BLUETOOTH / ZIGBEE NETWORKS
AND
DEVELOPMENT OF PORTABLE
6LOWPAN STACK

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Abstract

Wireless sensor networks (WSN’s) are becoming popular in military and civilian applications such as surveillance, monitoring, disaster recovery, home automation and many others. Prolonged network lifetime, scalability, node mobility and load balancing are important requirements for many WSN applications.

This thesis work presents the investigation of scalability and power consumption in different wireless module such as Bluetooth, Zigbee to deploy in the large scale wireless sensor network application by simulation the network topologies, analysis and comparison of both the wireless module in OPNET and running the WSN application using Zigbee in Real environment.

In order to increase the scalability and reduce the power consumption we use the Internet protocol version 6 (IPv6) over Low Power Wireless Personal Area Network (6LoWPAN), we worked on the programming of the 6LoWPAN protocol stack and analysis of the results using the perytons network protocol analyzer.
Acknowledgment

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Acronyms and Abbreviations

ACL Access Control List
AES Advanced Encryption Standard
CBR Constant Bit Rate
CSMA/CA Carrier Sense Multiple Access/Collision Avoidance
ETE End-to-End
IEEE Institute of Electrical and Electronics Engineers
ISM Industrial, Scientific and Medical
LR-WPAN Low Rate – Wireless Personal Area Network
MAC Medium Access Control
PAN Personal Area Network
ZDO ZigBee Device Object
FC Frame counter
IP Internet Protocol
FEC Erroneous Frame counter
BEC Erroneous Bit counter
LQI Link Quality Indicator
RSSI Received Signal Strength Indicator
CHAPTER 1

Introduction

In this section an introduction to Wireless Sensor Network (WSN) and motivation behind this project is explained.

1.1 Wireless Sensor Networks

Wireless Sensor nodes are becoming very popular nowadays because of their low power usage and are quite inexpensive and support ad-hoc and mesh topology. The network is setups with end nodes are responsible for sensing and reporting it to the central processing unit. The end nodes are constrained in processing speed, memory and energy.

Wireless Sensor Networks (WSN) were originally developed for military purposes since it has low power consumption and widely adopted for control applications in the start with military and now it is moved into the commercial mainstream with monitoring and control application, fire protection and home automation [1].

The Sensor Network’s are self configurable and have one or more sensors depending upon the type of application and the network coverage and capacity. They are deployed in a large number and usually they are used in a dangerous environment etc where there is no human access, disaster areas, battlefields, so it’s difficult to replace or change their batteries and moreover failure of one node can lead to network separation from the rest of the network. They have a long life cycle depending upon the life cycle of each node individually.

1.2 Motivation and objective

A WSN design is influenced by many factors, which include reliability, scalability, production costs, network topology, operating environment, transmission media and power consumption.

The primary objective is to investigate the scalability and power consumption in Bluetooth and Zigbee standards to using in the large scale WSN applications. The method we opted for our objective is simulations and analysis of the supported network topologies and comparing them in terms of scalability and power consumption. Further to increase the scalability and reduce the power consumption in low power personal area network we used the internet protocol version.
6(IPv6) its called as 6LoWPAN. Our objective includes the implementation of the 6LoWPAN protocol stack and testing of it by using the network protocol analyzer.

The main motivation of the project is to find how the scalability and a power consumption are influenced by using the different wireless standards in WSN application.

1.3 Outline

Thesis comprise of following framework:

- Chapter 1: Introduction – Presents the general introduction of the thesis project and the description of thesis problem statement. A description has been presented regarding the existing system and its limitations.
- Chapter 2: Theory – Gives a brief summary of basic fundamentals of wireless communication layers and brief explanation of Bluetooth, Zigbee and 6LoWPAN Wireless modules.
- Chapter 3: Results and Conclusion – shows the simulation and results of Bluetooth and Zigbee network in OPNET, programming and testing of 6LoWPAN protocol stack.
CHAPTER II

Theory

In this section we presents the basis fundamentals of wireless communication layers and brief explanation of the wireless modules.

2.1 Open systems Interconnection(OSI) model

The OSI model is a reference tool for understanding data communications between any two networked systems. It divides the communications processes into seven layer see figure 2.1. Each layer both performs specific functions to support the layers above it and offers services to the layers below it. The three lowest layers focus on passing traffic through the network to an end system. The top four layers come into play in the end system to complete the process [2].

<table>
<thead>
<tr>
<th>Layer 7 Application</th>
<th>Application and application interfaces for OSI networks. Provides access to lower layer functions and services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 6 Presentation</td>
<td>Negotiates syntactic representations and performs data transformations, e.g. compression and code conversion</td>
</tr>
<tr>
<td>Layer 5 Session</td>
<td>Coordinates connection and interaction between applications, established dialog, manages and synchronizes data flow direction.</td>
</tr>
<tr>
<td>Layer 4 Transport</td>
<td>Ensures end to end data transfer and integrity across the network. Assembles packets for routing by layer 3</td>
</tr>
<tr>
<td>Layer 3 Network</td>
<td>Routes and relays data units across a network of nodes. Manages flow control and call establishment procedures.</td>
</tr>
<tr>
<td>Layer 2 Data link</td>
<td>Transfers data units from one network unit to another over transmission circuit. Ensures data integrity between nodes</td>
</tr>
<tr>
<td>Layer 1 Physical</td>
<td>Delimits and encodes the bits onto the physical medium. Defines electrical, mechanical and procedural formats.</td>
</tr>
</tbody>
</table>

*Figure 2. 1: OSI model*
2.2 Internet Protocol version 6 (IPv6)

The OSI model is becoming very dated and its effectiveness will quickly diminish with the rise of the new version of the IP protocol (IPv6). The original versions of IP and user datagram protocol (UDP) provide services which lie in both the network and transport layers. The vast increase in the internet users every device on internet such as computer or mobile telephones must be assigned with IP address for identification and location addressing in order to communicate with other devices. Till 1995 we were using the IPv4 its uses 32-bit addressing and allows approximately 4.3 billion addresses but such a vast increase in internet users the researcher discovered that in 2011 no more IPv4 available so they came up with IPv6 which uses 128-bit addressing and allows approximately $3.4 \times 10^{38}$ addresses, or more than $7.9 \times 10^{28}$ times as many as IPv4.

2.2.1 IPv6 addresses

IPv6 uses 128-bits address it consists of eight groups of four hexadecimal digits separated by colons for example

$$2002:c10b:3eca:0000:0000:c10b:8a2e:3eca$$

An IPv6 address is never linked to a system (e.g. a PC), but to its interface. On the other hand an interface can have multiple IPv6 addresses. The addresses are categorized and sub-divided into unicast, any-cast and multicast.

2.2.2 IPv6 Header

The below Figure 2.2 show the IPv6 header and the fields are explained below. The first field specifies the version of the protocol, in this case version 6 and it is 4 bit length. The following fields Traffic class of 8 bits and Flow Label of 20 bits affect the treatment of IPv6 packets in routers (e.g. priority). Payload Length indicates the length of the subsequent payload data. The subsequent protocol (e.g. TCP or UDP) is identified via Next Header. The value Hop Limit defines the maximal number of hops (way from one network node to the next) an IPv6 packet can pass. In Source and Destination Address respectively the 128 bit long source and destination address are included.

<table>
<thead>
<tr>
<th>Version</th>
<th>Traffic Class</th>
<th>Flow Label</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Payload Length</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Next Header</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hop Limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Source Address</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destination Address</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 2. 2 : IPv6 Header*
2.3 Bluetooth Technology

Bluetooth technology aims at allowing wireless short range communication between several devices. Developed originally by Ericsson, Bluetooth and standardized by the IEEE under the reference IEEE 802.15.1 [3].

2.3.1 Architecture

Bluetooth communication requires two preliminary things. First we have to know the devices in the neighborhood and second there must be a pre-established circuit. Communication is also based on a master-slave principle. A group of equipment's forms a cell called piconet. A Piconet comprises a master and seven slaves at the maximum. Several piconets can overlap and form a scatter-net (see Figure 2.3). In a piconet, the communication is based on the master to harmonize the frequencies and channels. We know the neighbors through the discovery phase while in a scatter-net there is a need to route data between masters and relay nodes. Scatter-nets in Bluetooth is not well developed. It has been improved by routing procedures in later standards such as Zigbee[3].

![Figure 2.3: Scatternet](image)

Two slave devices cannot talk directly to each other except during the discovery phase, Channel allocation and communication establishment are under the responsibility of master device.

2.3.2 Frequency Band and RF channels

Bluetooth operation is in the 2.4 GHz ISM band. Using a spread spectrum, frequency hopping, full-duplex signal at a nominal rate of 1600 hops/sec. In many countries we have 83.5MHz that should be dedicated to this protocol. 79 channels are hence possible in this range with a bandwidth of 1MHz per channel. Table 2.1 gives some restrictions in different countries.

Range may vary depending on class of radio used in an implementation:

- Class 3 radios – have a range of up to 1 meter or 3 feet
- Class 2 radios – most commonly found in mobile devices – have a range of 10 meters or 33 feet
- Class 1 radios – used primarily in industrial use cases – have a range of 100 meters or 300 feet
<table>
<thead>
<tr>
<th>Countries</th>
<th>Frequency Range (MHz)</th>
<th>RF Channels(MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe and the United states</td>
<td>2400-2483.5</td>
<td>2402</td>
</tr>
<tr>
<td>France</td>
<td>2446.5-2483.5</td>
<td>2454</td>
</tr>
<tr>
<td>Spain</td>
<td>2445-2475</td>
<td>2449</td>
</tr>
</tbody>
</table>

*Table 2.1: Frequency band and RF*

### 2.3.3 Power characteristics

The most commonly used radio is Class 2 and uses 2.5 mW of power. Bluetooth technology is designed to have very low power consumption. This is reinforced in the specification by allowing radios to be powered down when inactive.

The Generic Alternate MAC/PHY in Version 3.0 HS enables the discovery of remote AMPs for high speed devices and turns on the radio only when needed for data transfer giving a power optimization benefit as well as aiding in the security of the radios.

Bluetooth low energy technology, optimized for devices requiring maximum battery life instead of a high data transfer rate, consumes between 1/2 and 1/100 the power of classic Bluetooth technology [4].

### 2.4 Zigbee

Zigbee is a new wireless technology included in the WPANs scope. As Bluetooth, Zigbee is a short-range wireless networking technology where little or no infrastructure is required (no network setups and no APs) providing ubiquitous, short-range communication.

Zigbee is the architecture developed on top of the IEEE 802.15.4 reference stack model and takes full advantage of its powerful physical radio layer [3].

#### 2.4.1 IEEE 802.15.4

IEEE 802.15.4 is a standard which specifies the physical layer and media access control for low power wireless embedded radio communication at 2.4GHz, 915MHz and 868MHz, data rate for the above frequencies are shown below Table 2.2.

Some of the characteristics are listed below

- It provides data rate up to 20-250 kbit/s depending on the frequency.
- Channel sharing is achieved using carrier sense multiple access (CSMA).
- It provides the security with 128-bit AES encryption.
- Addressing modes for 64-bit (long) and 16-bit (short) addresses are provided with uni-cast and broadcast capabilities.
• The available payload up to 72-116 bytes after framing, addressing and optional security.

The Medium access control (MAC) for the IEEE 802.15.4 is operated in two modes:
• Beacon – enable mode
• Beaconless mode

Beaconless mode uses pure CSMA channel access and Beacon-enabled mode uses a hybrid time division multiple access (TDMA)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Channel</th>
<th>Region</th>
<th>Data rate</th>
<th>Baud rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>868-868.6 MHz</td>
<td>0</td>
<td>Europe</td>
<td>20 kbit/s</td>
<td>20 kBaud</td>
</tr>
<tr>
<td>902-928 MHz</td>
<td>1-10</td>
<td>USA</td>
<td>40 kbit/s</td>
<td>40 kBaud</td>
</tr>
<tr>
<td>2400-2483.5 MHz</td>
<td>11-26</td>
<td>Global</td>
<td>250 kbit/s</td>
<td>65.5 kBaud</td>
</tr>
</tbody>
</table>

Table 2.2: IEEE 802.15.4 Radio characteristics

2.4.2 Zigbee protocol stack

We know that the OSI (Open System Interconnection) model was developed for the protocol architecture and a platform for making protocols standards by the International Organization for Standardization (ISO). Each layer in OSI model has a specific function to perform starting from the Physical layer up to Application layer see section 2.1. The top layers networking, security, and applications which have not been defined by the IEEE, are defined by the ZigBee (ZigBee Alliance). It is very important to consider the working of different layers and the interaction of the ZigBee protocol stack. The portion under the upper MAC layer including the lower MAC layer and the PHY layer (Silicon) has been defined by IEEE Figure 2.4 describes the ZigBee stack [5].

Figure 2.4: Zigbee protocol stack [5]
2.4.2.1 Physical Layer (PHY)
The PHY layer handles the signals, which are transmitted through the air. Modulation, DSSS and filtering are some of the operations performed by this layer. Zigbee is a spread spectrum technique as Bluetooth, which means that the information is spread in frequency when transmitted as opposed to narrow band communications where the information is constrained to a single channel. The IEEE Std 802.15.4 defines three different Industrial Scientific Medical license free bands as described in Table 2.2.

2.4.2.2 MAC Layer
Media Access Control (MAC) has different responsibilities [6]:
- The main function of MAC is to carry out the association and disassociation of the network involved. A large number of devices are managed or handled by this layer.
- It generates the network beacons according to the device, if it is a coordinator
- It also performs the function of synchronizing the beacons.
- It uses the CSMA-CA channel access mechanism
- It uses Guaranteed Time Slot (GTS) mechanism.
- It allows different mechanisms to conserve energy like collision avoidance using CSMACA and allowing the device to go into sleep mode.

There are different types of MAC frames
- Beacon Frame
- Data Frame
- Acknowledgement Frame
- Mac Command Frame

General MAC Frame format is given in Figure 2.5 [5].

<table>
<thead>
<tr>
<th>Octets: 2</th>
<th>1</th>
<th>0/2</th>
<th>0/2/8</th>
<th>0/2</th>
<th>0/2/8</th>
<th>0/5/6/10/14</th>
<th>variable</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Control</td>
<td>Sequence Number</td>
<td>Destination PAN Identifier</td>
<td>Destination Address</td>
<td>Source PAN Identifier</td>
<td>Source Address</td>
<td>Auxiliary Security Header</td>
<td>Frame Payload</td>
<td>FCS</td>
</tr>
<tr>
<td>Addressing fields</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MHR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MAC Payload</td>
<td>MFR</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 2.5: General MAC Frame format [5]*
2.4.2.3 Network (NWK)
The network layer is responsible for the creation and maintenance of networks providing addressing and routing capabilities. Self-healing is also implemented at this layer, in case of a node failure the network re-routes the message if alternative route paths are available. It is important to notice that networking capabilities are out of the scope of IEEE Std 802.15.4 and they are defined by the Zigbee Alliance. There are three Zigbee network routing types:

- **Star Network Routing**
  One coordinator with one or several end-devices (up to 65534).

- **Tree Routing**
  This is a “net mask” hierarchical style routing down or up the tree based on destination.

- **Mesh Network Routing**
  It is based on a modified version of Ad-hoc On Demand Distance Vector (AODV) originally developed by IETF in the scope of MANETs. This algorithm uses flooding to find out the routes from any source to any destination in the mesh. The routes are determined upon received route replies. The routes are stored in record tables.

2.4.2.4 Zigbee Application Layer
Each Zigbee device is defined by a set of endpoints (maximum 240). The endpoints are the different functionalities implemented at APP level. The endpoint 0 is reserved and corresponds to the Zigbee Device Object (ZDO). Each endpoint is described by a descriptor. A descriptor contains information about the clusters of the endpoint. A cluster is defined as a shared variable in the network and they are used to connect endpoints from different sensor nodes. In order to connect an endpoint outgoing cluster with another endpoint incoming cluster a binding process is required. Binding can be performed in two ways, on the one hand direct binding is used when the destination address is previously known, the PAN coordinator is then not required. On the other hand indirect binding is used when the PAN coordinator is needed to perform the operation once binding is performed the PAN coordinator will always be required to accomplish data transmissions. Application message acknowledgement is also implemented at this layer and it is intended to add reliability in multi-hop communications.

2.5 Zigbee Network topology
The network layer supports different kinds of topologies which enable different kinds of functions and properties. Topologies which can work on this ZigBee Network layer are Star, cluster tree and mesh (see Figure 2.6). Mesh network provides a scalable architecture by allowing more than one path, but star network is more commonly used topology used for carrying the battery operations. Cluster tree is the combination of both star and the mesh networks, so it has the properties of both topologies. Thus any type of topology can be used here according to the requirement of the system. If a large area has to be covered, then peer-to-peer networks can be made as it will handle the networks that are divided geographically. In
these geographically dispersed networks, the smaller networks inside them can combine to form the cluster tree networks [7].

![Zigbee Network Topologies](image)

**Figure 2. 6 : Zigbee Network Topologies**

The network are made up with the nodes, there are three kinds of nodes:
- Coordinator
- Full Function Device
- Reduce Function Device

In detail:

Coordinator
Coordinator is the one which initializes the network, stores the information of the nodes in the network and also manages the network once it has been initiated. It handles the routing of data to different nodes and suggests what routing techniques to use to transfer the data to different nodes of the network. There can be only one coordinator in a network; it has the ability to communicate with any device in the network.

Full Function Device
Full Function Device (FFD) as shown in figure 5, has the capacity to become a network Coordinator. Coordinator can use it to fulfill the purpose of carrying out the multi-hop routing of messages across the network. It can communicate with the other FFDs and RFDs and work properly in any topology used to make the network. One other responsibility is that it searches the other FFDs and the RFDs to create the communication link so that the transfer of data can be made possible to reach the desire node.
Reduce Function Device

Reduced Function Device (RFD) has the limited functionality as the name indicates. It acts as the end or the leaf node of the network and can only communicate with the FFD, but not with network coordinator. One of its other limitations is that it can only work in the star topology, as it only requires minimum RAM and ROM to be constructed. It is just for the purpose of sending or receiving. RFDs request the data from the network coordinator and can transfer it to some available network node, and then go to the sleep mode to conserve energy. It is generally battery powered.

2.6 6LoWPAN

Some of the standards currently developed for the WSN communication are listed below:

- Wireless HART is specifically designed for industrial applications like process monitoring and control, its an extension of the HART protocol.

- ZigBee standards to address the low-cost, low-power and control network used for home automation and medical data collections.

- 6LoWPAN is the IETF standards to use IPv6 over IEEE 802.15.4.

ZigBee, WirelessHART, and 6lowpan all are based on the same underlying radio standard IEEE 802.15.4.

The IETF 6LoWPAN (Low power wireless personal area network) working group was formed in 2004 to address the challenge of enabling wireless IPv6 (see section 2.2) communication over the newly standardized IEEE 802.15.4 low power radio for devices with limited space, power and memory. A new paradigm was needed to enable low-power wireless devices with limited processing capability to participate in the internet of things, forming what we call the Wireless Embedded Internet.

The vision behind the Internet of things is that embedded devices, also called smart objects, are universally becoming IP enabled and also integral part of Internet. Examples of embedded devices and systems using IP today range from mobile phones, personal health devices and home automation, to industrial automation, smart metering and environmental monitoring systems [8].

The Wireless Embedded Internet is as a subset of the Internet of things the embedded devices which enables the internet are resource limited, often they are battery powered, connected by low-power, low-bandwidth wireless networks to internet. 6LoWPAN is developed to enable the wireless embedded Internet by simplifying IPv6 functionality. IPv6, which is the newest version of the Internet protocol, was developed in the late 1990s solutions for rapid growing and challenges facing the Internet [8].

There are huge range of application which could benefit from Wireless Embedded Internet, there are different proprietary technologies to implement the application but its difficult to

The characteristics of 6LoWPAN are summarized below:
Low processing capability: - the common 6LoWPAN node has 8 bit process with clock rate around 10MHz.

Low Power: - The wireless radio 6LoWPAN devices are power by batteries, the RF transreceiver draws current up to 10 to 30 mA that is depending on the transmission power level, typically power level is set to 0 to 3 dBm for indoor and outdoor communication range.

Low bit rate: - The IEEE 802.15.4 standard defines a maximum over-the-air rate of 250 Kbits/sec.

6LoWPAN standards enable the efficient use of IPv6 over low-power, low-rate wireless networks on simple embedded devices through an adaptation layer and the optimization of related protocols [8].

Some of the application of 6LoWPAN is listed below:

• Home and building automation
• Healthcare automation and logistics
• Improved energy efficiency
• Industrial automation
• Smart metering and smart grid infrastructures
• Real-time environmental monitoring and forecasting
• Better security systems and less harmful defense systems
• More flexible RFID infrastructures and uses
• Asset management and logistics
• Vehicular automation

Figure 2. 7: RFID Infrastructure using 6LoWPAN[8]
Wireless RFID infrastructure using 6LoWPAN for data transfer between reader and RFID applications without using wireless technology it is very expensive, time consuming and need lot of cabling.

The wireless solution built with 6LoWPAN (IEEE 802.15.4) standard uses a frequency of 2.4 GHz. This technique enables easy and cost effective wireless data transfer between monitoring and controlling device.

An example for wireless RFID application in a camping area which access with both people and vehicles are managed from Reception. It is very expensive for linking large number of reader through cable and also time consuming. Instead, a wireless RFID solution can be installed quickly and practically without distance limitations. Readers connect automatically to one another and from a network which is managed from Reception (see Figure 2.7). The wireless data transfer between the readers to access control management by forming a network of nodes at different access point in camping area.

To better understanding the functional principles of 6LoWPAN the following sections introduces into the 6lowpan protocol stack, fundamentals of IPv6, and link layer technology.

2.6.1 Link Layer Technology
The IEEE 802.15.4 standard is the most common 2.4 GHz for wireless technology for embedded network applications, and has been used as the base line for the 6LoWPAN.

The sections 2.4.1 describe the IEEE 802.15.4 link layer technologies used by 6LoWPAN.

2.6.2 6LoWPAN adaption layer
6LoWPAN is to transmitting IPv6 over IEEE 802.15.4, the protocol stack with the reference of the OSI model (see section 2.1) shown in Figure 2.8.

There is no much difference in the both stacks where here in 6LoWPAN stack we use the IPv6 with 6LoWPAN adaption at Network layer because IPv6 defines the MTU(Maximum transmission unit) of 1280 Bytes but IEEE 802.15.4 transports up to 127 Bytes in order to resolve this we are using the IPv6 with 6LoWPAN adaption feature uses the header compression,IPv6 header is big in size see Figure 2. the IEEE 802.15.4 frame using the IPv6 with and without 6LoWPAN adaption feature, where in IEEE802.15.4 frame without 6LoWPAN adaption feature after all the header adding to the frame it leads to 53 Bytes of space to
payload it is not good enough to work with it (see figure 8), if we see the IPv6 with 6LoWPAN adaption feature the headers are compressed all together up to 11Bytes and it leads to 108 Bytes of space to payload it is good enough to work for the industrial usage (see figure 2.9).

![IEEE 802.15.4 frame](image)

Figure 2. 9 : IEEE 802.15.4 frame[8]

### 2.6.3 Chip Solution

To use the 6LoWPAN we need an special kind of consideration in the embedded device, there are two different model to embed 6LoWPAN protocol stack: single chip solution and two chip solution [8].

In single chip solution SoC (system on a chip) radio technology is used where the radio front end, transceiver and microcontroller are integrated together with flash, memory and other peripherals, where as in the two chip solution the application process and transceiver are separate they both communicate through the serial peripheral interface the block diagram of the both models in Figure 2.10a & 2.10b [8].

![Diagram of Chip Solutions](image)

Figure 2. 10 : (a)Single Chip solution (b) Two chip solution[8]

### 2.6.4 Contiki

In this section we look at common open source and commercial protocol stack which cover all the chip models discussed in the previous section.

A protocol stack for 6LoWPAN typically includes, at the minimum, these basic components [8]:

- Radio drivers
- Medium access control (e.g. IEEE 802.15.4)
- IPv6 [RFC2460] with 6LoWPAN [ID-6lowpan-hc, RFC4944]
- UDP [RFC0768]
- ICMPv6 [RFC4443]
• Neighbor Discovery [ID-6lowpan-nd]
• Socket-like or other API to the stack

The rest of this section gives an overview of open-source protocol stacks for embedded operating systems: Contiki

Contiki is an open source, highly portable, multi-tasking operating system for memory-efficient networked embedded systems and wireless sensor networks. Contiki is designed for microcontrollers with small amounts of memory. A typical Contiki configuration is 2 kilobytes of RAM and 40 kilobytes of ROM [9].

Contiki provides three network mechanism i.e. uIP TCP/IP which provides IPv4 networking, uIPv6 which provides IPv6 networking, and Rime stack. The uIPv6 stack also contains the RPL routing protocol for low-power lossy IPv6 networks and the 6LoWPAN header compression and adaptation layer for IEEE 802.15.4 links. Contiki is memory and power-constrained operating system many contiki systems are operated with batteries.

In order to run contiki efficiently on memory constrained systems, the contiki programming model is based on protothreads. A protothread is a memory-efficient programming abstraction that shares features of both multi-threading and event-driven programming to attain a low memory overhead of each protothread. The kernel invokes the protothread of a process in response to an internal or external event. Many Contiki systems are severely power-constrained. Battery operated wireless sensors may need to provide years of unattended operation and with little means to recharge or replace its batteries. Contiki provides a set of mechanisms for reducing the power consumption of the system on which it runs. The default mechanism for attaining low-power operation of the radio is called ContikiMAC. With ContikiMAC, nodes can be running in low-power mode and still be able to receive and relay radio messages.

![Figure 2. 11 : Architecture of Contiki and uIPv6[8]](image1)

![Figure 2. 12 : 6Lowpan stack](image2)
The architecture of Contiki and uIPv6 are shown in Figure 2.11. The low-level hardware abstraction is split into platform and CPU for portability, which include hardware drivers. The Contiki OS provides basic thread and timer support. The Rime system is a flexible medium access control and network protocol library which includes many low-level communication paradigms. The uIPv6 stack makes use of Rime, and provides a socket-like API for use by applications called protosockets. Both built-in and user applications are run over Contiki using a lightweight thread model called protothreads.

The 6Lowpan stack in contiki with reference to OSI model in section 2.1 (see Figure 2.12). In figure there is not much difference in protocol stack, here at the network layer it uses the uIPv6 with sicslowpan adaption layer and sicslowmac at the data link layer over IEEE 802.15.4 physical layer.

In order to simulate the WSN there are various Network simulators are available such as:

- Netsim
- NS2
- OPNET

Among this we found the OPNET is one of best to simulate above network is discussed below.

2.7 OPNET

A prototype data network modeling & Simulation system named as "Optimized Network Engineering Tools", It can be flexibly used to study communication networks, devices, protocols, and applications. OPNET is a commercial software provider. OPNET provides powerful GUI support which makes it relatively easy for the users to setup different scenarios and create different topology using various types of devices and variety of standards which are available in OPNET library[10].

2.7.1 Main features

OPNET basically have three main functions, first is to model the network and then simulating part and final is in-depth analysis of various parameters. For the modeling function, it offers a powerful graphical interface which is very helpful for creating different kind of protocols for model. For simulating, it uses advanced simulations technologies covering most of the communication related technologies. For analysis of the results OPNET provides variety of graphs plots e.g time average & histograms and various statistics and animation to show the flow of data and networking functioning [11].

OPNET supports four types of technologies for performing the simulation as we can see from Figure 2.13.

- Discrete Event Simulation (DES)
- Flow Analysis
- ACE QuickPredict
- Hybrid Simulation (within the DES environment)
Figure 2.13: OPNET simulation technologies

The Discrete Event Simulation technology gives the attention to details with explicitly simulating protocols and packets in the same manner as it is done in the real environment because of these vary reasons it takes longer time then other simulation methods.

Analytical and discrete techniques are combined to have the more accuracy and complete results and this methodology of simulation is known as Hybrid simulation. Its execution is considerably less compared with DES which takes significantly more time.

In Flow Analysis, analytical techniques and algorithms are used to model behavior of steady-state network and unlike Discrete Event Simulation it does not model the protocol or packets individually and results obtained are useful for only routing. The execution runtime is much faster than DES.

Application Characterization Environment (ACE) QuickPredict technique is used within Opnet is employed to analyze the effects of changing various network parameters e.g bandwidth, packet loss and latency on response time of applications. This technique is supported within the OPNET Application Characterization Environment (ACE).

Statistics
Opnet have three types of Statistics.

Global Statistics: Statistics for the entire network e.g., application response time.

Node Statistics: Statistics for the on individual nodes e.g., delay variation.

Link Statistics: Statistics for certain links e.g., link utilization, throughput, queuing delay

2.8 Hardware
The target board on which we were working is MEASHBEAN2 Board, it consists of Zigbit module which functions as ZigBee/802.15.4 transceiver. It also includes sensors, buttons, DIP-switch, and some interfaces on the Expansion connector( see figure 2.14).
2.8.1 Board components
Zigbit module is an ultra-compact, low-power, high-sensitivity 2.4GHz 802.15.4/ZigBee OEM module. It includes Atmega1281V Microcontroller and AT86RF230 RF Transceiver see figure 2.15.

Sensors: The board uses light sensor TSL2550T and temperature sensor LM73CIMK, both the sensors are connected in parallel to the inter-integrated circuit bus.

2.8.2 Board specifications
MeshBean2 basic parameters are presented in table 2.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td></td>
</tr>
<tr>
<td>Compliance</td>
<td>2.4 GHz IEEE 802.15.4-2003</td>
</tr>
<tr>
<td>Operating Band</td>
<td>2400-2483.5 MHz</td>
</tr>
<tr>
<td>TX Output Power</td>
<td>From -17 dBm to +3dBm</td>
</tr>
<tr>
<td>RF Transceiver</td>
<td>AT86RF230-ZU</td>
</tr>
<tr>
<td>Antenna</td>
<td>2.4 GHZ(PCB on-board antenna or on-chip antenna)</td>
</tr>
<tr>
<td>MCU</td>
<td></td>
</tr>
<tr>
<td>Microcontroller</td>
<td>Atmega1281V</td>
</tr>
<tr>
<td>RAM</td>
<td>8 kBytes</td>
</tr>
<tr>
<td>Flash Memory</td>
<td>128 kBytes</td>
</tr>
<tr>
<td>Category</td>
<td>Specification</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------------------------------------------</td>
</tr>
<tr>
<td>EEPROM</td>
<td>4 kBytes</td>
</tr>
<tr>
<td>Power</td>
<td></td>
</tr>
<tr>
<td>Power supply</td>
<td>Dual AA type Battery, automatically switched to USB</td>
</tr>
<tr>
<td>Operating Voltage Range</td>
<td>1.8 -3.6 V</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td></td>
</tr>
<tr>
<td>Switches</td>
<td>3 DIP Switches</td>
</tr>
<tr>
<td>Buttons</td>
<td>2 Programmable buttons</td>
</tr>
<tr>
<td>Size</td>
<td>60 x 63 x 24mm</td>
</tr>
</tbody>
</table>

*Table 2. 2: Meashbean 2 Board specifications*
CHAPTER III

Results and Conclusion

In section we present the simulation and results of Bluetooth and Zigbee network in OPNET, programming of the 6LoWPAN protocol stack and testing using the Network protocol analyzer.

3.1 Bluetooth Network simulation
We used the suittooth, its a bluetooth simulation model. Bluetooth Simulation Model Suite (Suitetooth) is an open, modular framework for advanced PAN network performance engineering. Built for the OPNET™ simulation environment, Suitetooth models allow users to predict performance characteristics and study behavioral interaction for personal area network applications that use both existing and emerging wireless technologies [12].Master node model is shown in Figure 3.1.

![Master node model](image)

Figure 3.1 : Master node model

3.1.1 Piconet Network topology
Two or more Bluetooth units shares the single channel to form a piconet, To regulate the traffic in the channel one of the unit should act as master and rest units will act as slave see figure 3.2.
3.1.2 Results

Bluetooth uses the frequency hopping technology in which the carrier frequency always changes for every packet of transmission. Since we are using only one piconets in an area there is no collision on a particular channel. If we use more than one piconet in an area there might randomly collide on the same frequency that results in overload of channel.

Channel utilisation: The channel utilisation varies over the simulated period, the mean estimated values is about 0.45. Channel never overloaded see figure 3.3.

In order to establish a new connection it uses the inquiry and paging procedures. Inquiry procedure used to discover the Bluetooth units within the range and the paging procedure will establish the actual connection with other units.

Connection delay: The connection delay should be very small, form the figure 3.4. The connection delay for one of the slave is 0.05 sec it is tolerable for the small network area but when it come to using in the area...
large network area the connection delay much higher. The lenghty connection establishment prevents Bluetooth to use in the large scale wireless sensor network applications

3.2 Zigbee Network Simulation
Opnet provides in-depth model for Zigbee as shown in figure 3.5. A well defined Zigbee stack with Application layer and the Network layer and Mac layer is connected with the transmitter and receiver.

As we know Zigbee supports three basic types of topologies Star, Mesh and Tree see section 2.5. As from the theoretical knowledge we found out Tree Topology is venerable as one failing node can cause the network to not perform in a desired way so we only use Star and Mesh Topologies.

3.2.1 Star topology
In this scenario Star topology communication is carried out through the PAN coordinator which acts as a central controller and maintains the communication between devices. The central PAN is usually mains powered and end devices uses battery due to their position and not so much energy consumption. In figure 3.6 shows the Star topology setup with one coordinator and 5 end devices named as End_device_01 to End_device_05.
Figure 3.6: Star topology OPNET simulation

Figure 3.7: Traffic from End devices to Coordinator

Figure 3.7 below shows the traffic being sent by the end devices and received by the destination coordinator. The traffic sent by the five end devices is same indicated by the red line and the traffic received by the coordinator is very high because in star topology the coordinator is the responsible for all the end devices. Initially the end-to-end (ETE) delay of traffic from the coordinator delay is very less because coordinator is connected to one of the end device.

3.2.2 Mesh Topology

In peer to peer or mesh topology all devices can communicate with each other as long as they are in the range of one another. It also has one PAN coordinator. Usually this sort of network is temporarily setup and adjust accordingly to the present of the neighboring devices and without the human intervention carried out the network operation if some of the node breaks down. In figure 3.8 we have setup mesh topology. We have one coordinator and three End Devices and two Router.

Figure 3.8: Mesh Topology OPNET simulation

Figure 3.9: Mesh routing table
In this scenario, the number and type of the devices are identical with star topology. The difference is the topology of the network, here we are using the mesh topology in this every device sends packet of 1024 bytes to a random destination with the interval of 1 second.

The Mesh topology is the only setup that was allowed to generate and use a mesh routing table the generated mesh routing table for above scenario is show in figure 3.9.

In the table it show the packet routing by hopping from one device to another device inorder to reach the specific destination. Figure 3.10 shows the traffic being received and sent (routed) by the two routers. The amount of traffic being routed is equivalent to the traffic received by the coordinator (see Figure 3.11).

![Figure 3.10: Traffic from End devices to Routers](image1)

![Figure 3.11: Traffic from End devices to Coordinator](image2)

Figure 3.11 shows the traffic being sent by the end devices and received by the destination coordinator. It can be seen that the traffic is sent without disruption. Small spikes in the coordinator graph indicates the management and control traffic sent and received to determine the presence of devices.

### 3.3.3 Comparison of star and mesh network topology

Now we focus on differences of star and mesh topology with the values captured from global statistics.

- End-to-End delay
- Number of hops

**End-to-End delay**

Global statistics provides overall information related to the topology. Figure 3.12 shows the end-to-end delay result of the two topologies. The end-to-end delay of star topology is indicated with blue line where the mesh topology is indicated with red line. From the graph we see that the delay in the star topology is more compared to the mesh topology.
Number of hops

The number of hops is the number of times a packet travels from the source through the intermediate nodes to reach the destination. In our case the number of hops for the star topology is one indicated in scenario 1 that is we are not using any intermediate node. The mesh topology uses a routing table and the average number of hops is two indicated in scenario2 (see Figure 3.13).

From above comparison the mesh network is extensively used for extension of the communication range. It has the advantage of routing message from any device to any devices which gives different path for the traffic. This configuration is used in application involving wireless sensor network, industrial control and monitoring and inventory tracking.

3.4 6LoWPAN Stack Implementation

In this section we present the work related to the porting the 6lowpan stack from the contiki(see section 2.6.4) and make an independent stack without overhead of contiki i.e removing the dependency of protothread.

Protothreads are extremely lightweight stackless threads designed for severely memory constrained systems, some feature are listed below

- Very small RAM overhead
- Highly portable
- Can be used with or without an OS

The main motive of removing the dependency of protothreads, give very less room to the application and uses the large size of foot print.

The function calling for the ported 6lowpan stack is shown in figure 3.14.
Sicslowpan, MAC and Radio Relationship as follows:

- Output function of the 6LoWPAN layer (sicslowpan.c) is the input function to the MAC (sicslowmac.c). The output function of the MAC is the input function of the radio (radio.c).
- Radio contains the low level HAL drivers to access and control the radio as well as the low level frame formatting and parsing functions.

### 3.4.1 Programming the device

To program the Meshbean2 (see section 2.8) we are using the Atmel Studio 6, it an integrated development platform (IDP) for developing and debugging Atmel AVR microcontroller based applications.

The overview of sending and receiving directions is shown below figure 3.16. Firstly, we started with link layer programming i.e. implementation of radio (IEEE.802.15.4) with beacon MAC in devices then after we replace the beacon MAC with the Siclowmac.

Our first approach is sending a “Hello” Message from the device for that we ported the radio from the contiki in support to the zigbit platform, then download the firmware into the device using JTAGICE mkII.

Burning the firmware in two devices, which operates in the different channels, the data sent from the devices is captured using the Adaptive Network Solutions @ANY2400 USB Dongle (see figure 3.16) and analyzed using the The Perytons™ Protocol Analyzer.

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**Figure 3. 14**: Functional calling of 6Lowpan stack

**Figure 3. 15**: sending and receiving direction of stack

---

**Figure 3. 16**: Adaptive Network Solutions @ANY2400 USB Dongle
4.2 Perytons Protocol Analyzer

The Perytons™ Protocol Analyzer is an enhanced professional wireless protocol analysis tool. With the 6LoPWAN and IP layers integrated support, the Perytons™ Protocol Analyzers address the need for an easy to use and yet professional tool essential to help understanding of the 6LoWPAN and IP over sensor networks. The combination of a tool capable of both handling IEEE 802.15.4 based networks as well as 6LoWPAN and IP layers analysis is crucial for helping in identifying and quickly resolving problems. Most of the Perytons™ Protocol Analyzer features are unique and cannot be found in other analysis tools available in the market. We discuss detailed in further sections.

3.4.3 Test set up

The test set up is shown in the figure 3.17, where two devices are operated in different channels and the Adaptive Network Solutions ® ANY2400 USB Dongle is connected to the pc to capture the data from the devices.

![Figure 3.17: Test setup](image)

![Figure 3.18: Data capturing in peryton](image)

3.4.4 Data capture

The Perytons™ Protocol Analyzer uses off the shelf IEEE 802.15.4 USB dongles as front-ends to capture data in both the 2.4GHz and the Sub1 GHz frequency bands.

They include a diversity feature allows improving in-door reception performance by using two receivers per channel, enabling the analyzer to capture a more complete wireless picture (see figure 3.18).

In addition, multi-channel capture allows to monitor networks that use frequency hopping 802.15.4 (e.g. wireless HART), automatic channel selection algorithms and multiple networks coexisting in the same proximity.
3.4.5 IEEE 802.15.4 decoding and analysis

The Perytons™ Protocol Analyzer decodes the IEEE 802.15.4 MAC traffic, displays the data in a variety of views (vs. time, network topology, various displays of packet fields, statistical charts, etc.) and includes an enhanced sophisticated toolbox for further analysis see fig.

The data captured by ANY2400 USB Dongle from the selected device channel is shown in the display (see figure 3.19).

The device is assigned with short and long addresses and its destinations addressess with payload in the script.

After, buring the firmware in the device the data captured by the ANY2400 USB Dongle can be displayed and analysed from the selected operation of channel see figure 3.19.

![Figure 3.19: channel of operation](image1)

![Figure 3.20: Received Siclowpan packet](image2)

The recieved frams by ANY2400 USB Dongle is analysed using peryon, Meashbean2 is programmed to transmit the sisclowpan packet from sicslowpan layer(see figure 3.15) the recieved Siclowpan packet is shown in figure 3.20.

The received packets can be analysed by check the frames formatting there are some errors in the frame format that is are represented by red in colour that is because there is an error cyclic reducency check in MAC layer. we can view at the left side of the screen the timing and the layer at which the dongle is receiving the packets.

3.5 Running Wireless Sensor Network Application

3.5.1 Overview

The Networking performance of the Zigbit platform is demonstrated with the WSN Demo application. This application comprises embedded firmware, supporting function for coordinator, router and end device and GUI part-the WSN monitor which is run on PC.

In the lab we demonstrated the WSN demo application with the two devices one device functions as coordinator and other as end device the setup is shown below figure 3.21.
In duty circle, end devices update the on-board sensor readings and send them in packets to coordinator. The data displayed on WSN Monitor panes as temperature, light and battery level measurements.

End device is mostly sleeping, consuming very low power, and it wakes up shortly for activities each 10 seconds. During the sleep period, you can force end device for waking up by pressing the sw1 button.

The network size is not limited by WSN Demo. In real time, WSN Monitor visualizes the network topology in a tree form. It also displays the node parameters like addresses, node sensor information and node link quality data (see figure 3.22).

Measured in dBm, RSSI indicates link’s current condition. With the resolution not better than 3 dBm, this is not a very accurate measurement. LQI is a certain numeric value defined within the 0-255 range to measure the link quality. Larger values mean better link, while values close to zero indicate poor condition.

3.5.2 Starting WSN on MeshBean2 nodes
First, connect the coordinator node to the USB port (see the figure 3.21). Then run the WSN monitor application. At start up, WSN Monitor need to set proper COM port to connect to the coordinator. The WSN Monitor screen pops up the node Icone and connected end device node appear on the Topology pane (see figure 3.22).

3.5.3 Using the Boards
At node startup, current channel mask is regularly read from EEPROM. Press and hold the sw1 onboard button first. Turn power on the board with holding the button pressed for at least 1 second. The LED1 will get flashing 3 times. Next, LED1, LED2 and LED3 will start blinking for 2 sec to indicate the acceptance of channel mask in EEPROM.
Table 3.1: DIP switch configuration used in WSN Demo

<table>
<thead>
<tr>
<th>DIP-switches</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ON, 2 ON, 3 X</td>
<td>Board is configured to be a coordinator</td>
</tr>
<tr>
<td>1 ON, 2 OFF, 3 X</td>
<td>Board is configured to be a router</td>
</tr>
<tr>
<td>1 OFF, 2 OFF, 3 X</td>
<td>Board is configured to be an end-device</td>
</tr>
</tbody>
</table>

Coordinator organizes the wireless network automatically. Upon starting, any node informs the network on its role. At the moment LED1, LED2 and LED3 are flashing twice on end device and they are flashing three times on coordinator.

After joining the network, a node starts sending data to the coordinator which is indicated by LEDs.

Table 3.2: LED indication implied in WSN Demo

<table>
<thead>
<tr>
<th>Node State</th>
<th>LED state</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LED1 (Red)</td>
</tr>
<tr>
<td>Network searching</td>
<td>OFF</td>
</tr>
<tr>
<td>Having joined to network</td>
<td></td>
</tr>
<tr>
<td>Message receiving</td>
<td></td>
</tr>
<tr>
<td>Message transmitting</td>
<td>Flashing</td>
</tr>
<tr>
<td>Channelizing channel mask</td>
<td>Blinking</td>
</tr>
<tr>
<td>Sleeping (for end device only)</td>
<td>OFF</td>
</tr>
<tr>
<td>Role indication (at startup)</td>
<td>All LEDs are flashing once on router, twice on end device and three times on coordinator</td>
</tr>
<tr>
<td>Idle(invalid DIP switch configuration)</td>
<td>ON</td>
</tr>
<tr>
<td>MAC address missed</td>
<td>ON</td>
</tr>
</tbody>
</table>

In rare cases, if radio channel is busy on the selected frequency channels the coordinator node will stay in the network searching mode. If this happened, we have to change the channel in channelizing channel mask, using the WSN monitor.

Each board measures temperature, light and its own battery level; they send the data values to the coordinator and, further to the PC (see figure 3.22).
Typical accuracy of the battery voltage indicator is about 0.1 V, which is enough for most applications and self monitoring tasks

4 Conclusion and Future work

From above work we conclude that the in order to increase the scalability and reduce the power consumption in large scale WSN application zigbee best solution over Bluetooth some of the differences listed below. Further, the 6LoWPAN is emerging and best solution among the current WSN communication standards because it scalability supports up to $2^{128}$ node in network with IPV6 routing.

<table>
<thead>
<tr>
<th></th>
<th>Bluetooth</th>
<th>Zigbee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Stack</td>
<td>256 Kb</td>
<td>32&lt;kb (4kb)</td>
</tr>
<tr>
<td>Range</td>
<td>10-100 Meter</td>
<td>30-100 Meters</td>
</tr>
<tr>
<td>Link Rate</td>
<td>1Mbps</td>
<td>256 Kbps</td>
</tr>
<tr>
<td>Battery</td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td>Devices</td>
<td>8</td>
<td>$2^{16}$</td>
</tr>
<tr>
<td>Air interface</td>
<td>FHSS</td>
<td>DSSS</td>
</tr>
<tr>
<td>Usage</td>
<td>Frequently</td>
<td>Infrequently</td>
</tr>
<tr>
<td>Network joining time</td>
<td>Long</td>
<td>Short</td>
</tr>
<tr>
<td>Security</td>
<td>PIN 64 bits 128 bits</td>
<td>128 bits , AES</td>
</tr>
</tbody>
</table>

The current available opensource solution for the 6LoWPAN has operating system limitation the development of portable 6LoWPAN stack allow us to work with any platform, it can be improved the efficiency of routing using low power routing protocol and COAP protocol to the portable stack.
References


