 802.15.4 as well as IEEE 802.15.6 on these nodes.

Keywords: Wireless Personal Area Networks, Wireless Sensor Networks, Body Area Networks.

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1.1 Motivation

As research in the field of low-power embedded systems (or micro-electro mechanical systems) such as Bluetooth [1], IEEE 802.11 [2] etc was done, new networking concepts were thought of which led to the creation of new concepts such as Wireless Sensor Networks (WSNs), Body Area Networks (BANs). A network having a large number of sensor nodes is said to be a Wireless Sensor Network. A WSN features limited computation and sensing in each of its sensors. When a network consists of wearable computing devices, then that network is known as a Body Area Network. In a BAN, the devices can either be implanted inside the body or directly worn by the user's body.

Wireless Sensor Networks were earlier designed to be used for defence purposes but due to the availability of the industrial, scientific and medical (ISM) band these networks came to be used for civilian purposes also. The WSNs require collaborative effort from a large number of sensors in order to communicate therefore, they are densely deployed in an area to be monitored. Each sensor node communicates to its neighbouring node in order to transfer a message. WSNs can provide a reliable network because of the following features: self-organisation, low power, low memory, low bandwidth, self-configurable, wireless and infrastructure less. Therefore, if these features are kept in mind during the design of a network, a reliable communication medium can be created.

Body Area Networks were designed due to the advancements in the field of networks in order to maintain high level of connectivity and at the same time miniaturising the devices used for communication. BANs combine connectivity and miniaturisation of devices. BANs were developed due to rapid research in the field of WSNs which required the use of sensor nodes. But BANs cover a smaller area as compared to WSNs due to the use of smaller but intelligent physiological nodes which can be used in a wide variety of areas ranging from health monitoring to control of devices. A

BAN can also include sensors directly implanted inside a being rather than a wearable. The information transmitted by the sensors in a BAN is limited due to various reasons. The energy resources are also not capable of powering the sensors for a long time hence limiting the use of BANs in more practical purposes. Therefore, a thorough understanding of the concepts and standards is required in order to efficiently apply the WSN as well as BAN in real life.

1.2 Importance of the Study

The IEEE 802.15 working group of the IEEE 802 standards committee categorizes Wireless Personal Area Networks (WPANs) which further includes Wireless Sensor Networks and Body Area Networks as its task groups. The IEEE 802.15.4 task group categorizes Wireless Sensor Networks into Low Rate Wireless Personal Area Network. The IEEE 802.15.6 task group defines the Body Area Networks. Since both the networks are relatively newer, therefore there are a lot of areas which need to be improved in order to make these technologies more useful in real life situations. Some of the areas which need to be improved are power consumption (due to the dependence on batteries), topology creation (the nodes may be static or dynamic), security (data may be vulnerable to attacks due to medium being wireless), packet loss (recovery of lost data). So, the study helps in understanding the concepts of WSN and BAN better and set a pathway for the seamless interconnectivity of the two concepts.

1.3 Thesis Outline

This thesis is organised into 7 chapters which include Introduction; Background Information; Literature Review; Problem Statement and Objective; Installation and Simulation; Results and Analysis and finally Conclusion and Future Scope.

Chapter 1 describes the motivation behind the pursuit of this thesis, the importance of this thesis and the thesis outline. Chapter 2 describes the background information behind the WSNs and BANs. Chapter 3 has the survey of literature including details about IEEE 802.15.4, IEEE 802.15.6 and Zigbee. Chapter 4 discusses the problem statement and objective of this thesis. Chapter 5 shows the installation of tools and the simulation environment. Chapter 6 describes the results and analysis based on the results and finally Chapter 7 concludes the thesis along with future scope.

2.1 Wireless Sensor Networks

A wireless sensor network (WSN) is basically a wireless network consisting of tiny computing devices. These devices are autonomous (work independently) and are distributed over a particular area. Each of the tiny computing devices (called a sensor node) is equipped with a sensor, a wireless radio, a processor, and a power source. The National Research Council of USA defines sensor network as:

“Sensor Networks are massive numbers of small, inexpensive, self-powered devices pervasive throughout electrical and mechanical systems and ubiquitous throughout the environment that monitor (i.e. sense) and control (i.e. effect) most aspects of our physical world” [3].

Earlier, sensor networks consisted of small number of sensor nodes that were wired to a central processing station, but nowadays, the focus is more on wireless distributed sensing nodes. The wireless sensor network is composed of a large number of these sensor nodes, which are very densely deployed. The deployment may either be inside the phenomenon (something which is known by sense perception) or very close to it [4]. A wireless sensor network can be deployed in a physical environment in order to monitor a wide range of environmental phenomena. But in almost all the cases, the environment to be monitored does not have an existing infrastructure for energy and/or communication. Therefore, it is crucial for sensor nodes to survive on small sources of energy.

Since the sensor nodes have limited memory and may be difficult-to-access (due to deployment), a radio is used for wireless communication to transfer the data to a base station via sink node. Battery is the main power source in a sensor node. However, secondary power supply such as solar panels may be added to the node depending on the requirement and the location of deployment. The sensor nodes have to perform the tasks of monitoring and collecting data, assessing and evaluating the information,

storing the information and sending the useful data to the external network respectively.

A sensor node can observe values such as temperature, sound, pressure, motion etc and forwards it to a data collection point for further processing. The WSN applications are suite with IEEE 802.15.4 standard [5]. This standard is for low rate wireless personal area network and is defined for wireless Medium Access Control Layer and Physical Layer [6][7].

2.1.1 Wireless Sensor Network Model

A WSN is a resource limited network in which the sensor nodes are deployed densely (several times greater in number than ad-hoc networks). These nodes are prone to failures therefore the topology of the WSN is constantly changing. Also these sensor nodes do not possess a global identification tag [8].

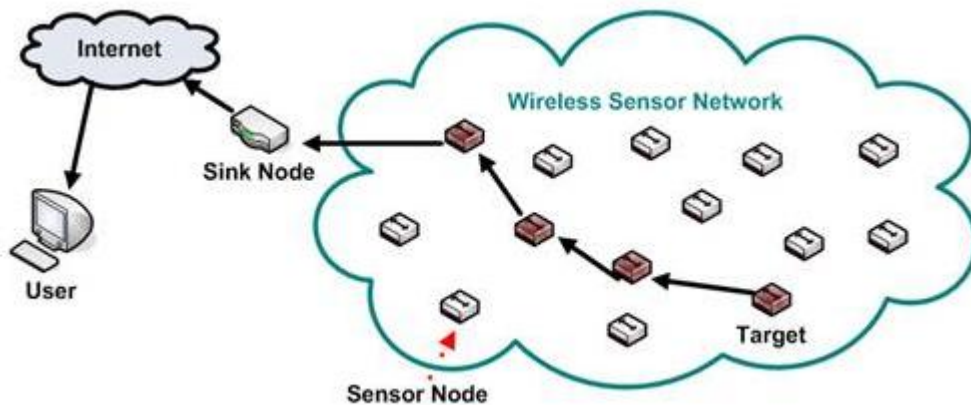


Figure 2.1: A WSN Setup

The major components of a WSN are:

- Sensor Field: The area in which sensor nodes are placed.
- Sensor Node: The main part of a WSN. Collection of data and sending it back to the sink node are the main jobs of a sensor node.
- Sink Node: The node which receives process and stores data from other nodes.

2.1.2 Wireless Sensor Network Protocol Stack

There are five layers in a wireless sensor network protocol stack viz.: application layer, transport layer, network layer, data link layer and physical layer. The protocol stack used by all sensor nodes is given in the figure below. The protocol stack is in 3D as Power Management Plane, Mobility Management Plane and Task Management Plane can work simultaneously on all the five layers of the stack. The power, mobility, and task management planes monitor the power, movement, and task distribution among the sensor nodes respectively [9].

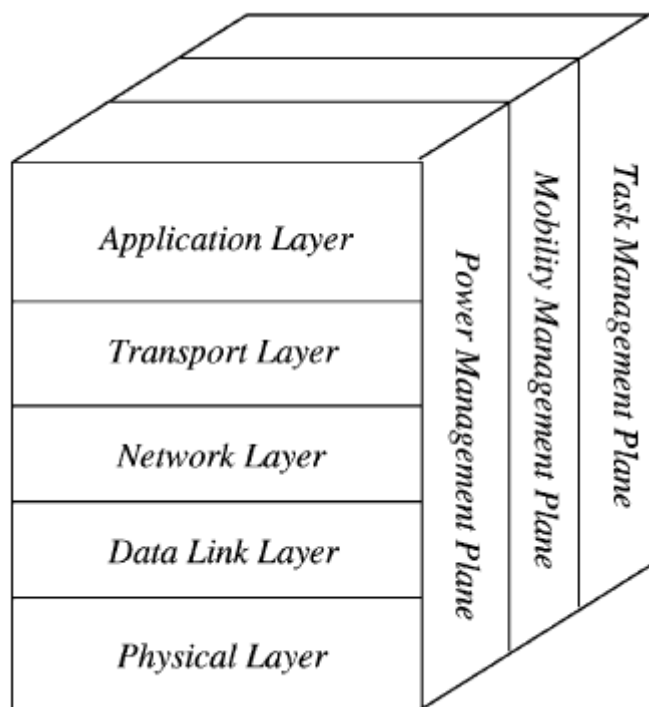


Figure 2.2: WSN protocol stack

The physical layer is responsible for carrier frequency generation, frequency selection, signal detection, modulation, transmission and receiving mechanism. The data link layer performs medium access, error control, multiplexing of data stream and data frame detection. The information received from the transport layer is transferred via the most efficient path towards its destination. The transport layer connects the WSN to the internet. The application layer presents the information to the application and sends requests to the lower layers.

2.1.3 Wireless Sensor Network Applications

Some of the important applications of WSN are listed as follows:

- Military Applications
 - Monitoring the equipment and ammunition of friendly forces.
 - Battlefield surveillance.
 - Reconnaissance and targeting of opposing forces and terrain.
 - Assessment of battle damage.

- Disaster Management Applications
 - Forest fire detection.
 - Flood detection.

- Health Applications
 - Monitoring doctors and patients inside a hospital.
 - Drug administration.

- Home Applications
 - Home automation.
 - Smart environment.

- Traffic Control Applications
 - Vehicle tracking and detection.

2.1.4 Routing Techniques in Wireless Sensor Networks

As WSN are mostly different from one another, many kinds of routing algorithms exist for these networks. The characteristics of sensor nodes are considered on the

basis of application and underlying architecture. Almost all the routing protocols are either flat, hierarchical or location based.

2.1.5 Sensor Coverage in Wireless Sensor Network

One of the important parameter for the evaluation of the effectiveness of a wireless sensor network is sensor coverage. Sensor coverage can be defined as the area in which a node can sense phenomena. Various protocols for sensor coverage are discussed below.

- **Coverage Configuration Protocol (CCP) [10][11]**

CCP works on the principle of scheduling sleep intervals for nodes which are not being used at a time. A node has three states in CCP viz.: sleep, active, and listen. It involves the use of K-coverage eligibility algorithm. This is used to check the eligibility of a node to change state. A node can become active if and only if every location within a node's coverage is not covered by another active node. The node will remain in sleep state (i.e. turns off its radio) for the duration for which the sleep timer is set. After the sleep timer expires, the node will enter into listen state and start communicating with its neighbouring nodes via hello messages. After this the K-coverage eligibility algorithm is executed again. In this way battery power can be preserved by scheduling sleep intervals for nodes which are not being used.

- **Differentiated Surveillance Service Protocol [11][12]**

This protocol is based on an adaptive energy-efficient sensing coverage scheme which means that the coverage of the sensor nodes can change dynamically to achieve energy efficiency. The sensor nodes have two modes viz.: sleeping mode and working mode. Each sensor node first undergoes through initialization phase in which it firstly determines its own location. This is done so that the node is made aware of its own location (the nodes are static). Then the node synchronizes the time with its neighbouring nodes. Then after this, the node enters the sensing phase in which a schedule is made which includes the durations and time when the node will remain awake and when it

will sleep. Nodes can be made to stay awake or asleep for a long or short period of time by manipulating the parameters in the schedule.

2.1.6 Cross-layered approach in Wireless Sensor Networks

As data can be shared between different layers, thus reducing overhead, if a cross layered approach is used, therefore this makes them more efficient than simple layered approach

- **Joint routing, MAC, and Link optimization approach [13]**

As its name suggest, this approach implements a cross layer design between the link layer (data link), MAC layer and the routing layer (network layer). In this design, the nodes become active in their assigned time slot. Transmission of data takes place when the node reaches active mode at the assigned time slot. After the data is transmitted the node again goes to sleep mode to save battery power. The node enters the third mode i.e. the transient mode when that particular node reaches the particular time slot when it has to wake up from sleep mode to transmit data (i.e. go into active mode). This approach not only makes the system energy efficient but also can be used to maximize a node's life. This is achieved by link adaption. To calculate the energy consumed by the node, both routing and scheduling are optimised along with link adaption. It is due to the fact that link adaptation can help in significant reduction of transmission time between the nodes, it can be said that this approach can make the system efficient as it reduces the energy consumption across the nodes.

- **Unified cross-layer protocol [14]**

This protocol similar to the joint routing, MAC and link optimization approach combines transport, network and MAC layer into a single module. In this the functionalities of these layers are also combined. In this protocol, a node has the choice of participating in a transmission. The choice is made by the node on the basis of a set of four conditions i.e. the node will participate in the communication if and only if all the four conditions are satisfied. The

conditions are as follows: i) The link should be reliable for communication i.e. the signal to noise ratio must be above the minimum specified threshold. ii) There should be no congestion at the node. iii) The data must be transmitted efficiently i.e. no bottleneck should be there. This condition also prevents buffer overflow as the amount of input will be controlled so that the buffer cannot be overflowed. iv) The node must have at least the minimum energy required for participation in communication. As all the four conditions have to be met before the communication to start, a reliable event driven communication is achieved along with energy efficiency. As the conditions have to be first met therefore, the nodes act in a systematic manner to forward the packets using the receiver based routing [15]. The routing level (network layer) in each node is used to prioritize the nodes which will send the packet first. As everything happens in a structured way, this protocol can achieve higher level of network performance and efficiency than simple layered protocol (whose layers are not crossed).

- **Jointly-optimal congestion-control and power-control (JOCP) algorithm [16][17]**

As its name suggest, this algorithm joins congestion control with power control i.e. Transport and Physical layers are joined with a goal to increase energy efficiency. In this the communication process is divided into time slots and at each of the time slots four simultaneous operations are performed viz.: update delay due to weighted queue at each intermediate node, measurement of total delay at source node for updating TCP window size, calculation and passing of received messages from transmitting node to other nodes, and finally analysis of the queuing delay and messages received in order to adjust the power for transmission at the source node. These four operations are performed simultaneously and form the basis of the JOCP algorithm.

- **Joint physical, MAC, and routing layer optimization approach [18]**

This approach follows the optimization of the physical, MAC and network layer (routing) to form a cross layer. The main purpose of this approach is to increase the life of the network by optimizing transmission, data rate and link schedule. This approach has four constraints viz.: flow conservation (balanced flow at each time slot in the network), energy conservation (energy consumed should be less than initial energy), range constraint (transmission power should be less than or equal to maximum transmission power and rate constraint (maximum data rate is defined for each node). if these four constraints are taken into consideration while designing the cross layer then lifetime of the network can be increased as we can get optimal transmission power at each node.

2.2 Body Area Networks

As advances in wireless personal area networks were made, a new technology known as Body Area Networks came into the scene around 1995. The purpose of developing Body Area Networks was to implement communications on, near, and around the human body. It may also be referred to as Body Sensor Network as it involves the use of low powered sensors in or around the body. A typical BAN comprises a series of miniature sensor nodes. Each node has its own power supply and storage. Each node is capable of communicating with other sensor nodes and/or with a central node worn on the body [19]. A Body Area Network is formally defined by IEEE 802.15 as

“A communication standard optimized for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics / personal entertainment and other [20]”.

The physiological sensors used in BANs are helpful in monitoring of activity such as biological functions (like ECG, EEG), motion of the user etc.

2.2.1 Difference between WSN and BAN

The BANs are different from WSNs in many aspects, some of which are mentioned below [21]:

- **Deployment and Density:** BANs are not as densely located as compared to WSNs. Only the required amount of nodes are placed on the body and redundant nodes are not placed. Therefore, in case of node failure the specific node can be easily replaced.
- **Data Rate:** BANs have comparatively stable data rates as compared to WSNs. This is due to the fact that BANs are used to monitor physiological functions of the user as compared to event based use of WSN nodes.
- **Latency:** BANs suffer lower latency as in the case of a failure or a used battery the same can be amended much easily in comparison to WSNs.
- **Mobility:** A BAN node shares the same mobility pattern as its users as it is worn/attached to the user. But WSN nodes that are usually stationary.

2.2.2 Body Area Network Applications

As body area networks operate around a personal operating space of a user, therefore, these have a wide range of applications. Some of the major applications of BANs which can be used in our daily life are as follows:

- **Home Computing:** To control various computing appliances such as:
 - Operate a Laptop
 - Use a Printer remotely
 - Use a Scanner remotely
 - Operate a Webcam
- **Smart Appliances:**
 - Using gestures for operating Smart TV's

- Remotely operate Washing Machines
- Set temperature of Refrigerators using gestures
- Control Air Conditioner's temperature

- Security Systems:
 - Motion Detectors
 - Motion detection based CCTV Camera
 - Motion based Security Alarm

- Entertainment Systems:
 - Smart TV's
 - Control volume and other functions of a Stereo System
 - Perform various operations on DVD Players

- Monitoring Operations
 - Patient Monitoring in hospitals
 - Monitoring of prisoners
 - Monitoring of children at a school

2.2.3 Suitability of various candidate technologies with BANs

The following candidate wireless technologies can be used by body area networks [22].

- **Bluetooth classic:** Bluetooth classic has the following advantages when used with BANs. It is an established standard with widespread adoption in cell phones and laptops. The health device profile for Bluetooth classic is defined. It has sufficient data rate and is a low cost technology. But it uses higher power along with limited scalability and QoS. Furthermore coexistence with ISM band technologies is limited and security is also limited. It can be used as an on-body only.
- **Bluetooth Low Energy:** BLE is Interoperable with Bluetooth but uses lower power than Bluetooth thus making it leverage Bluetooth brand. But its compatibility requirements limit its design freedom and therefore limit its scalability. QoS is also limited due to low coexistence with ISM band technologies. It is also an on-body technology only.
- **ZigBee:** Zigbee is an emerging standard with a defined healthcare profile. It uses lower power than Bluetooth and is much more scalable. Zigbee has a small memory footprint. But it also suffers from low data rate, limited QoS and low coexistence with ISM band technologies. It is an on-body only candidate technology.
- **ANT:** ANT is a relatively simple protocol. It can operate on low power. Healthcare device profiles are defined for ANT and it also has a smaller footprint. ANT is a proprietary protocol with limited throughput, limited QoS and coexistence with ISM band technologies. It is a general-purpose design for specific situations.

2.2.4 Cross-Layered approach in BANs

Combination of two or more layers from the protocol stack improves the efficiency of the network. It facilitates the interaction between the different protocols. A lot of research interest has been generated following this approach however BANs being a comparatively new area lag in the field of cross layer implementation.

- A cross-layer energy efficient protocol built on IEEE 802.15.4 is proposed [23]. The network is divided into time zones. The nodes in the farthest time zone start the transmission. In the next slot, the farthest but one sends its data and so on until the sink is reached. The protocol almost doubles the lifetime compared to regular IEEE 802.15.4. The protocol was developed for regular sensor networks, but usefulness for WBANs is claimed by the author.
- Another protocol uses a data gathering tree. The communication is maintained using distributed slot assignment. It has low packet loss and high sleep ratios while the network flexibility is preserved. The use of a duty cycle even further improves the lifetime of the network [24].

The IEEE 802.15 Working Group for Wireless Personal Area Networks (WPANs) was created by the Local and Metropolitan Area Network Standards Committee (IEEE 802) in March 1999. The aim of this group was to address the requirements for wireless personal area networking for a new class of computing devices which were to communicate and interoperate with one another. These were referred to as pervasive computing devices. The IEEE 802.15 consists of mainly seven task groups each having a different goal. But our concern is only with the IEEE 802.15.4 (categorizes WSNs) and IEEE 802.15.6 (defines BANs) standards.

3.1 IEEE 802.15.4 Standard

The IEEE 802.15.4 standard is also known as LR-WPAN meaning that it is a low rate wireless personal area network. This standard defines the physical and MAC layer of the LR-WPAN [25]. The LR-WPAN is easy to install and provides reliable data transfer. Due to the use of unlicensed radio bands (ISM) these are said to be extremely low cost, flexible and extendable networks. The LR-WPAN is used for short range of operations while maintaining integrated intelligence for network setup as well as routing. It maintains a simple and flexible protocol stack which helps LR-WPAN in achieving a reasonable battery life.

3.1.1 Network Topologies

Some of the network topologies used by LR-WPAN are as follows:

- Star Topology: Central node linked to other nodes in the network and all messages pass through the central node.
- Tree Topology: Top node with a branch/leaf structure below. Message travels up the tree until it reaches a desired node and then downwards to the destination node.

- Mesh Topology: A mesh like structure with some nodes directly linked. Message travels through the suitable path which is available across the mesh.

3.1.2 The Physical Layer

The physical layer of the LR-WPAN consists of 27 channels divided into three different frequency bands [26]. The first band is of 2450 MHz frequency and has 16 channels out of the available 27 channels. The second band has 915 MHz frequency with 10 channels out of the remaining 11 channels. The last channel of physical layer is in an 868 MHz frequency band. The data rate is very low (up to 250 kbps) as compared to other WPAN standards. An interface between the MAC sub layer and the physical radio channel is provided by the physical layer.

The tasks which are specifically to be performed by the physical layer are as follows:

- Activation/Deactivation of radio transceiver: As requested by the MAC sub layer, the radio is set into one of the three predefined states viz. Transmitting, receiving, sleep state.
- Energy Detection: It estimates the received signal power within the bandwidth of the channel. The result may be used for clear channel assessment in the channel selection algorithm by the network layer.
- Link Quality Indication: Receiver energy detection and signal to noise ratio are used individually or together to measure the strength or quality of a link from which it is received.
- Transmission/Reception of packets over physical medium: Modulation techniques are used along with spreading techniques to transmit packets over the medium.
- Channel Selection: Out of the 27 available channels, a specific part of the channels is chosen by the network by the physical layer upon the request by the MAC sub layer.

3.1.3 The MAC Sub-Layer

An interface between the service specific convergence sub layer and the physical layer is provided by the MAC layer along with the provision of the data service and the management service. The MAC layer is responsible for the following sub tasks:

- **Generating and managing beacons:** A coordinator device can determine whether to use the beacon enabled mode or not. For this the device has to be a coordinator. In the beacon enabled mode, a superframe structure is used.
- **Channel Access:** The carrier sense multiple access with collision avoidance (CSMA-CA) is employed for channel access. 802.15.4 being a standard for wireless networks uses CSMA-CA for channel access. Due to the low data rate in LR-WPAN, the request to send and clear to send mechanisms are not used in CSMA-CA.
- **Guaranteed Time Slot management:** When beacon enabled mode is used then a portion of the active superframe can be allocated to a device. This is done by the coordinator. This portion is known as a guaranteed time slot.
- **Frame Validation and Acknowledged frame delivery:** This enhances the reliability of the link between two peers. The frame acknowledgement and retransmission is amongst the two peers, the data verification is done by a 16 bit CRC and the CSMA-CA.

3.1.4 Carrier Sense Multiple Access - Collision Avoidance

In CSMA-CD, when a node cannot detect another transmitting node resulting in collision, this is known as a hidden node problem. This problem is solved using the CSMA-CA approach. CSMA-CA has the following steps:

- Before transmission, listen (sense) for a signal. If signal detected then wait for random time and check again.
- If no signal is detected, then ready to send (RTS) message is sent to all nodes. The RTS contains destination address and duration of transmission.
- The destination sends clear to send (CTS) message to the source.

- The destination sends acknowledgement for each packet to the source. If acknowledgement not received then packet is assumed to be lost and is resent till an acknowledgement is received.

IEEE 802.15.4 uses two types of channel access mechanisms:

- Slotted CSMA-CA: used in beacon enabled networks. Backoff slots are aligned with the start of beacon transmission. Boundary of the next backoff slot is located before every transmission by the device. If channel is busy following the random backoff, the device waits for a random number of backoff slots before trying to access the channel again.
- Unslotted CSMA-CA: used in non beacon enabled networks. A device waits for a random period before sending data. If after waiting the channel is idle, then data is transmitted else the wait continues for another random period of time.

3.2 IEEE 802.15.6 Standard

A standard model was required for making the BAN implementation efficient and fruitful for its real life applications which also include the medicine field. So, the IEEE 802.15.6 task group was setup by the IEEE 802 with the purpose of defining new Physical (PHY) and Medium Access Control (MAC) layers for BAN. The IEEE 802.15.6 defines the physical layer into three separate layers and the MAC as a sophisticated protocol to control channel access.

3.2.1 The Physical Layer

The IEEE 802.15.6 defines three separate layers viz. Narrow Band (NB), Ultra-wide Band (UWB) and Human Body Communications (HBC) [27]. Every BAN has one hub; while there can be up to 64 nodes. The purpose of the hub is to establish a time base to divide the time into beacon periods.

- **Narrow Band:** It is responsible for activation/deactivation of the radio transceiver, Clear Channel Assessment (CCA) within the current channel and data transmission/reception.
- **Ultra Wideband:** This layer operates in two frequency bands: low band and high band. Each band is divided into channels of 499.2 MHz bandwidth each. The low band has 3 (1,2,3) channels out of which channel 2 is mandatory channel. The high band has eight channels (4,5,6,7,8,9,10,11) with channel 7 being mandatory. There must be at least one mandatory channel in a UWB.
- **Human Body Communications:** it has two frequency bands at 16 MHz and 27 MHz having 4 MHz bandwidth each. United States, Japan, and Korea allows both bands while only 27MHz is valid for Europe. It covers the entire protocol for WBAN such as packet structure, modulation, preamble/SFD, etc.

3.2.2 The MAC Layer

In IEEE 802.15.6, the entire channel is divided into superframe structures. Each superframe is bounded by a beacon period of equal length. The hub selects the boundaries of the beacon period and thereby selects the allocation slots [28].

- **Beacon mode with beacon period superframe boundaries:** In this mode, the beacons are transmitted by the hub in each beacon period except in inactive superframes or unless prohibited by regulations.
- **Non-beacon mode with superframe boundaries:** In this mode, the entire superframe duration is covered either by a type I or a type II access phase but not by both phases.
- **Non-beacon mode without superframe boundaries:** In this mode, the coordinator provides unscheduled Type II polled allocation only. The access mechanisms used in each period of the superframe are divided into three categories: 1) Random access mechanism, which uses either CSMA/CA or a slotted Aloha procedure for resource allocation, 2) Improvised and unscheduled access (connectionless contention-free access), which uses

unscheduled polling/posting for resource allocation, and 3) Scheduled access and variants (connection oriented contention-free access), which schedules the allocation of slots in one or multiple upcoming superframes, also called 1-periodic or m-periodic allocations.

3.3 Zigbee

ZigBee is a standard based on IEEE 802.15.4 [29]. Zigbee uses radio frequency (RF) for communications. In this, a coordinator is responsible for creation of the network. Each device in the system is a Zigbee device managed by the coordinator. All communication between devices propagates through the coordinator to the destination device. The ZigBee standard provides up to 250kbps data rate, and as 40kbps can meet the requirements of most control systems, it is sufficient for controlling most automation devices. The data rate along with the low cost of installation can help tackle complex problems which may arise during the design of a system and thus reducing overall cost of a system design. Hence, Zigbee is a preferred standard in most of the applications of IEEE 802.15.4 due to its rock bottom cost of creation. There are many standards that can provide mid to high data rates for voice, PC LANs, video, etc. But none of them can meet the unique needs of sensors such as low latency and very low energy consumption for long battery lives [30]. The proprietary wireless systems for various applications do not require high data rates provided by other standards but do require low cost. These legacy systems are creating significant interoperability problems with each other and with newer technologies.

Problem Statement and Objective

4.1 Problem Statement

The effect of advancement in the field of computer science is slowly starting to be felt in day to day life. Everyday a new revolution in the area of WSNs and BANs is seen. Smart homes, wearable computers, smart cars and other similar technologies are slowly but surely starting to influence the way we live our day to day lives. The concept of wearables (BANs) are changing the whole scenario of how we consume media and control different devices. Similarly, WSNs are being deployed in such a way that they can be used to monitor a person and therefore can be implemented along with BAN concept in smart homes. But, still there are many challenges to be faced before these two can be simultaneous implemented to create an efficient system.

The problem addressed in this thesis is while WSN and BAN appear to be similar, they are not yet used together efficiently. The IEEE 802.15.4 categorizes WSNs as a Low Rate Wireless Personal Area Network and IEEE 802.15.6 defines a BAN. Both of them fall under the category of Wireless Personal Area Networks (IEEE 802.15 Group).

The difference in the architecture of the nodes of WSN and BAN cause both the systems to act differently while appearing to be similar i.e. when used under the IEEE 802.15 group. The BANs are not as densely located as compared to WSNs, BANs have stable data rate, have low latency and are more mobile as compared to WSNs.

4.2 Objective

In order to create a system where IEEE 802.15.4 and IEEE 802.15.6 are used together, the effects of each of the standard working in a similar situation must be studied first. So the main objective of this thesis is to create a system to compare the working of IEEE 802.15.4 and IEEE 802.15.6 under similar conditions having similar parameters.

5.1 Ubuntu

Ubuntu is Linux based operating system. Ubuntu is freely available to any one and is the most popular Linux based operating system yet. Ubuntu is developed and distributed by Canonical Limited. Ubuntu can be installed on the hard disk using Ubiquity Installer available freely. A new version of Ubuntu is released almost after every 6 months with support to the same provided for another 9 months. Ubuntu provides a wide range of software (such as LibreOffice, Firefox, Empathy, Transmission) by default. Additional software such as Synaptic Package Manager can be downloaded and installed using the Ubuntu Software Center. Programs meant for windows can be run using VirtualBox and VMware software. The sudo tool can be used to temporary grant admin privileges to users so that a user cannot cause any catastrophic damage by having access to the root. Ubuntu provides buffer overflow protection by default and that too at the expense of only 1% of the CPU power for a 32 bit version.

5.2 Castalia Simulator

5.2.1 Overview

Castalia is a simulator based on the OMNet++ platform. It is designed for Wireless Sensor Networks (WSN), Body Area Networks (BAN) and other networks having low-power nodes/devices. It can test distributed algorithms in a realistic wireless channel and radio models, with realistic node behaviour. Castalia Simulator is highly parametric therefore it can simulate a wide range of platforms and specific applications of the same. The modularity, reliability, and speed of Castalia is partly because it is based on OMNeT++, which is an excellent framework to build event-driven simulators.

The main features of Castalia are as follows:

- Advanced channel model based on empirically measured data
- Advanced radio model based on real radios for low-power communication
- Extended sensing modelling provisions
- Node clock drift, CPU power consumption.
- Designed for adaptation and expansion.

5.2.2 Structure

Castalia simulator is based on the OMNeT++ platform. Its basic concepts are modules (basic unit of execution) and messages. Messages are accepted from other modules or itself as desired by the user. Composite modules can also be created by joining one or more simple and/or composite module.

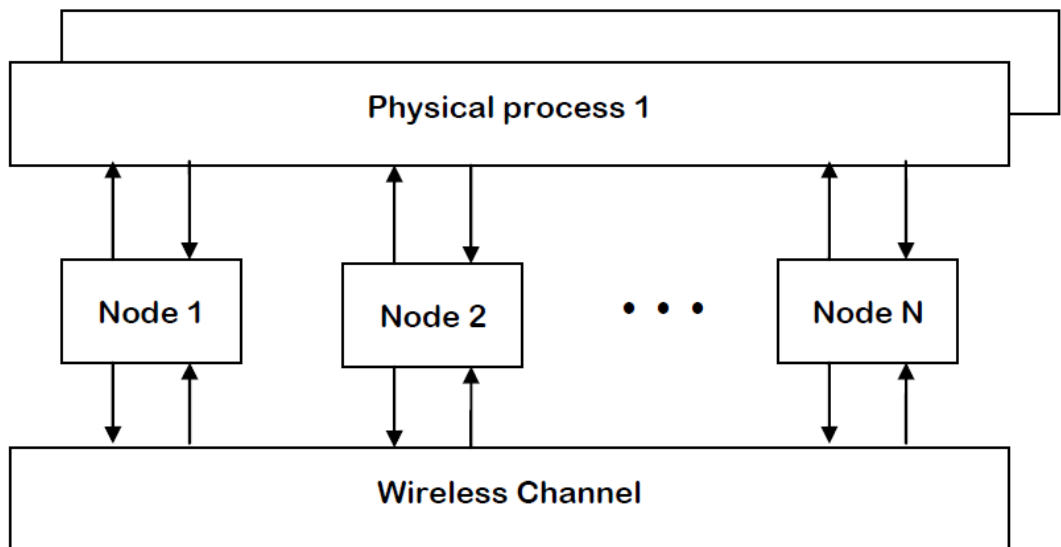


Figure 5.1: Module Structure

The nodes are connected to each other via the wireless channel module. Message passing between modules is shown by the arrows. When a node has to send a packet, it sends that packet to the intermediate wireless channel which reads the information

on the packet and forwards it to the appropriate node. The monitored physical process are attached with the nodes and a special module for each physical process is created which holds the value which the physical process is showing. The nodes then check the physical process by getting their value from the corresponding module in the given space time to get readings. The number of physical devices can vary according to the problem at hand.

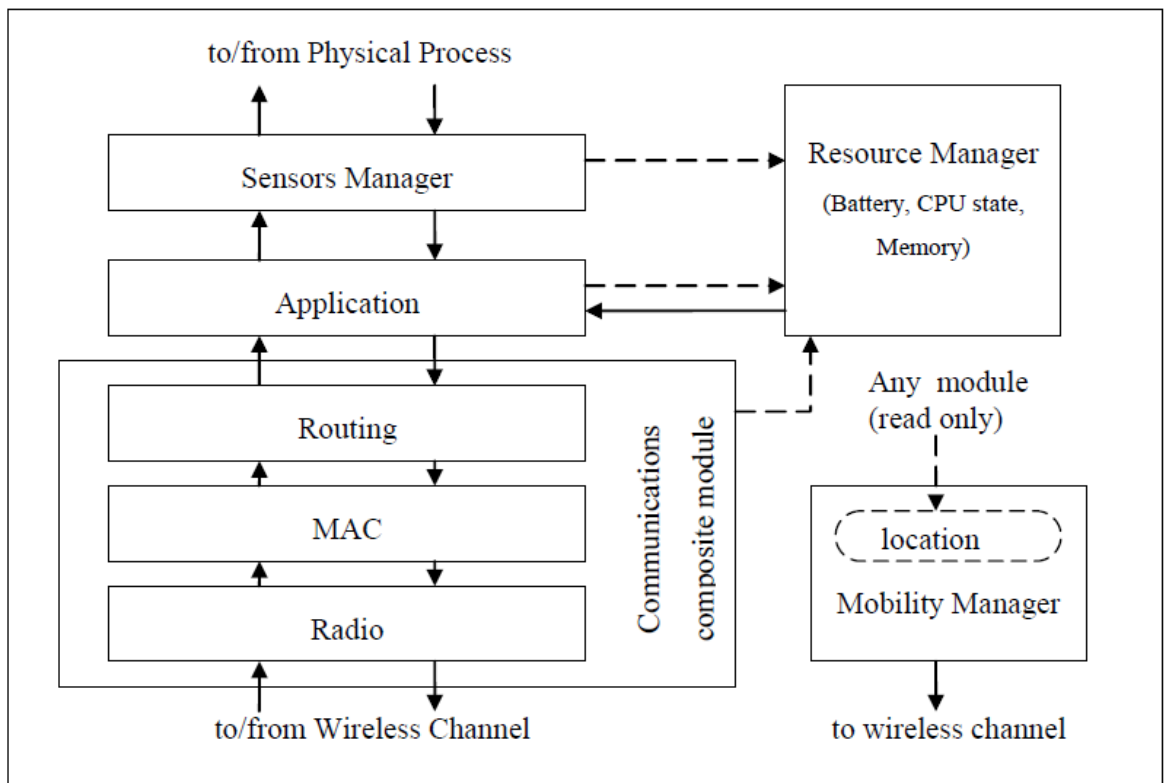


Figure 5.2: Composite Node Module

The node module can be a composite one comprising of one or more simple/composite modules. The arrows show message passing between different layers. Whereas the dotted arrows show the calling of functions between different areas of the system. Resource manager is almost always called due to the fact that energy will be consumed during a process. The application module is the place where a user implements a new algorithm. Similarly MAC, Routing and Mobility manager can be changed by the user at will. If the user wants then he can customise various parameters at will without any hindrance.

These composite modules are made using OMNet++ NED language. Module names, parameters as well as interfaces can be defined in NED. Sub modules can also be created. These are stored in .ned files.

5.3 Simulation

A simulation is made in order to study the working of the IEEE 802.15.4 and IEEE 802.15.6 when they are activated under similar conditions. For this simulation we use Guaranteed Time Slot mechanism for both IEEE 802.15.4 (WSN) and IEEE 802.15.6 (BAN). The temporal loss for the simulation has been turned off. In this simulation, we use 5 nodes randomly deployed in a field of 10x10 sq m. The time limit for the simulation is 100 seconds. An application is created to test the throughput of the system which sends data packets to the sink node (node 0) at all time intervals.

Simulation Parameter	Value
Simulation Area	10x10 sq m
Simulation Time	100 seconds
Number of Nodes	5
MAC Protocol	IEEE 802.15.4
	IEEE 802.15.6

Table 5.1: Simulation Parameters

Chapter 6

Results and Analysis

This chapter shows the results of the simulation which has been run. As mentioned earlier, the simulation is used for IEEE 802.15.4 and IEEE 802.15.6 respectively with similar parameters. The results are shown using the “CastaliaResults” script which generate a readable output from the text file created during the simulation. The simulation shows output for when the GTS has been turned on and when it is turned off for both the cases.

```
ms@ubuntu:~/Castalia-3.2/Simulations/BANtests$ ../../bin/CastaliaResults -i 140709-113218.txt
```

Module	Output	Dimensions
Application	Application level latency, in ms	1x1(31)
	Packets received per node	1x5
Communication.MAC	Fraction of time without PAN connection	5x1
	Number of beacons received	5x1
	Number of beacons sent	1x1
Communication.Radio	Packet breakdown	5x1(6)
	RX pkt breakdown	6x1(5)
	TXed pkts	6x1
ResourceManager	Consumed Energy	6x1
wirelessChannel	Fade depth distribution	1x1(14)

Figure 6.1: General output format for simulation run using IEEE 802.15.4

From Figure 6.1, CastaliaResults script converts the data from text file into a readable format. Each output has XxY dimension where X is the number of modules that produce this output and Y is the number of indices (nodes involved) an output from a single module has. If an output is not scalar then its multiplicity is written in the parenthesis. In figure 6.1, the application level latency of the application module is 1x1(31) which means that 1 module is involved in the production of an output and 1 node receives output from the module (i.e. node 0). Similarly it shows the remaining outputs generated by the script.

```
ms@ubuntu:~/Castalia-3.2/Simulations/BANtest$ ../../bin/CastaliaResults -i 140709-113409.txt
```

Module	Output	Dimensions
Application	Application level latency, in ms	1x1(31)
	Packets received per node	1x5
Communication.MAC	Data pkt breakdown	5x1(5)
	Mgmt & Ctrl pkt breakdown	6x1(3)
	pkt TX state breakdown	5x1
	var stats	6x1(2)
Communication.Radio	RX pkt breakdown	6x1(5)
	TXed pkts	6x1
ResourceManager	Consumed Energy	6x1
wirelessChannel	Fade depth distribution	1x1(14)

Figure 6.2: General output format for simulation run using IEEE 802.15.6

In Figure 6.2, we see that the Communication.MAC module shows different output as compared to Figure 6.1. This difference in output is due to the fact that the working of both the standards is different and the Guaranteed Time Slot mechanism has no effect on 802.15.6.

```
Application:Packets received per node
```

	rate=14	rate=16	rate=18	rate=20	rate=22	rate=24	rate=26	rate=28	rate=30
GTSoff	645.44	736.04	823.6	904.44	1003.8	1088.8	1163.24	1235.2	1261.52
GTSon	677	770.68	860.4	968.04	1058.96	1134.28	1247.56	1311.72	1365.16

Figure 6.3: Packets received at different sending rates by IEEE 802.15.4

In Figure 6.3, the packets received at node 0 are shown for different packet sending rates (packets/second). This means that node 0 received 677 packets at 14 packets/second when GTS was on and 645 when it is turned off. Similarly, the result is shown for other rates. This shows that GTS is helpful in increasing the throughput when used in the implementation of IEEE 802.15.4.

```

Application:Packets received per node
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
|         | rate=14 | rate=16 | rate=18 | rate=20 | rate=22 | rate=24 | rate=26 | rate=28 | rate=30 |
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
| GTSoff | 459.32  | 499.28  | 572.6   | 655     | 700.16  | 744.52  | 811.68  | 882.76  | 916.36  |
| GTSon  | 459.32  | 499.28  | 572.6   | 655     | 700.16  | 744.52  | 811.68  | 882.76  | 916.36  |
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+

```

Figure 6.4: Packets received at different sending rates by IEEE 802.15.6

In Figure 6.4, there is no effect of GTS on the packets received at node 0. This shows that GTS plays no role in IEEE 802.15.6. The packets received remain the same when regardless of the state of GTS for each rate. This shows that IEEE 802.15.4 has higher throughput than IEEE 802.15.6 in both the scenarios (GTS on/off).

```

Application:Packets received per node
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
|         | rate=14 | rate=16 | rate=18 | rate=20 | rate=22 | rate=24 | rate=26 | rate=28 | rate=30 |
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
| GTSoff | 3227.2  | 3680.2  | 4118    | 4522.2  | 5019    | 5444    | 5816.2  | 6176    | 6307.6  |
| GTSon  | 3385    | 3853.4  | 4302    | 4840.2  | 5294.8  | 5671.4  | 6237.8  | 6558.6  | 6825.8  |
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+

```

Figure 6.5: Sum of Packets received at different sending rates by IEEE 802.15.4

Figure 6.5 shows the sum of all packets received at node 0 for different packet sending rates (packets/second) for GTS on/off.

```

Application:Packets received per node
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
|         | rate=14 | rate=16 | rate=18 | rate=20 | rate=22 | rate=24 | rate=26 | rate=28 | rate=30 |
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
| GTSoff | 2296.6  | 2496.4  | 2863    | 3275    | 3500.8  | 3722.6  | 4058.4  | 4413.8  | 4581.8  |
| GTSon  | 2296.6  | 2496.4  | 2863    | 3275    | 3500.8  | 3722.6  | 4058.4  | 4413.8  | 4581.8  |
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+

```

Figure 6.6: Sum of Packets received at different sending rates by IEEE 802.15.6

Similar to Figure 6.4, Figure 6.6 shows no change while GTS on and off.

```
ms@ubuntu:~/Castalia-3.2/Simulations/BANtest$ ../../bin/CastaliaResults -i 140709-113218.txt -s packets -n
```

Application: Packets received per node

	index=1	index=2	index=3	index=4	index=5
GTSoff, rate=14	653.4	689.2	616.4	660.2	608
GTSoff, rate=16	740	783.4	714.8	743.8	698.2
GTSoff, rate=18	818.8	878.2	800.4	843.6	777
GTSoff, rate=20	892.2	971.2	862.4	938.4	858
GTSoff, rate=22	1005.8	1065.2	978.4	1020.6	949
GTSoff, rate=24	1090.6	1154.4	1056.4	1102	1040.6
GTSoff, rate=26	1139.6	1249.2	1138	1182	1107.4
GTSoff, rate=28	1243	1344.8	1210.6	1252.6	1125
GTSoff, rate=30	1259.2	1423.6	1171.8	1279.4	1173.6
GTSon, rate=14	676.8	697.2	654.2	688.2	668.6
GTSon, rate=16	770.8	796.2	745	780	761.4
GTSon, rate=18	856.2	901.4	823.4	876.4	844.6
GTSon, rate=20	963.4	995	938	986	957.8
GTSon, rate=22	1054.8	1097.8	1012.4	1071	1058.8
GTSon, rate=24	1139.4	1194.2	1047.2	1158.2	1132.4
GTSon, rate=26	1267	1244.4	1198.6	1277.4	1250.4
GTSon, rate=28	1364.8	1353.8	1239.6	1328.2	1272.2
GTSon, rate=30	1327.6	1466.4	1326.8	1472.6	1232.4

Figure 6.7: Packets received at different sending rates by IEEE 802.15.4 by different nodes.

Figure 6.7 shows the number of packets each node send to sink node (node 0) for every sending rate and for GTS on as well as off in IEEE 802.15.4. The packets received greatly vary when GTS is turned on/off for each node. But always receive higher number when GTS is turned on as compared to when it is turned off. From here we can gauge that for IEEE 802.15.4 when GTS is turned on, it receives higher number of packets from a node than as compared to when it is turned off.

```
ms@ubuntu:~/Castalia-3.2/Simulations/BANtest$ ../../bin/CastaliaResults -i 140709-113409.txt -s packets -n
```

Application: Packets received per node

	index=1	index=2	index=3	index=4	index=5
GTSoff, rate=14	463.4	469.8	447.6	464.6	451.2
GTSoff, rate=16	508.6	500.8	492.8	501	493.2
GTSoff, rate=18	576	584.4	554.2	585.6	562.8
GTSoff, rate=20	655	679.8	642.8	659	638.4
GTSoff, rate=22	706.2	719.8	682.8	701.2	690.8
GTSoff, rate=24	740.2	750.8	732.8	752.2	746.6
GTSoff, rate=26	820.6	823.8	799.2	815.8	799
GTSoff, rate=28	887	920.4	867.6	890.4	848.4
GTSoff, rate=30	916.6	964.4	893.2	927.4	880.2
GTSon, rate=14	463.4	469.8	447.6	464.6	451.2
GTSon, rate=16	508.6	500.8	492.8	501	493.2
GTSon, rate=18	576	584.4	554.2	585.6	562.8
GTSon, rate=20	655	679.8	642.8	659	638.4
GTSon, rate=22	706.2	719.8	682.8	701.2	690.8
GTSon, rate=24	740.2	750.8	732.8	752.2	746.6
GTSon, rate=26	820.6	823.8	799.2	815.8	799
GTSon, rate=28	887	920.4	867.6	890.4	848.4
GTSon, rate=30	916.6	964.4	893.2	927.4	880.2

Figure 6.8: Packets received at different sending rates by IEEE 802.15.6 by different nodes.

Figure 6.8 shows the number of packets each node send to sink node (node 0) for every sending rate and for GTS on as well as off in IEEE 802.15.6. The GTS meant for use with IEEE 802.15.4 has no effect on IEEE 802.15.6 so, the packets received remain the same regardless of GTS state when implemented in IEEE 802.15.6.

CastaliaPlot script is used for plotting the above results in a graphical manner. A stacked bar graph, linespoints graph and a histogram can be plotted with the available data. The graphs are shown as follows.

Figure 6.9 shows the results of figure 6.7 in the form of a stacked bar graph. Figure 6.10 shows the results of figure 6.7 in the form of a linespoints graph and Figure 6.11 shows the results of figure 6.7 in the form of a histogram. Each color shows the packets received from a particular node. In the stacked bar graph example red signifies packets received from node 1, green from node 2, blue from node 3, pink from node 4 and sky blue from node 5. The linespoints show how each node sends packets to the sink node.

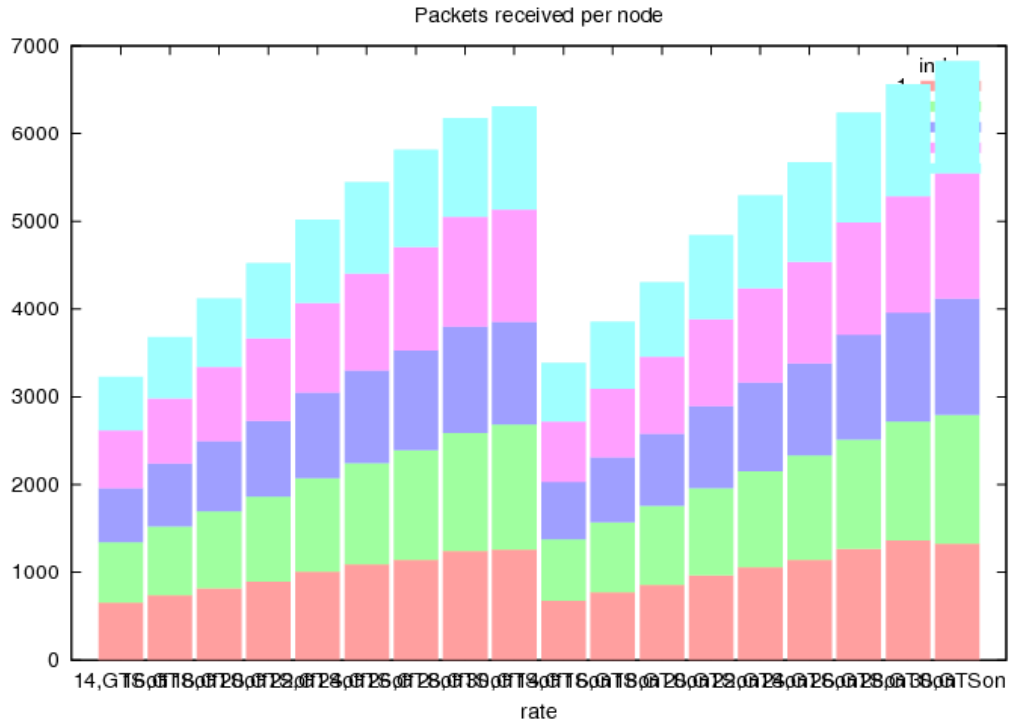


Figure 6.9: Stacked Bar Graph showing packets received at different sending rates by IEEE 802.15.4 by different nodes.

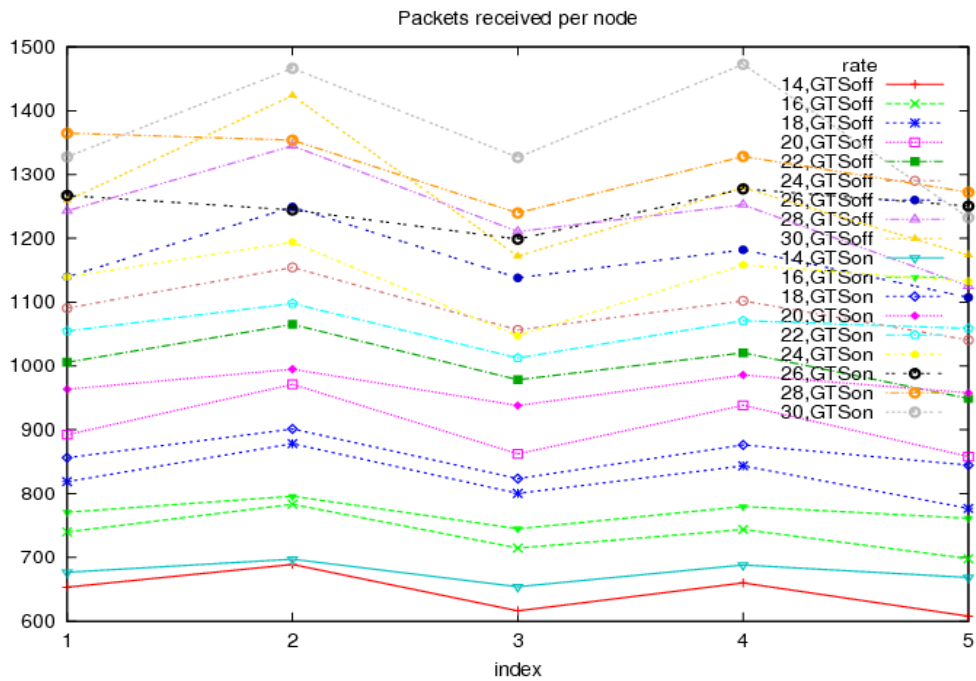


Figure 6.10: Linespoints Graph showing packets received at different sending rates by IEEE 802.15.4 by different nodes.

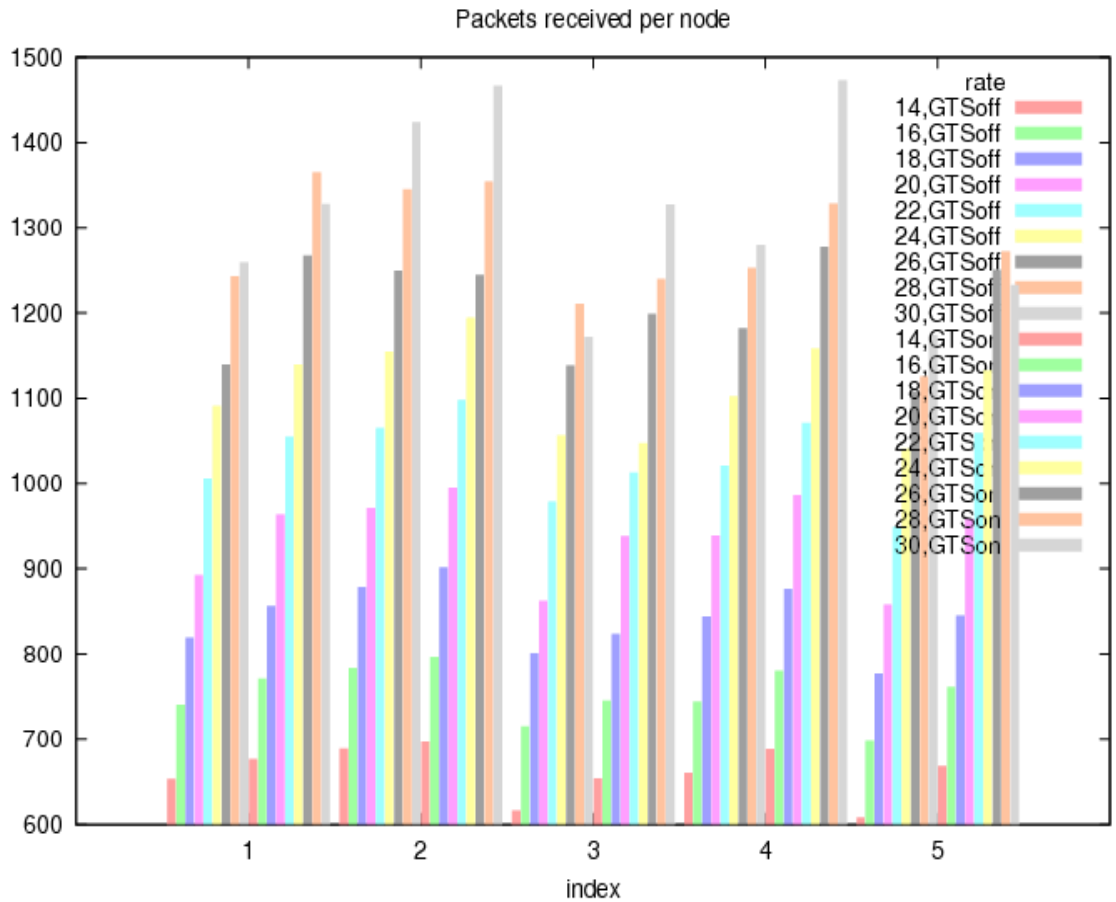


Figure 6.11: Histogram showing packets received at different sending rates by IEEE 802.15.4 by different nodes.

Figure 6.12 shows the results of figure 6.8 in the form of a stacked bar graph. Figure 6.13 shows the results of figure 6.8 in the form of a linespoint diagram and Figure 6.14 shows the results of figure 6.8 in the form of a histogram. Each color shows the packets received from a particular node. In the stacked bar graph example red signifies packets received from node 1, green from node 2, blue from node 3, pink from node 4 and sky blue from node 5. The linespoints show how each node sends packets to the sink node.

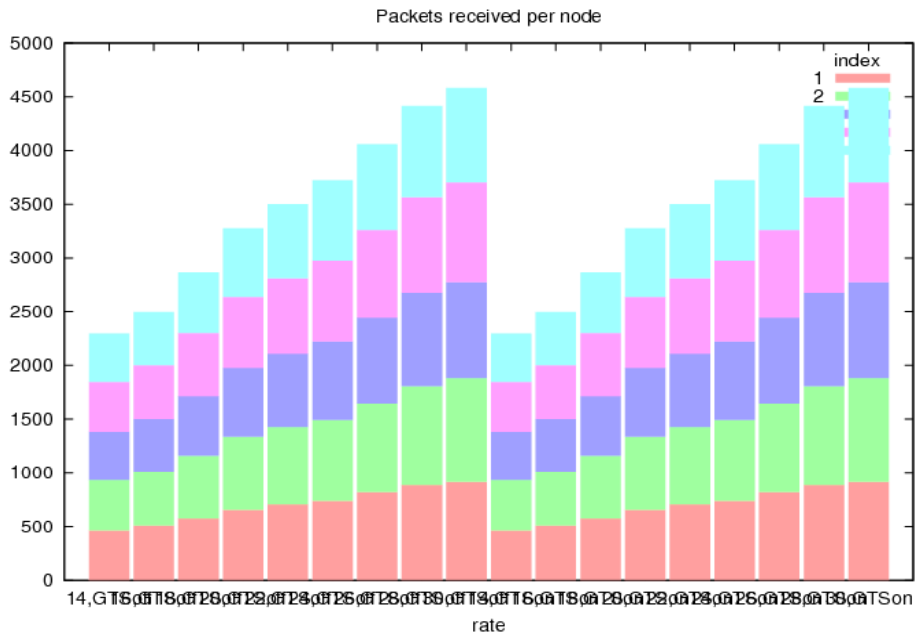


Figure 6.12: Stacked bar graph showing packets received at different sending rates by IEEE 802.15.6 by different nodes.

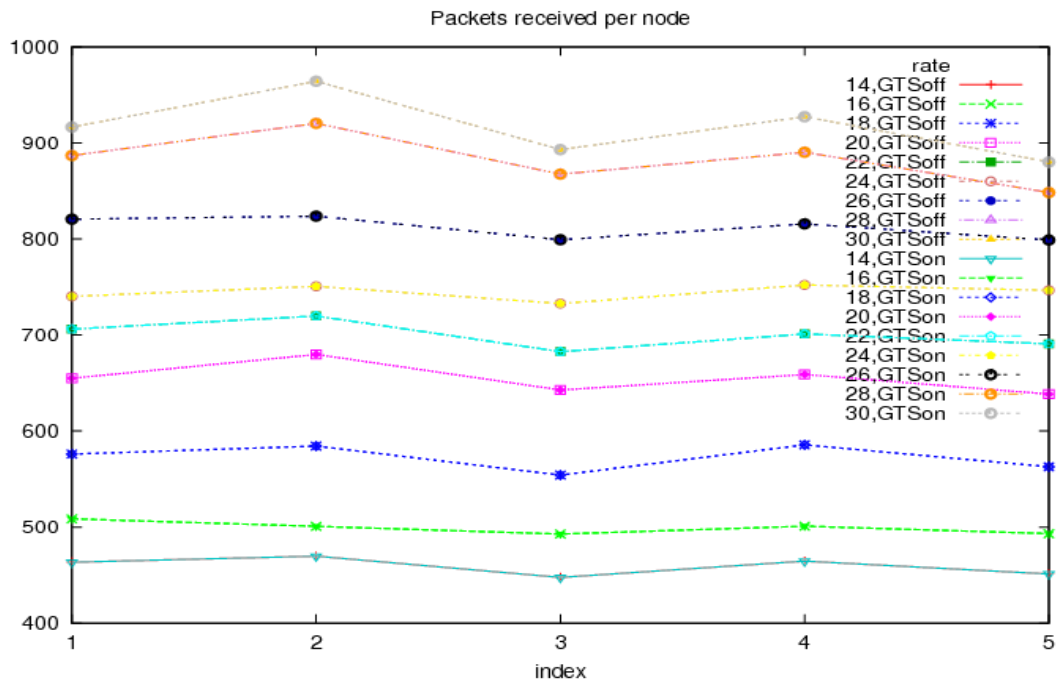


Figure 6.13: Linespoints showing packets received at different sending rates by IEEE 802.15.6 by different nodes.

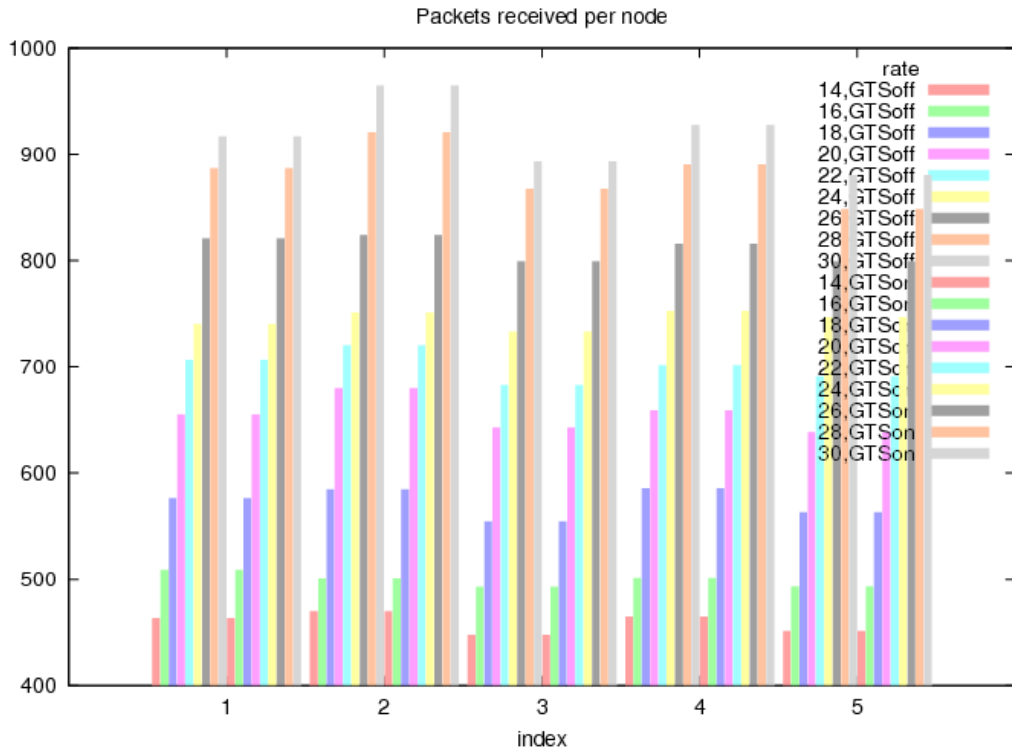


Figure 6.14: Histogram showing packets received at different sending rates by IEEE 802.15.6 by different nodes.

By studying these graphs we concur that the packets received by the sink node vary with the state of GTS in IEEE 802.15.4 but remains the same in IEEE 802.15.6. This gives an overview of how these two standards behave when faced with similar situations. This also shows how well these two can be used in an alternate manner with each other i.e. if the nodes are to be used in alternate technology WSN in BAN and vice versa the output received can be predicted by these graphs. Under similar circumstances, IEEE 802.15.4 gives higher throughput (6825 for highest rate) as compared to IEEE 802.15.6 (4581 for highest rate) due to the fact that GTS is supported by it.

7.1 Conclusion

With all the advancements in computer science meant for the betterment of human life, the technologies are rapidly evolving. Wireless personal area networks also come under this category. In this thesis, a system involving similar setup is created for IEEE 802.15.4 and IEEE 802.15.6.

The significance of this work is to understand the working IEEE 802.15.4 and IEEE 802.15.6. Further, an insight into the various characteristics of these protocols has also been provided. The packets received remain the same for IEEE 802.15.6 regardless of the state of GTS but a significant improvement is seen when GTS is turned on while implementing IEEE 802.15.4 and shows that IEEE 802.15.4 is better than IEEE 802.15.6. It is also observed how these two standards will work if their roles are interchanged. If the nodes are used in IEEE 802.15.4 then they can work but will have less number of packets due to the smaller power of the nodes. One of the important outcomes of the thesis is that the change in specifications and requirements in order to extend IEEE 802.15.4 so that it can perform as IEEE 802.15.6 necessitated by the extension of devices using IEEE 802.15.4 so that they can interface with IEEE 802.15.6 seamlessly.

7.2 Future Scope

Wireless Personal Area Networks is at the core of interactive networks which can be used by anyone regardless of any knowledge of computers like in smart homes, smart cars, wearables etc. So, there is a need of understanding the underlying principles related to the system. It would be interesting to see the effects of varying other parameters such as packet rates and retransmission attempts in case of failure in one or all the nodes. The system can also be adjusted to set the rate and power of the nodes voluntarily. Further, the interconnectivity of different networks can be improved by designing protocols to work with multiple standards.

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BAN	Body Area Network
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to send message
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
LR-WPAN	Low Rate Wireless Personal Area Network
MAC	Medium Access Control
PHY	Physical
QOS	Quality of Service
RTS	Ready to send message
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network

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