# ANALYSIS OF POWER CONSUMPTION OF AN END DEVICE IN A ZIGBEE MESH NETWORK

by

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# ABSTRACT

CHAITANYA MISAL. Analysis of Power Consumption of an End Device in a ZigBee Mesh Network. (Under the direction of DR. JAMES M. CONRAD)

Zigbee is a set of protocols specifically for low-bandwidth applications. Emphasize is to support standard based wireless networks for low data rates, low power consumption, security, reliability and low cost. This thesis is an effort to present the power consumption model, based on empirical measurements, of ZigBee end node when different sizes of data packets are transmitted and received in mesh network topology. Work also includes an estimate of the effect of retries in the network.

ZigBee technology is well suited to a wide range of building automation, industrial, medical and residential control and monitoring applications. Essentially, applications that require interoperability and/or the RF performance characteristics of the IEEE 802.15.4 standard would benefit from a ZigBee solution. Low power consumption being the important aspect of ZigBee solution, the thesis would prove to be useful for building ZigBee applications for various target environments. This thesis work shows the effect on battery life, based on average current consumption of the end node. Empirical measurements are used for battery life calculations.

# ACKNOWLEDGEMENTS

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# CHAPTER 1: INTRODUCTION

IEEE 802.15.4 is a standard, which specifies the physical layer and medium access control for low rate wireless personal area network (LR-WPAN). ZigBee is the established set of specification built on top of 802.15.4 for wireless personal area networking (WPAN). It provides specifications for devices that have low data rates, low cost, small form factor, low power consumption characterized by long battery life, and simple implementation.

ZigBee wireless standards-based technology has following characteristics:

- It addresses the unique needs of remote monitoring and control and sensory network applications [1].
- It enables broad-based deployment of wireless networks with low cost, low power solutions [1].
- It provides the ability to run a device for years on inexpensive primary batteries for a typical monitoring application [1].

The ZigBee offers three different device types that operate in self-organizing application network, namely ZigBee Coordinator, which acts as the network head and is typically mains powered, ZigBee Router, which are full function devices, powered my mains or battery depending on the application and the End devices which are reduced function devices and are always battery powered.

Battery driven devices operate on an extremely frugal energy budget. They are required to have lifetime of order of months to years since battery replacement is not desired. Energy loss in the battery depends on the node and communication characteristics.

Node characteristics include:

- Microcontroller and Radio supply voltages
- Active and sleep current consumption for radio and microcontroller
- Microcontroller clock frequency
- External circuitry (viz. power amplifiers)
- Code Size

Communication characteristics include:

- Network Topology (i.e. Star, Tree, Mesh)
- Routing Algorithms
- Data packet size
- Retransmission of packets

The work provides the effect on battery life of an End Device in a ZigBee mesh network due to following factors:

- Data packet size exchanged over the air (viz. 24, 48, 72 bytes of data)
    - Node as a transmitter
    - Node as  receiver
- Data transmission retries in the network

The results are based on empirical data obtained in laboratory and validated in an industrial manufacturing environment.

The first step towards completing this thesis was learning the ZigBee protocol using the ZigBee 1.0 specifications. Most of the ZigBee related articles and tutorials are proprietary for the ZigBee Alliance members and not available to independent researchers. Hence, understanding the protocol using the specification sheets and limited available papers and articles was a challenge. The ZigBee stack was not freely available when the work started, hence I did not have visibility of code used to implement the protocol.

It was a challenge to work on unreleased/beta Xbee Series 2 modules, as they were in the development stage and did not behave as expected. In the process, I was able to identify several bugs in the product and report them to the company that were later corrected.

As a part of this thesis work I needed to understand the hardware and firmware and implement it to fit the requirements. Selecting the most appropriate method to sample and log the data started with the use of Maxim's DS2740 Coulomb Counter. The DS2740 provides high-precision current-flow measurement data to support battery-capacity monitoring. Through its 1 wire interface it allows the host system to read and write to the device to obtain status and current measurement data. The effort did not give good results, as the maximum sampling rate achieved was only four samples per second. It was required to have a more precise measuring technique to obtain a large number of samples per unit time to have a better understanding for analysis of the system behavior.

## 1.1 Motivation

ZigBee networks are used in embedded applications that require low data rates and low power consumption. The resulting networks will use small amounts of power so individual devices may run for year or more using originally installed battery.

Hence, the need to study the power consumption of battery operated end nodes under various natures of transmissions is considered important in industrial world. The study was undertaken using empirical data.

Empirical data is the information based on observation and experience and often very accurate, although it is not accepted as scientifically sound; however, no area of science is devoid of a real-world/empirical component [2].

The work consists of empirical measurements of current consumption of the battery powered end device for various types of transmissions and estimating the battery life by calculations based on real data.

In real networks, it was observed that some nodes in the network fail much before the expected lifetime. On further investigation, it was suspected that the transmission retries have caused the battery life to reduce substantially Therefore data is used to estimate the effect of retries in the battery life of the device.

## 1.2 Current Work

There is currently a lot of active research being carried out in the field of IEEE 802.15.4 based ZigBee power consumption and its effect on performance on the network.

The paper titled “Extended Energy Model for the Low Rate WPAN” [3] provides the extension of an energy model previously developed for the Chipcon CC2420, an IEEE 802.15.4 device. The model takes into account the transitions energy cost between the Chipcon CC2420 operational states. A comparison is made between the extended model and the previous model to illustrate the importance of incorporating the transition energy requirements.

The paper titled “An experiment on Performance study of IEEE 802.15.4 Wireless Networks” [4] establishes a realistic environment for the preliminary performance evaluation of the IEEE 802.15.4 wireless networks. The results established depend on several sets of practical experiments which include the effect of i) Direct and indirect data transmissions ii) CSMA-CA mechanism iii) data payload size, and iv) beacon enabled mode. It investigates data throughput and received signal strength indication (RSSI) as performance metrics.

The article “The Importance of Sleep Mode Power Consumption in ZigBee/802.15.4 applications” [5] emphasizes the importance of sleep mode power consumption, which is frequently buried behind the active power consumption by the device. The power consumed by the node depends on supply voltages of radio and microcontroller, active current drawn by the radio and microcontroller, the controller clock frequency, system peripheral components (viz. power amplifiers), and code size.

The performance of the 802.15.4 based ZigBee network also depends on the other networks operating at the same frequency band. The paper “IEEE 802.15.4 Low Rate – Wireless Personal Area Network Coexistence Issues” [6] analyzes the coexistence impact of an IEEE 802.15.4 network on IEEE 802.11b devices. The paper “Bluetooth strengths and weaknesses for industrial applications" [7] compares wireless technologies with Bluetooth for industrial applications, with focus on 802.15.4 based ZigBee. It states that ZigBee meets wide variety of needs compared to Bluetooth due to its long term unattended battery operation, greater useful range, flexibility in number of dimension and inherent resilience and mesh networking architecture [7].

The paper "Power Conservation in ZigBee Networks using Temporal Control" [8] discusses power reduction technique in Wireless Sensor Networks (WSNs) by proposing application level solution for IEEE 802.15.4 compliant ZigBee protocol. It discusses power conserving network design, which uses multimode scheduler at application level for all nodes that bring the net up and down [8].

The packet size transmitted in the wireless network affects the battery power consumption for the device. Under error prone environments, optimal packet size can improve the energy efficiency. The paper titled "Effects of Contention Window and Packet Size on the Energy Efficiency of Wireless Local Area Network" [9] discusses factors, such as the number of contending nodes, packet size, contention window, packet transmission collision probability and channel condition, that affect the energy efficiency of 802.11 [9]. The work is comparable for various wireless technologies available.

### 1.3 Organization of Thesis

The thesis is divided into six major chapters. Chapter 2 introduces the ZigBee protocol, and helps understand it's working. Chapter 3 introduces the hardware used to complete the work. Chapter 4 introduces the firmware components. It describes the ZigBee software and the programming of the hardware. Chapter 5 presents the results followed by conclusion and future work in Chapter 6.

# CHAPTER 2: ZIGBEE OVERVIEW

## 2.1 History of ZigBee

The past few years have seen a great expansion in remote controlled devices in our everyday life. This number is only going to increase as more devices are controlled or monitored remotely. To interact with all these remotely controlled devices, the need was felt to put them under one standardized control interface that can interconnect into a personal area network (PAN). One of the most promising protocols is ZigBee, a software layer based on IEEE 802.15.4 standard [11].

A PAN is a computer network used for communication among information technology devices close to the person. PAN may be wired with computer buses or wireless known as Wireless PAN (WPAN). IEEE 802.15 is the fifteenth workgroup of IEEE 802, which specializes in Wireless PAN Standards.

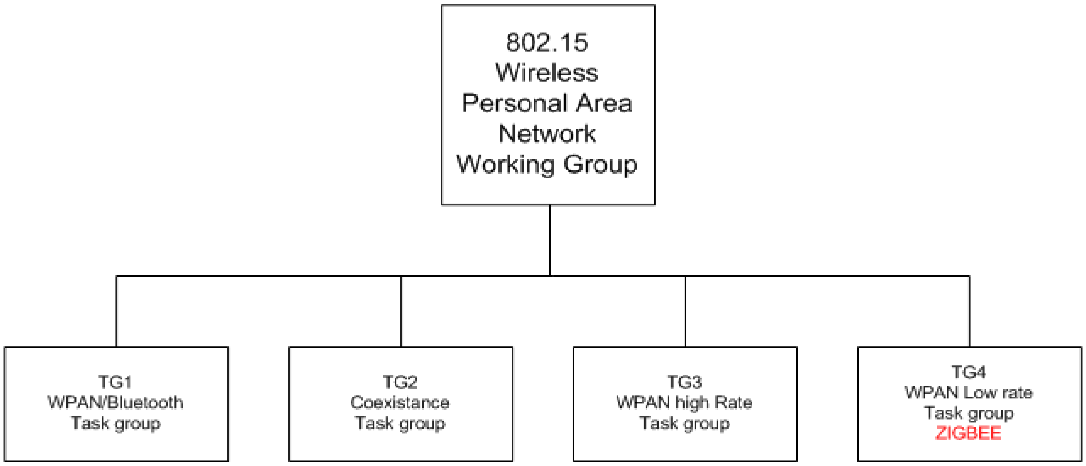


FIGURE 2-1: 802.15 Personal Area Network Working Group

- TG1: IEEE 802.15.1, a WPAN standard based on Bluetooth specifications. It is based on MAC and PHY layer specifications [13].

- TG2: IEEE 802.15.2 addresses the issue of coexistence of WPAN with other wireless devices operating in unlicensed frequency band such as wireless local area networks (WLAN) [13].

- TG3: IEEE 802.15.3 defines MAC and PHY standard for high rate WPAN (11 – 55 Mbps) [13].

- TG4: IEEE 802.15.4 (Low rate WPAN) deals with low data rate but very long battery life and low complexity. The ZigBee, set of high level communication protocol, is based on specifications produced by this task group [13]

IEEE 802.15.4 is a standard defined by the IEEE (Institute of Electrical and Electronics Engineers, Inc.) for low-rate; wireless personal area networks (WPANs). This standard defines the ‘physical layer’ (PHY) and the ‘medium access layer’ (MAC). The specification for the physical layer, defines a low-power spread spectrum radio operating at 2.4 GHz with a basic bit rate of 250 kilobits per second. There are also physical specifications for 915 MHz and 868 MHz that operate at lower data rates. More information can for IEEE 802.15.4 is available at:

http://www.ieee802.org/15/pub/TG4.html [12].

ZigBee is a stack of protocols targeting low bandwidth applications. It’s emphasize is to support standard-based wireless network for low data rates, low-cost, low power consumption, security and reliability [14].

Consortium of over 100 companies came together to form the ZigBee alliance (www.ZigBee.org) and looked at what the short range, low power radio frequency (RF) 802.15.4 could do, and built on it ZigBee stack which is interoperable between multiple vendors. This group is working closely with IEEE to ensure an integrated and complete network for the market [14]. The ZigBee Alliance membership comprises technology providers and original equipment manufacturers worldwide. Membership is open to all [15].

## 2.2 ZigBee Stack

The ZigBee stack architecture is made up of a set of blocks called layers. Each layer performs a specific set of services for the layer above: a data entity provides a data transmission service and a management entity provides all other services. Each service entity exposes an interface to the upper layer through a service access point (SAP), and each SAP supports a number of service primitives to achieve the required functionality [16].

The ZigBee stack architecture, which is depicted in Figure 2-2, is based on the standard Open Systems Interconnection (OSI) seven-layer model (see [18]) but defines only those layers relevant to achieving functionality in the intended market space. The IEEE 802.15.4-2003 standard defines the lower two layers: the physical (PHY) layer and the medium access control (MAC) sub-layer. The ZigBee Alliance builds on this foundation by providing the network (NWK) layer and the framework for the application layer, which includes the application support sub-layer (APS), the ZigBee device objects (ZDO) and the manufacturer-defined application objects[16].

IEEE 802.15.4-2003 has two PHY layers that operate in two separate frequency ranges: 868/915 MHz and 2.4 GHz. The lower frequency PHY layer covers both the 868 MHz European band and the 915 MHz band that is used in countries such as the United States and Australia. The higher frequency PHY layer is used virtually worldwide [16]. A complete description of the IEEE 802.15.4-2003 PHY layer can be found in [17].

The IEEE 802.15.4-2003 MAC sub-layer controls access to the radio channel using a CSMA-CA mechanism. Its responsibilities may also include transmitting beacon frames, synchronization and providing a reliable transmission mechanism [16]. A complete description of the IEEE 802.15.4-2003 MAC sub-layer can be found in [17].

The responsibilities of the ZigBee NWK layer includes mechanisms used to join and leave a network, to apply security to frames and to route frames to their intended destinations. In addition, the discovery and maintenance of routes between devices devolve to the NWK layer. In addition, the discovery of one-hop neighbors and the storing of pertinent neighbor information are done at the NWK layer. The NWK layer of a ZigBee coordinator (see "Network topology") is responsible for starting a new network, when appropriate, and assigning addresses to newly associated devices [16].

The ZigBee application layer consists of the APS, the Application Framework (AF), the ZDO and the manufacturer-defined application objects. The responsibilities of the APS sub-layer include maintaining tables for binding, which is the ability to match two devices together based on their services and their needs, and forwarding messages between bound devices. The responsibilities of the ZDO include defining the role of the device within the network (e.g., ZigBee coordinator or end device), initiating and/or responding to binding requests and establishing a secure relationship between network devices. The ZDO is also responsible for discovering devices on the network and determining which application services they provide [16].

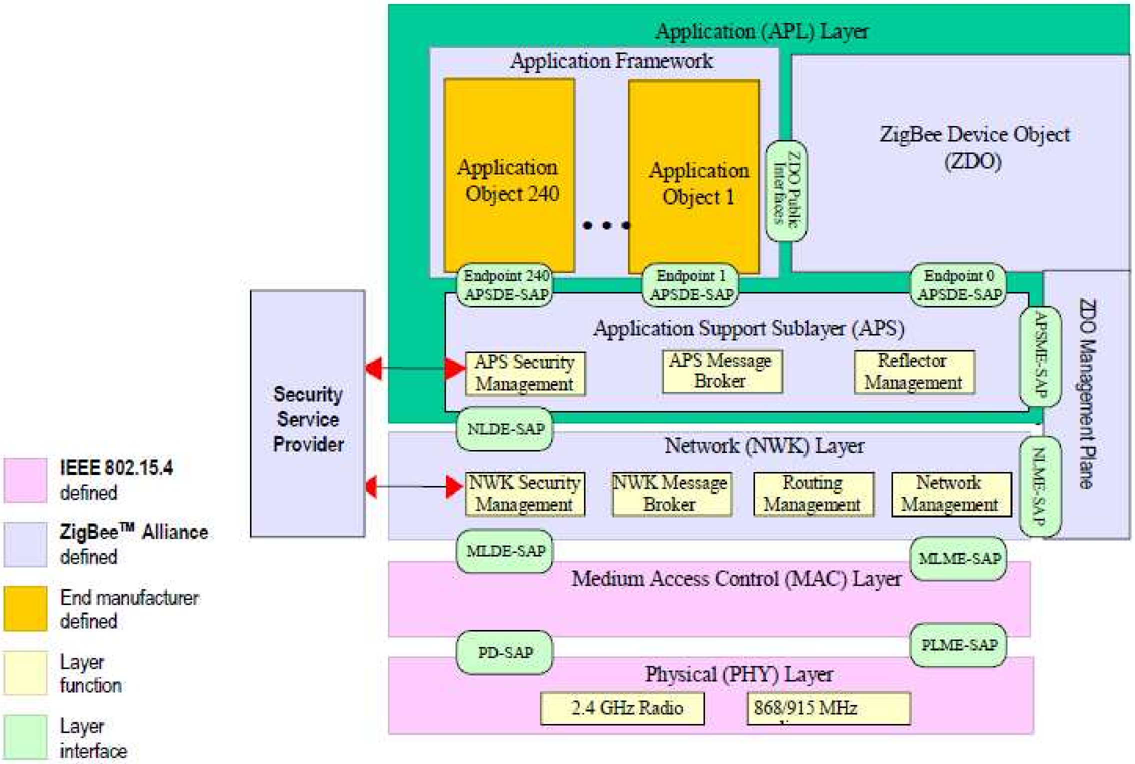


FIGURE 2-2 : ZigBee stack Architecture [16]

## 2.3 ZigBee Node Types

A ZigBee PAN consists of one Coordinator and one or more Routers and/or End Devices. Refer to the Coordinator and Router sections of the “RF Module Operation” chapter for more information regarding each node type [19].

### 2.3.1 Coordinator

A node has the unique function of forming a network. The Coordinator is responsible for establishing the operating channel and PAN ID for an entire network. Once established, the Coordinator can form a network by allowing Routers and End

Devices to join to it. Once the network is formed, the Coordinator functions like a Router (it can participate in routing packets and be a source or destination for data packets) [19].

- One Coordinator per PAN
- Establishes/Organizes PAN
- Can route data packets to/from other nodes
- Can be a data packet source and destination
- Mains-powered

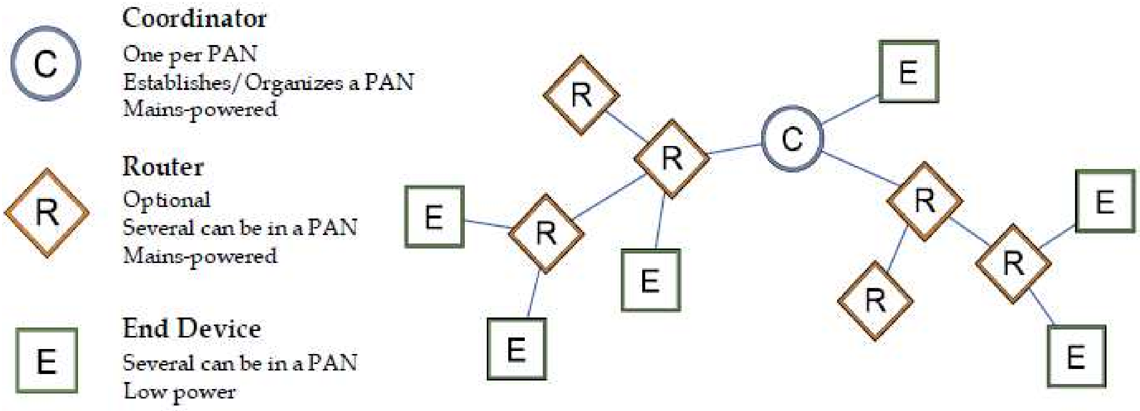


FIGURE 2-3 : ZigBee Node Types [19]

### 2.3.2 Routers

A node creates/maintains network information and uses this information to determine the best route for a data packet. It must join a network before it can allow other Routers and End Devices to join to it. It can participate in routing packets and is intended to be a mains-powered node [19].

- Several Routers can operate in one PAN
- Can route data packets to/from other nodes
- Can be a data packet source and destination

- Mains-powered (Can be battery powered in some cases)

### 2.3.3 End Device

End Devices must always interact with their parent to receive or transmit data. They are intended to sleep periodically, and therefore have no routing capacity. End Devices must always interact with their parent node (Router or Coordinator) in order to transmit or receive data. An End Device can be a source or destination for data packets but cannot route packets. End Devices can be battery-powered and offer low-power operation [19].

- Several End Devices can operate in one PAN
- Can be a data packet source and destination
- All messages are relayed through a Coordinator or Router
- Low power battery operation

## 2.4 Network Topology

The ZigBee network layer (NWK) supports star, tree and mesh topologies. In a star topology, the network is controlled by one single device called the ZigBee coordinator. The ZigBee coordinator is responsible for initiating and maintaining the devices on the network, and all other devices, known as end devices, directly communicate with the ZigBee coordinator. In mesh and tree topologies, the ZigBee coordinator is responsible for starting the network and for choosing certain key network parameters but the network may be extended through the use of ZigBee routers. In tree networks, routers move data and control messages through the network using a hierarchical routing strategy. Tree networks may employ beacon-oriented communication as described in the IEEE 802.15.4-2003 specification. Mesh networks shall allow full peer-to-peer communication [19].

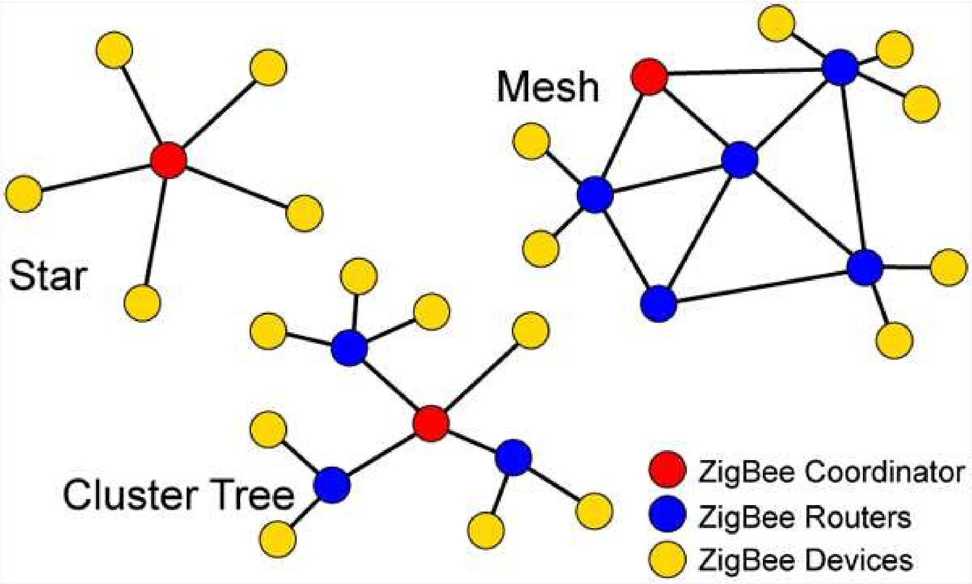


FIGURE 2-4 : ZigBee Network Topologies [14]

### 2.4.1 Mesh Network Topology

The thesis work implements mesh network topology for the network for all the experimental measurements.

Mesh topology, also called peer-to-peer, consists of a mesh of interconnected routers and end devices. Each router is typically connected through at least two pathways, and can relay messages for its neighbors [20].

Mesh topology supports "multi-hop" communications, through which data is passed by hopping from device to device using the most reliable communication links and most cost-effective path until its destination is reached. The multi-hop ability also helps to provide fault tolerance, in that if one device fails or experiences interference, the network can reroute itself using the remaining devices [20].

Benefits of Mesh Network

- This topology is highly reliable and robust. Should any individual router become inaccessible, alternative routes can be discovered and used [20].
- The use of intermediary devices in relaying data means that the range of the network can be significantly increased, making this topology highly scalable [20].
- Weak signals and dead zones can be eliminated by simply adding more routers to the network [20].
- The network is self-healing, with connections between devices being dynamically updated and optimized in difficult conditions. By ensuring that each device is connected to several others (redundancy), if one drops out of the network, its neighbors simply find another route [20].
- One can extend distance, add redundancy, and improve link quality and the general reliability of a mesh network simply by adding devices [20].

On the negative side, the paper titled “Impact of Node Heterogeneity in ZigBee Mesh Network Routing” discusses that routing in ZigBee is not the same as MANET (Mobile and Ad hoc network). The node heterogeneity in ZigBee network degrades the routing performance and further worsens for larger networks [10].

## 2.5 ZigBee Addressing

The 802.15.4 protocol upon which the ZigBee protocol is built specifies two address types:

§ 16-bit Network Addresses

A 16-bit Network Address is assigned to a node when the node joins a network. The Network Address is unique to each node in the network. However, Network Addresses are not static - it can change.

§ 64-bit Addresses

Each node contains a unique 64-bit address. The 64-bit address uniquely identifies a node and is permanent.

Each node has a unique IEEE and Network (ZigBee Network Layer) address that is assigned when a node joins the network. Endpoint number unique within a node addresses every subunit and thus Application Object in a node. An Application Object receives commands from outside world addressed to pair: (node address, endpoint number). Commands may be of two types: Key-Value Pair (KVP) and Generic Messages (MSG) [12].

## 2.6 ZigBee Data Transmission

All data packets are addressed using both device and application layer addressing fields. Data can be sent as a broadcast, multicast, or unicast transmission.

### 2.6.1 Broadcast Transmission

Broadcast transmissions are destined for all devices in a PAN. When a device sends a broadcast data packet, all devices that receive the packet will transmit the packet

3 times. Each node that transmits the broadcast will also create an entry in a local broadcast transmission table. This entry is used to keep track of each received broadcast packet to ensure the packets are not endlessly transmitted. Each entry persists for 8 seconds. The broadcast transmission table holds eight entries. Since each device in the network retransmits broadcast transmissions, broadcast messages should be used sparingly [19].

Broadcast transmissions within the ZigBee protocol are intended to be propagated throughout the entire network such that all nodes receive the transmission. This requires each broadcast transmission be retransmitted by all Router nodes to ensure all nodes receive the transmission. Broadcast transmissions use a passive acknowledgment scheme. This means that when a node transmits a broadcast transmission, it listens to see if all of its neighbors retransmit the message. If one or more neighbor nodes do not retransmit the data, the node will retransmit the broadcast message and listen again for the neighbor nodes to forward the broadcast transmission [19].

### 2.6.2 Multicast Transmissions

Multicast transmissions operate similar to broadcast transmissions. Data packets are broadcast throughout the network in a similar fashion. However, only devices that are part of the multicast ID will receive the data packets [19].

### 2.6.3 Unicast Transmissions

Unicast ZigBee transmissions are always addressed to the 16-bit address of the destination device. However, only the 64-bit address of a device is permanent; the 16-bit address can change. Therefore, ZigBee devices may employ network address discovery to identify the current 16-bit address that corresponds to a known 64-bit address. Once the 16-bit address is known, a route to the destination device must be discovered. ZigBee employs mesh routing using the Ad-hoc On-demand Distance Vector routing (AODV) protocol to establish a route between the source device and the destination [19].

## 2.7 Data Routing

ZigBee mesh network uses AODV (Ad-hoc On-demand Distance Vector) Routing Algorithm. Routing under the AODV protocol is accomplished using tables in each node that store in the next hop (intermediary node between source and destination nodes) for a destination node. If a next hop is not known, route discovery must take place in order to find a path. Since only a limited number of routes can be stored on a Router, route discovery will take place more often on a large network with communication between many different nodes.

When a source node must discover a route to a destination node, it sends a broadcast route request command. The route request command contains the source Network Address, the destination Network Address and a Path Cost field (a metric for measuring route quality). As the route request command is propagated through the network, each node that re-broadcasts the message updates the Path Cost field and creates a temporary entry in its route discovery table.

When the destination node receives a route request, it compares the ‘path cost’ field against previously received route request commands. If the path cost stored in the route request is better than any previously received, the destination node will transmit a route reply packet to the node that originated the route request. Intermediate nodes receive and forward the route reply packet to the Source Node (the node that originated route request) [19].

## 2.8 ZigBee Transmission Range and Data Rates

ZigBee-compliant products operate in unlicensed bands worldwide, including 2.4GHz (global), 902 to 928MHz (Americas), and 868MHz (Europe). The transmission distance is expected to range from 10 to 75m, depending on power output and environmental characteristics. Like Wi-Fi, Zigbee uses direct-sequence spread spectrum in the 2.4GHz band, with offset-quadrature phase-shift keying modulation. Channel width is 2MHz with 5MHz channel spacing. The 868 and 900MHz bands also use direct-sequence spread spectrum but with binary-phase-shift keying modulation [11].

Raw data throughput rates of 250Kbps can be achieved at 2.4GHz (16 channels), 40Kbps at 915MHz (10 channels), and 20Kbps at 868MHz (1 channel) [11]. For any given quantity of data, transmitting at a higher data rate allows the system to shut down the transmitter and receiver more quickly, saving significant power. Higher data rates at a given power level mean there is less energy per transmitted bit, which generally implies reduced range [12].

## 2.9 Battery Life Consideration

The basic 802.15.4 node is fundamentally efficient in terms of battery performance. You can expect battery lifetimes from a few months to many years as a result of a host of system’s power-saving modes and battery-optimized network parameters [12].

## 2.10 ZigBee Applications

ZigBee is the wireless technology that:

- Enables broad-based deployment of wireless networks with low cost, low power solutions [15].
- Provides the ability to run for years on inexpensive primary batteries for a typical monitoring application [15].
- Addresses the unique needs of remote monitoring & control, and sensory network applications [15].

ZigBee technology is well suited to a wide range of building automation, industrial, medical and residential control & monitoring applications. Essentially, applications that require interoperability and/or the RF performance characteristics of the IEEE 802.15.4 standard would benefit from a ZigBee solution.

Examples applications [15].

- Lighting controls
- Automatic Meter Reading
- Wireless smoke and CO detectors
- HVAC control
- Heating control
- Home security
- Environmental controls
- Blind, drapery and shade controls
- Medical sensing and monitoring

§ Universal Remote Control to a Set-Top Box which includes Home Control

§ Industrial and building automation

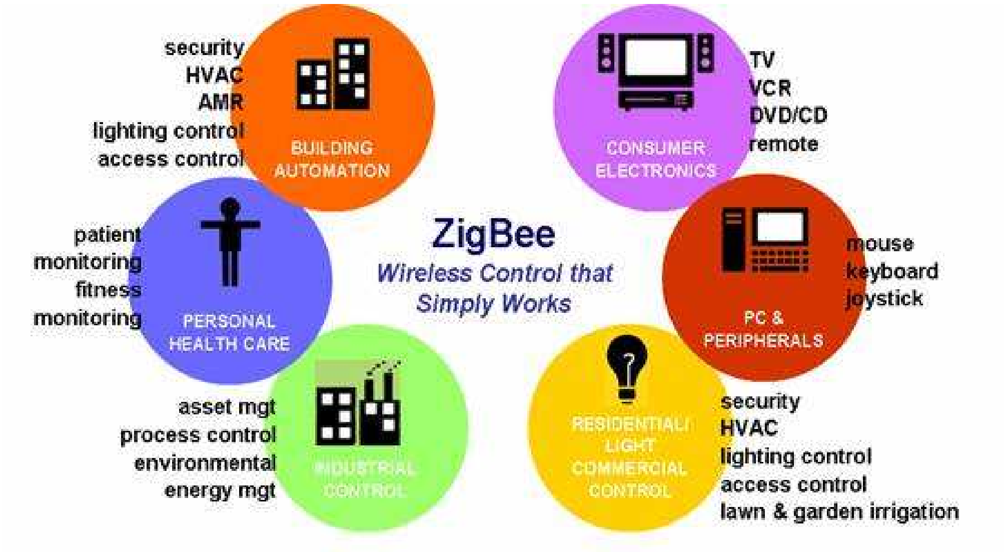


FIGURE 2-5 : ZigBee Applications [21]

# CHAPTER 3: HARDWARE DISCRIPTION

## 3.1 Choice of Components

The components include Maxstream ZigBee series 2 modules, programming board, Maxstream firmware, National Instruments GPIB card (PCMCIA/USB) and Power supply.

## 3.2 Maxstream XBee Series 2 RF Module

Maxstream XBee series 2 are engineered to operate within the ZigBee protocol and support unique needs of low cost low power wireless sensor networks. These modules provide reliable data delivery at minimal power. The modules operate within the ISM 2.4GHz frequency band and are pin for pin compatible with each other [19].

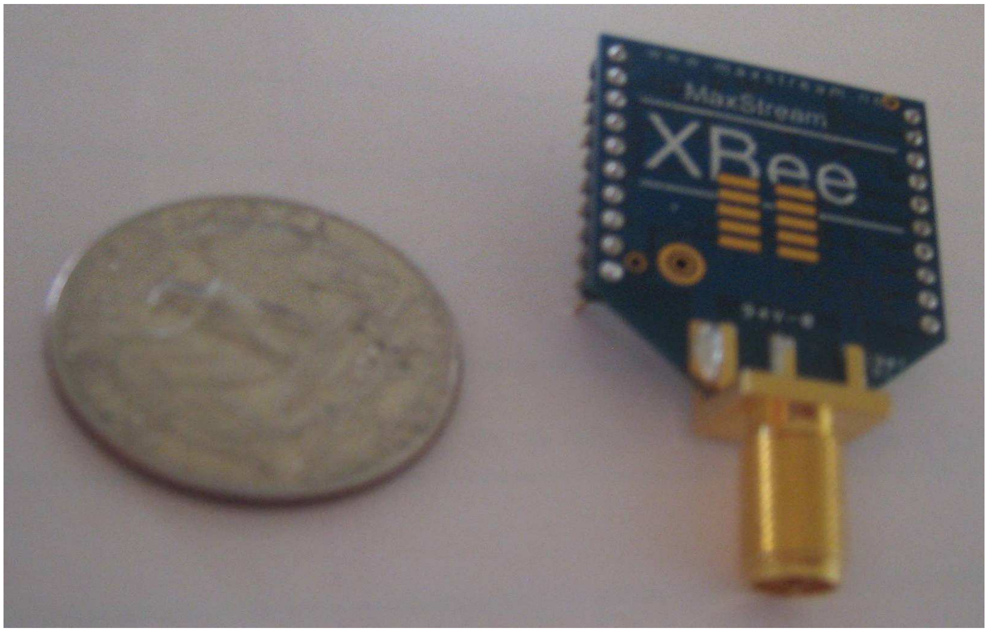


FIGURE 3-1 : Xbee Series 2 module

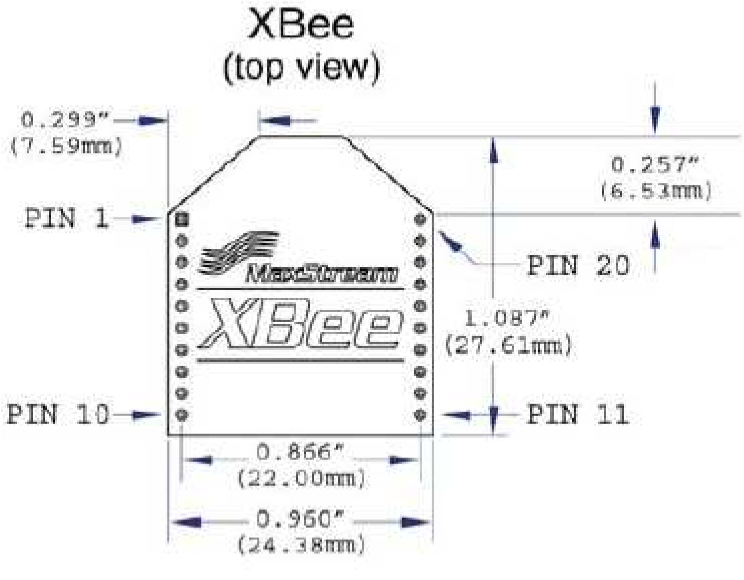


FIGURE 3-2 : Mechanical Drawing of the Module [19]

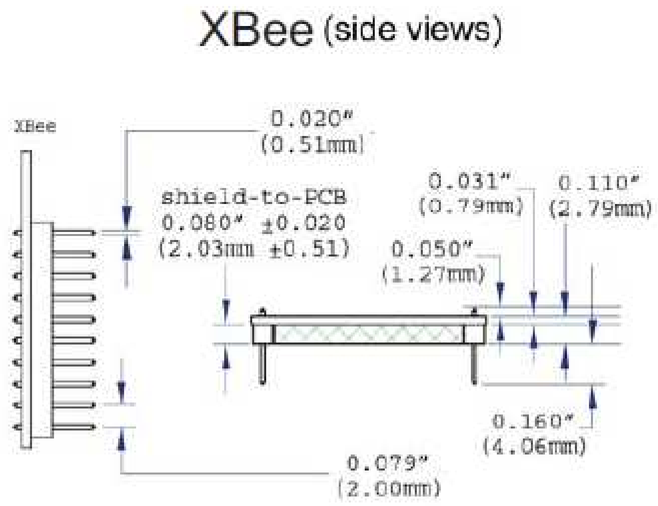


FIGURE 3-3 : Module Side View [19]

TABLE 3-1 : Module Pin Description [19]

| **Pin #** | **Name** | **Direction** | **Description** |
|---|---|---|---|
| 1 | VCC | - | Power supply |
| 2 | DOUT | OUTPUT | UART Data Out |
| 3 | DIN/ $\overline{CONFIG}$ | INPUT | UART Data In |
| 4 | DIO8 | EITHER | Digital I/O 12 |
| 5 | $\overline{RESET}$ | INPUT | Module Reset (reset pulse must be at least 200 ns) |
| 6 | PWM0/RSSI/DI8 | OUTPUT | PWM Output 0 / RX Signal Strength Indicator / Digital IO |
| 7 | PWM/DIO11 | EITHER | Digital I/O 11 |
| 8 | RESERVED | - | Do not connect |
| 9 | $\overline{DTR}$ /SLEEP_RQ/DI8 | INPUT | Pin Sleep Control Line or Digital IO 8 |
| 10 | GND | - | Ground |
| 11 | DIO4 | EITHER | Digital I/O 4 |
| 12 | $\overline{CTS}$ /DIO7 | EITHER | Clear-to-Send Flow Control or Digital I/O 7 |

| | | | |
|---|---|---|---|
| 13 | ON/$\overline{SLEEP / DIO9}$ | OUTPUT | Module Status Indicator or Digital I/O 9 |
| 14 | RESERVED | - | Do not connect |
| 15 | ASSOCIATE/DIO5 | EITHER | Associated Indicator, Digital I/O 5 |
| 16 | $\overline{RTS}$ /DIO6 | EITHER | Request-to-Send Flow Control, Digital I/O 6 |
| 17 | AD3/DIO3 | EITHER | Analog Input 3 or Digital I/O 3 |
| 18 | AD2/DIO2 | EITHER | Analog Input 3 or Digital I/O 2 |
| 19 | AD1/DIO1 | EITHER | Analog Input 3 or Digital I/O 1 |
| 20 | AD0/DIO0 | EITHER | Analog Input 0, Digital I/O 0, or Node Identification |

### 3.2.1 RF Module Operation

The XBee Series 2 OEM RF Modules interface to a host device through a logic-level asynchronous serial port. Through its serial port, the module can communicate with any logic and voltage compatible UART; or through a level translator to any serial device (For example: Through a MaxStream proprietary RS-232 or USB interface board) [19].

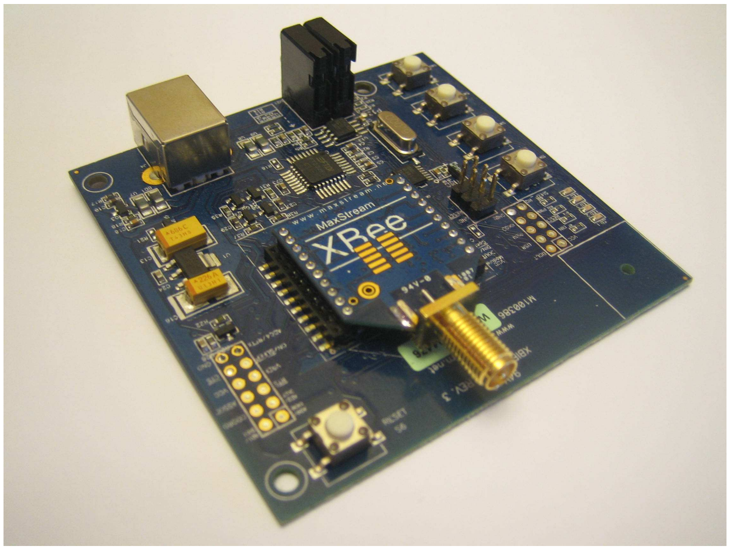


FIGURE 3-4 : Xbee Series 2 module on the USB programming board (XBIB - U Rev 3)

### 3.2.2 UART Data Flow

Devices that have a UART interface can connect directly to the pins of the RF module as shown in the figure below.

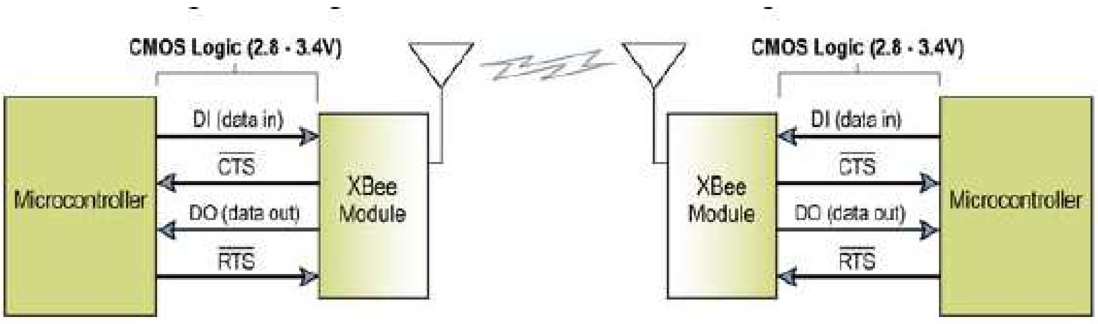


Figure 3-5 : System Data Flow Diagram in a UART-interfaced environment [19]

Serial Data

Data enters the module UART through the DI pin (pin 3) as an asynchronous serial signal. The signal should idle high when no data is being transmitted. Each data byte consists of a start bit (low), 8 data bits (least significant bit first) and a stop bit (high). The following figure illustrates the serial bit pattern of data passing through the module.

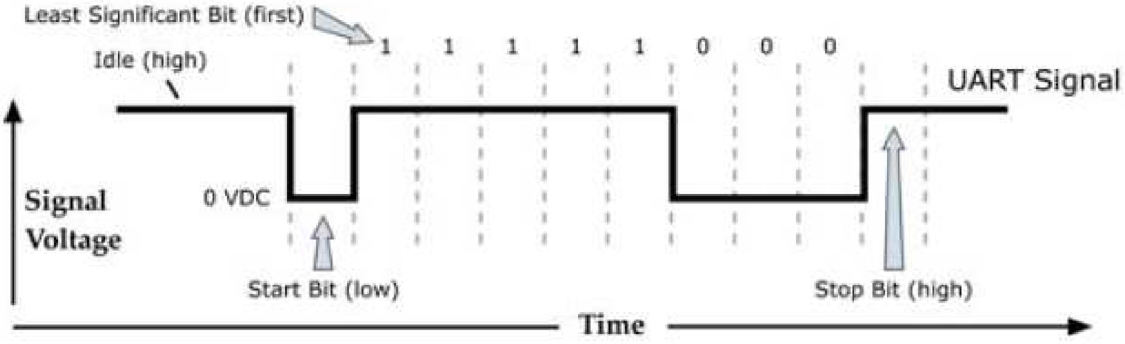


FIGURE 3-6 : UART data packet 0x1F (decimal number "31") as transmitted through the RF module (Example Data Format is 8-N-1 (bits - parity - # of stop bits) [19]

The UART module performs tasks, such as timing and parity checking, that are needed for data communications. Serial communications requires two UARTs to be configured with compatible settings (baud rate, parity, start bits, stop bits, data bits).

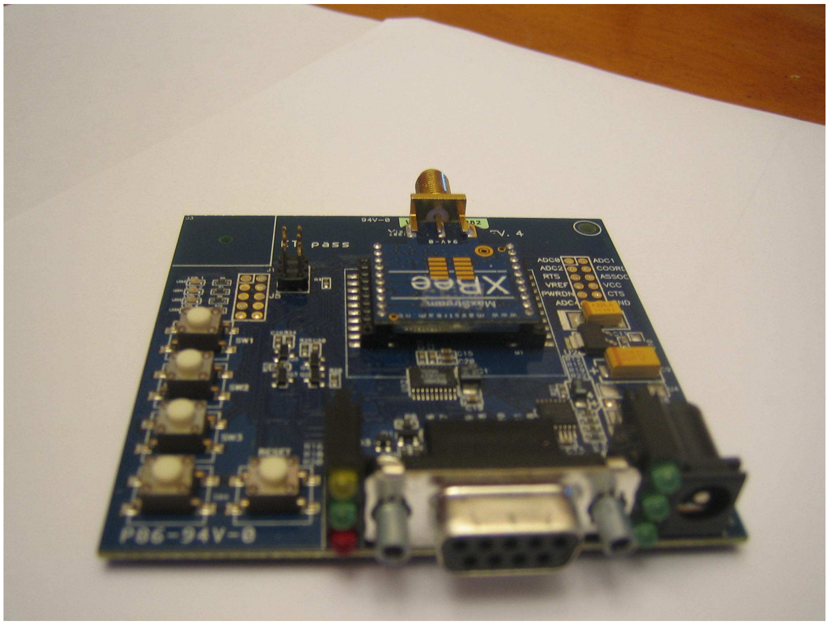


FIGURE 3-7: Xbee Series 2 module on the RS-232 Programming Board (XBIB – R, Rev 4)

FIGURE 3-8 : SMA Connector Antenna

### 3.2.3 Flow Control

The internal flow control looks as depicted below in Figure 3-9

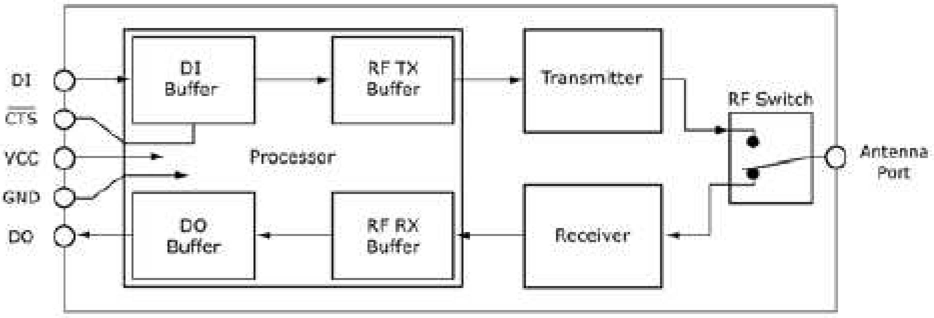


FIGURE 3-9 : Module's Internal Flow Control [19]

## 3.3 General Purpose I/O Bus Card (GPIB)

GPIB a standard interface bus, also known as IEEE-488 bus, is used largely for computer-to-instrumentation interface. The GPIB standard was designed to connect several instruments to computers for data acquisition and control. Data can be transferred over GPIB at 200 Kbytes per second, over distances of two meters.

The compact National Instruments GPIB-USB-HS and PCMCIA-GPIB is used for the purpose of data acquisition. The sampled current values were collected at the sampling rate of approximately 2000 samples per second.

The IEEE-488.1 standard greatly simplified the interconnection of programmable instruments by clearly defining mechanical, hardware, and electrical protocol specifications. The instruments from different manufactures can be connected by a standard cable. This standard does not address data formats, status reporting, message exchange protocol, common configuration commands, or device specific commands.

The IEEE-488.2 standard enhances and strengthens the IEEE-488.1 standard by specifying data formats, status reporting, error handling, controller functionality, and common instruments commands. It focuses mainly on the software protocol issues and thus maintains compatibility with the hardware- oriented IEEE-488.1 standard. IEEE-488.2 systems tend to be more compatible and reliable.

### 3.3.1 GPIB Interface for PCMCIA

The National Instruments PCMCIA-GPIB is a low-cost, high-performance IEEE 488 interface for computers with PC Card (PCMCIA) slots, such as laptop and notebook computers.

FIGURE 3-10 : NI PCMCIA – GPIB Card and Interface Cable [23]

The system automatically configures the PCMCIA-GPIB on startup or when you insert the card. A National Instruments TNT family ASIC makes the PCMCIA-GPIB a maximum-performance IEEE 488.2 interface [22]. It costs $629.00[23].

### 3.3.2 GPIB Controller for USB

The compact National Instruments GPIB-USB-B transforms any computer with a USB port into a full-function, IEEE 488.2 controller that can control up to 14 programmable GPIB instruments. The GPIB-USB-B is easy to install and use because there are no external DIP switches. The GPIB-USB-B is a plug-and-play interface that the OS automatically recognizes and configures as soon as you physically attach it to the USB port on your computer [25]. It costs $528.00 [24]

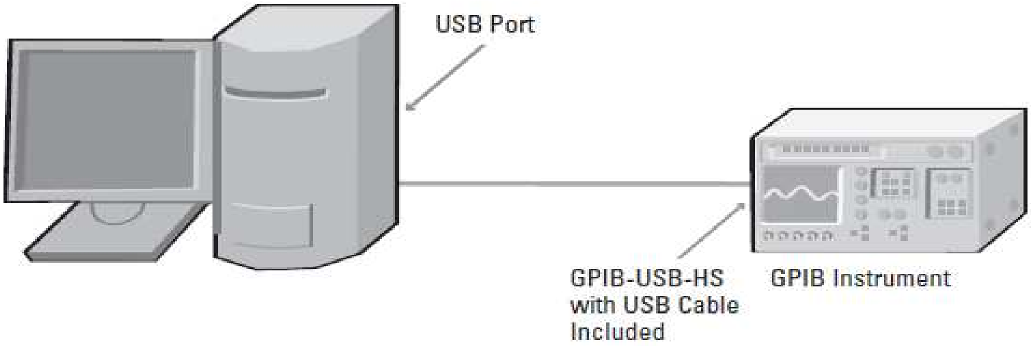


FIGURE 3-11 : GPIB Data Acquisition System Overview [25]

FIGURE 3-12 : NI GPIB USB – B

## 3.4 Keithley 2602 Power Supply

It is a Model 2602 Dual-Channel System Source Meter Instrument which offers electronic component and semiconductor device manufacturers a scalable, high throughput, highly cost-effective solution for precision DC, pulse, and low frequency AC source-measure testing [26].

The analog-to-digital converters provide simultaneous I and V measurements in less than 100µs (10,000 rdgs/s) and source-measure sweep speeds of less than 200µs per point (5,500 points/s) [26].

The work makes use of this precision instrument to provide constant power supply and record the changes in current, drawn by the XBee series 2 module, at the sampling rate of 2000 samples per second [26].

FIGURE 3-13: Keithley 2602 power supply (front view) [26]

FIGURE 3-14 : Keithley 2602 power supply (rear view) [26]

### 3.4.1 Key Features

- Combines a precision power supply, true current source, DMM, arbitrary waveform generator, V or I pulse generator with measurement, electronic load, and trigger controller-all in one instrument
- Contact check function ensures high integrity measurements
- 10,000 readings/s and 5,500 source-measure points/s to memory provide faster test times [26]

# CHAPTER 4: FIRMWARE DESCRIPTION

Firmware is system software or hardware that is written and stored in a device's memory that controls several operation of the device. The operation of the node depends on the proper configuration of the firmware. It makes the node behave as a ZigBee complaint module. The Maxstream Inc provides the proprietary firmware for the nodes with the flexibility of changing the behavior by setting the parameters and other network variables using the X-CTU software with graphical user interface. The functionality can also be modified by readily available ZigBee stack.

## 4.1 ZigBee Network Formation

A ZigBee Personal Area Network (PAN) is created when a Coordinator selects a channel and PAN ID to start on. Once the Coordinator has started a PAN, it can allow routers and end devices to join the network. When a router or end device joins a PAN, it receives a 16-bit network address. The network address of the PAN coordinator is always 0. When a router joins a PAN, it can also allow other routers and end devices to join to it. Joining establishes a parent/child relationship between two nodes. The node that allowed the join is the parent, and the node that joined is the child. The parent/child relationship however is not necessary for routing data [19].

Routers and end devices must join a ZigBee network before they can communicate with other devices on the network. A router or end device discovers operating ZigBee networks by issuing a beacon request frame on a channel and listening for beacons. Any nearby routers or coordinators that are a part of PAN will respond to the beacon request by transmitting a beacon. The beacon indicates which PAN ID the device is operating on, and whether or not the device is allowing other devices to join to it. The joining device may issue beacon request frames on multiple channels. If the joining device discovers a device that allows joins and that operates on a valid PAN ID, it will attempt to join the network by sending an associate request frame. If successful, the device becomes part of the network. When a router joins a network, it can route data packets and allow other devices to join to it. End devices that join a network cannot participate in routing data packets, nor can they allow other devices to join the PAN [19].

## 4.2 XBee Series 2 RF Module Operation

The RF module operates in two modes namely transparent operation and API operation. Both are discussed below in detail.

### 4.2.1 Transparent Operation

When operating in Transparent Mode, modules are configured using AT Commands and API operation is not supported. The modules act as a serial line replacement - all UART data received through the DI pin is queued up for RF transmission. Data is sent to a module as defined by the DH (Destination Address High) and DL (Destination Address Low) parameters. When RF data is received that is addressed to the module’s 64-bit Address, the data is sent out to the DO pin [19].

### 4.2.2 API Operation

API (Application Programming Interface) Operation is an alternative to the default Transparent Operation. The frame-based API extends the level to which a host application can interact with the networking capabilities of the module. When in API mode, all data entering and leaving the module is contained in frames that define operations or events within the module. Transmit Data Frames (received through the DI pin (pin 3)) include: • RF Transmit Data Frame • Command Frame (equivalent to AT commands) Receive Data Frames (sent out the DO pin (pin 2)) include: • RF-received data frame • Command response • Event notifications such as reset, associate, disassociate, etc. The API provides alternative means of configuring modules and routing data at the host application layer. A host application can send data frames to the module that contain address and payload information instead of using command mode to modify addresses. The module will send data frames to the application containing status packets; as well as source, RSSI and payload information from received data packets. The API operation option facilitates many operations such as the examples cited below [19]:

- Transmitting data to multiple destinations without entering Command Mode
- Receive success/failure status of each transmitted RF packet
- Identify the source address of each received packet

## 4.3 Modes of Operation

The RF module operates in four modes namely Idle, Transmit, Receive and Sleep. The module is always is in one of the four modes mentioned. Only the ZigBee end device (reduced function device) supports the sleep mode, along with all other modes supported by all types of nodes.

### 4.3.1 Idle Mode

When not receiving or transmitting data, the RF module is in Idle Mode. During Idle Mode, the RF module is also checking for valid RF data.

### 4.3.2 Transmit Mode

When serial data is received and is ready for packaging, the RF module will exit Idle Mode and attempt to transmit the data. The destination address determines which node(s) will receive the data. Prior to transmitting the data, the module ensures that a 16-bit Network Address and route to the destination node have been established. If the 16-bit Network Address is not known, Network Address Discovery will take place. If a route is not known, route discovery will take place for establishing a route to the destination node. If a module with a matching Network Address is not discovered, the packet is discarded. The data will be transmitted once a route is established. If route discovery fails to establish a route, the packet will be discarded [19].

When data is transmitted from one node to another, a network-level acknowledgement is transmitted back across the established route to the source node. This acknowledgement packet indicates to the source node that the data packet was received by the destination node. If a network acknowledgement is not received, the source node will re-transmit the data [19].

The transmit mode sequence can seen in the following flowchart:

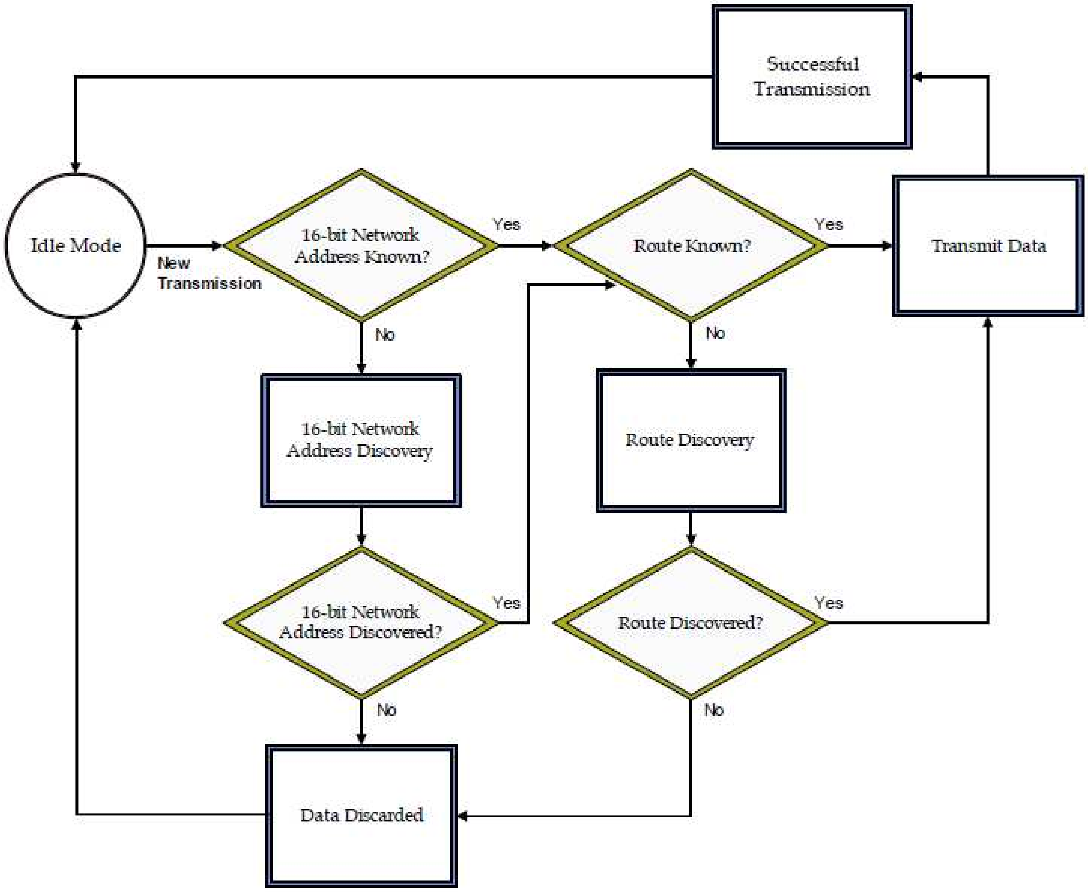


FIGURE 4-1 : Transmit mode sequence [19]

### 4.3.3 Receive Mode

If a valid RF packet is received and its address matches the RF module's MY (16-bit Source Address) parameter, the data is transferred to the DO buffer [19].

### 4.3.4 Sleep Mode

Sleep modes are supported on End devices (Reduced function devices) only. Router and coordinator devices participate in routing data packets hence, are intended to be mains powered. End devices must be joined to a parent (router or coordinator) before they can participate on a ZigBee network. The parent device does not track when an end device is awake or asleep. Instead, the end device must inform the parent when it is able to receive data. The parent must be able to buffer incoming data packets destined for the end device until the end device can awake and receive the data. When an end device is able to receive data, it sends a poll command to the parent. When the parent router or coordinator receives the poll command, it will transmit any buffered data packets for the end device. Routers and coordinators are capable of buffering one broadcast transmission for sleeping end device children [19].

#### 4.3.4.1 Cyclic Sleep

Cyclic sleep allows modules to wake periodically to check for RF data and sleep when idle. When the SM parameter is set to 4, the module is configured to sleep for the time specified by the SP parameter. After the SP time expires, the module will wake and check for RF or serial data. To check for RF data, the module sends a transmission to its parent router or coordinator (called a poll request) to see if its parent has any buffered data packets for the end device. If the parent has data for the module, the module will remain awake to receive the data. Otherwise, the module will return to sleep. If serial or RF data is received, the module will start the ST timer and remain awake until the timer expires. While the module is awake, it will continue to send poll request messages to its parent to check for additional data. The ST timer will be restarted anytime serial or RF activity occurs. The module will resume sleep when the ST timer expires. When the module wakes from sleep, it asserts On/Sleep (pin 13) to provide a wake indicator to a host device. If a host device wishes to sleep longer than SP time or to wake only when

RF data arrives, the SN command can be used to prevent On/Sleep from asserting for a multiple of SP time [19].

For example, if SP = 20 seconds, and SN = 5, the ON/SLEEP pin will remain de-asserted (low) for up to 100 seconds. If CTS flow control is enabled, CTS (pin 12) is asserted (0V) when the module wakes and de-asserted (high) when the module sleeps, allowing for communication initiated by the host if desired [19].

## 4.4 Programming Xbee Series 2 Modules

Firmware on the XBee Series 2 modules can be upgraded using the MaxStream x-CTU program to interface with the DIN and DOUT serial lines, or with an InSight programmer device via InSight header.

### 4.4.1 Configuring the Module Using API Operation

Throughout the study, the modules have been configured using API operation. API operation requires that communication with the module be done through a structured interface (data is communicated in frames in a defined order). The API specifies how commands, command responses and module status messages are sent and received from the module using a UART Data Frame [19].

#### 4.4.1.1 API Frame Specifications

Two API modes are supported and both can be enabled using the AP (API Enable) command. Use the following AP parameter values to configure the module to operate in a particular mode:

§ AP = 1: API Operation

Any data received prior to the start delimiter is silently discarded. If the frame is not received correctly or if the checksum fails, the module will reply with a module status frame indicating the nature of the failure [19].

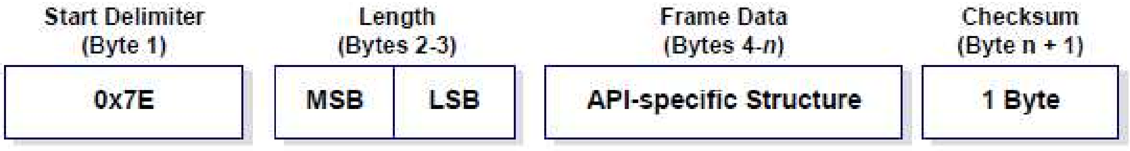


FIGURE 4-2 : UART data frame structure [19]

- AP = 2: API Operation (with escaped characters)

When sending or receiving a UART data frame, specific data values must be escaped (flagged) so they do not interfere with the data frame sequencing. To escape an interfering data byte, insert 0x7D and follow it with the byte to be escaped XOR'd with 0x20.

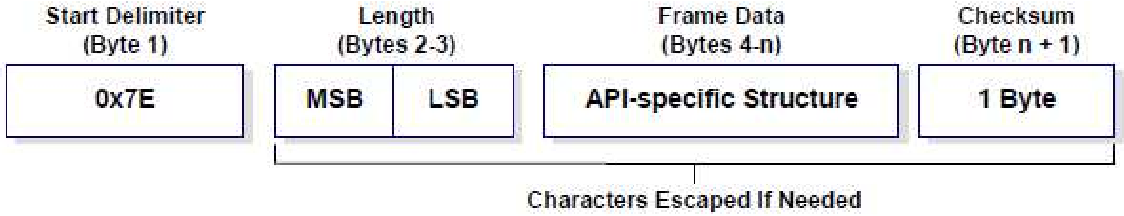


FIGURE 4-3 : UART Data Frame Structure with escape control characters [19]

### Checksum

To test data integrity, a checksum is calculated and verified on non-escaped data.

To calculate: To calculate checksum, exclude frame delimiters and length, and add all bytes keeping only the lowest 8 bits of the result and subtract the result from 0xFF.

### 4.4.2 API Frame Structure

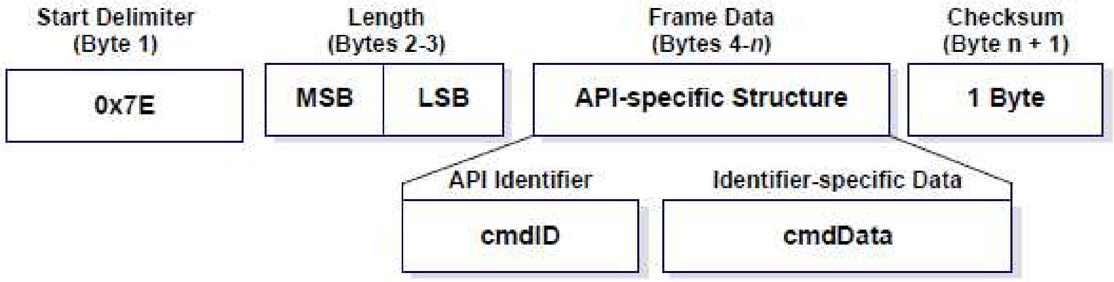


FIGURE 4-4 : UART Data Frame & API Specific Structure [19]

The cmdID frame (API-identifier) indicates which API messages will be contained in the cmdData frame (Identifier-specific data). The multi-byte values are sent big endian.

The Xbee series 2 module supports following frame formats:

TABLE 4-1 : API Frame Names and Values [19]

| API frame names | Values |
|---|---|
| Modem Status | 0x8A |
| Advanced Modem Status | 0x8C |
| AT Command | 0x08 |
| AT command - queue parameter value | 0x09 |
| AT command response | 0x88 |
| Remote Command request | 0x17 |
| Remote command response | 0x97 |
| ZigBee transmit request | 0x10 |
| Explicit addressing ZigBee command frame | 0x11 |
| ZigBee transmit status | 0x8B |
| ZigBee receive packet | 0x90 |

| | |
|---|---|
| ZigBee explicit Rx indicator | 0x91 |
| ZigBee sensor read indicator | 0x94 |
| Node identification indicator | 0x95 |

#### 4.4.2.1 ZigBee Transmit Request Frame

API Identifier Value: (0x10)

A TX Request message will cause the module to send RF Data as an RF Packet.

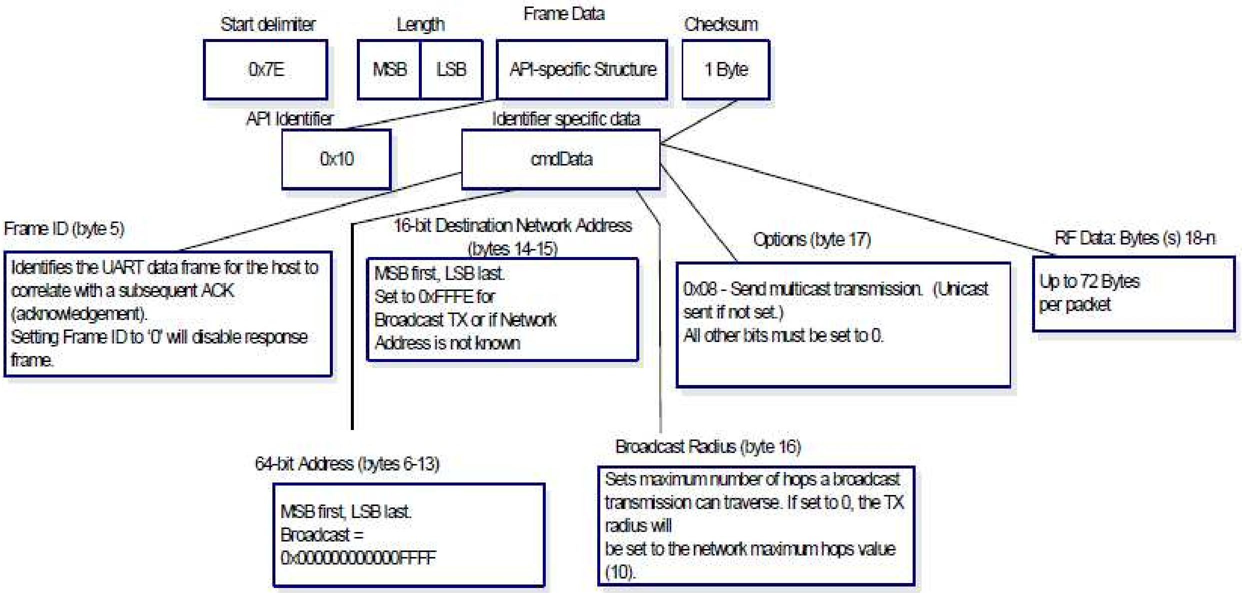


FIGURE 4-5 : Zigbee transmit request frame structure [19]

#### 4.4.2.2 Explicit Addressing ZigBee Command Frame

API Identifier Value: (0x11)

Allows ZigBee application layer fields (endpoint and cluster ID) to be specified for a data transmission.

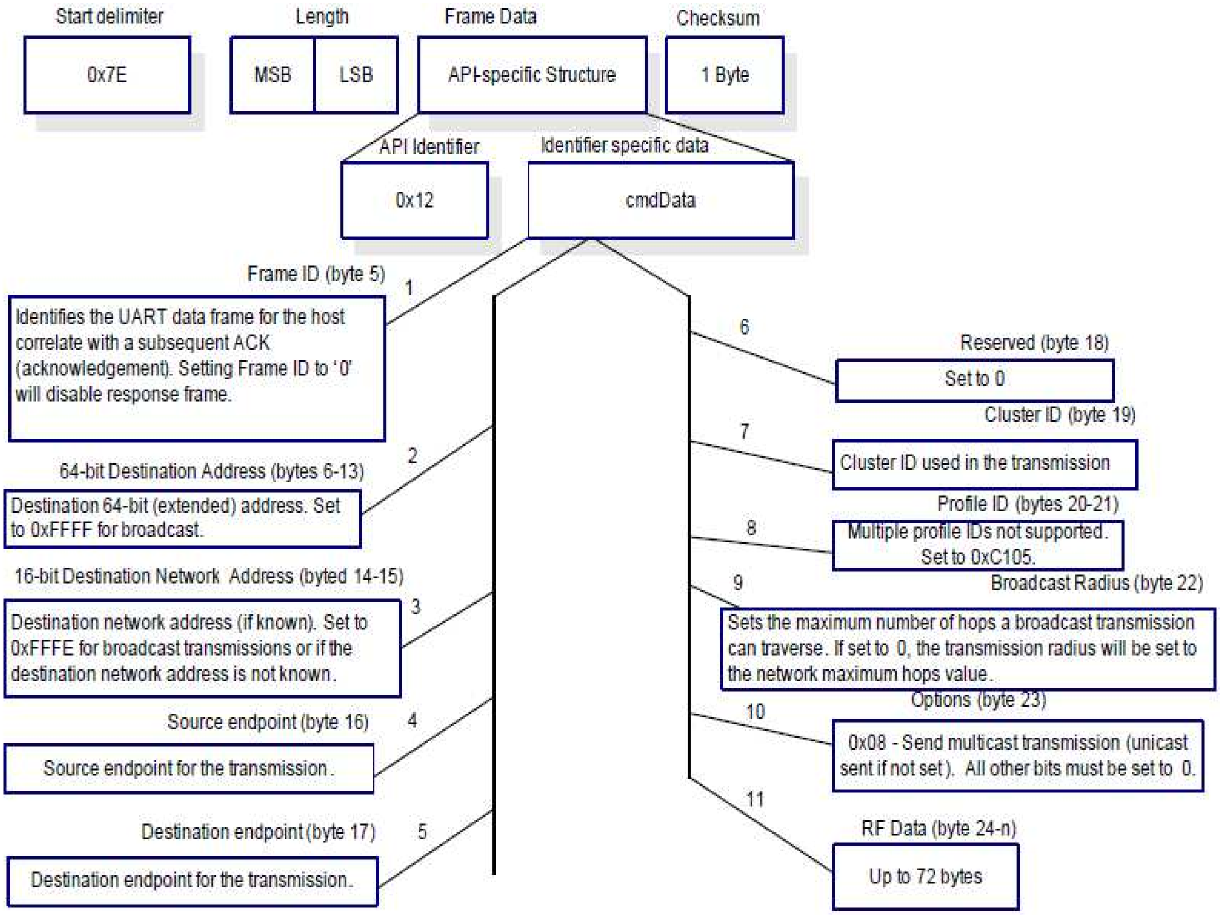


FIGURE 4-6 : Explicit Addressing ZigBee Command Frame [19]

### 4.4.2.3 ZigBee Transmit Status

API Identifier Value: 0x8B

When a TX Request is completed, the module sends a TX Status message. This message will indicate if the packet was transmitted successfully or if there was a failure.

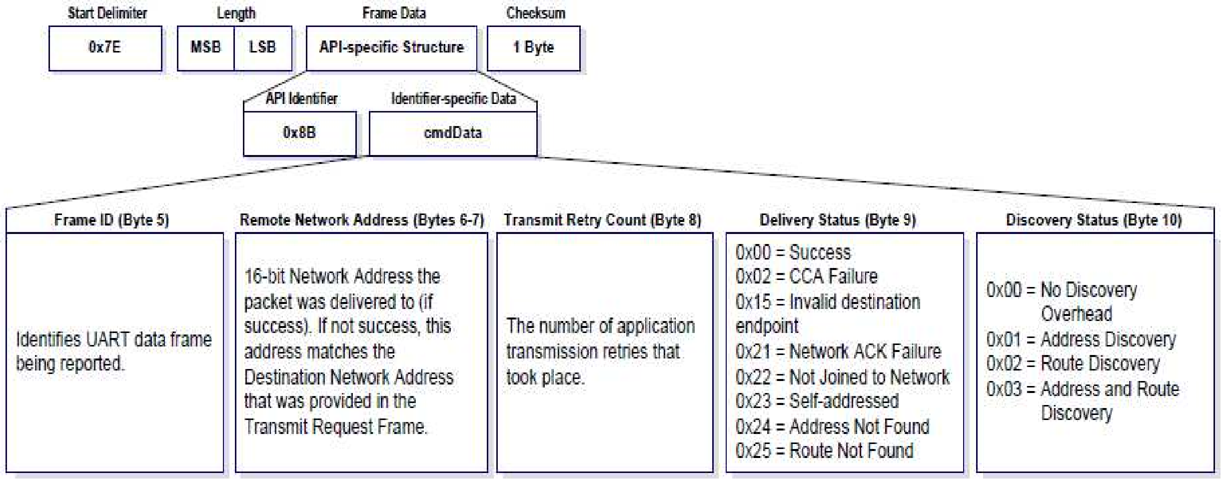


FIGURE 4-7 : TX Status Frame [19]

#### 4.4.2.4 ZigBee Receive Packet

API Identifier Value: (0x90)

When the module receives an RF packet, it is sent out the UART using this message type.

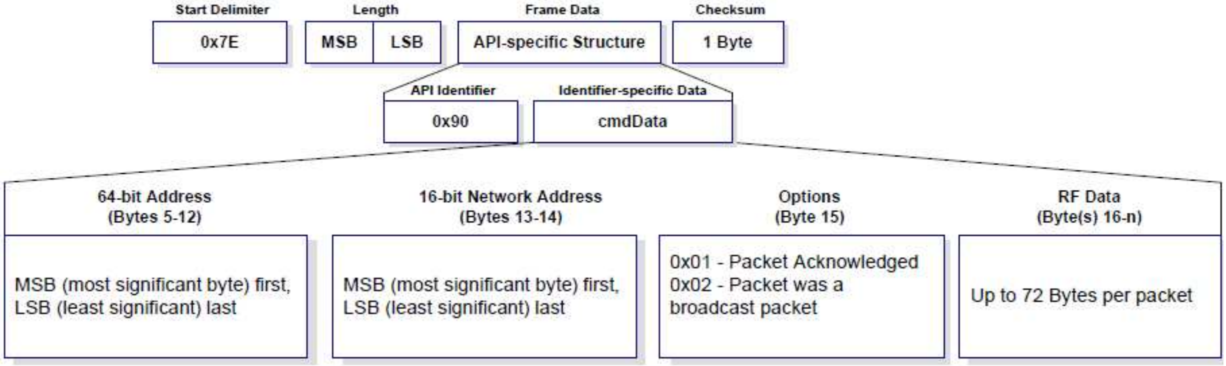
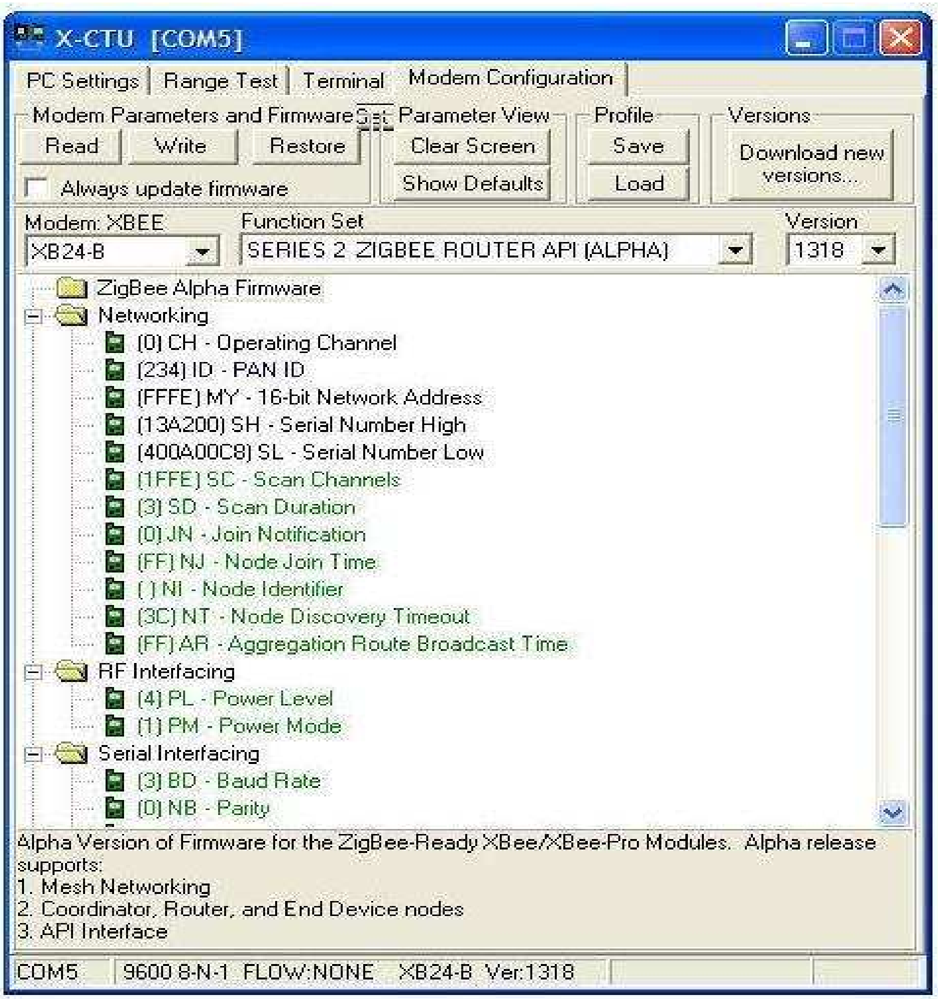


FIGURE 4-8 : ZigBee Receive Packet [19]

### 4.4.3 Example

The X-CTU software is used to configure the module to be Coordinator, Router or End Device. It helps define the node settings by modifying the parameters and flashing it in the ROM.

The Figures 4-9 and 4-10 show the snapshot of the X-CTU software and shows the modem configuration tab wherein the module parameters can be modified and can be flashed to the ROM by hitting the WRITE button.



Modem: XBEE: XB24-B

Function Set: SERIES 2 ZIGBEE ROUTER API (ALPHA)

Version: 1318

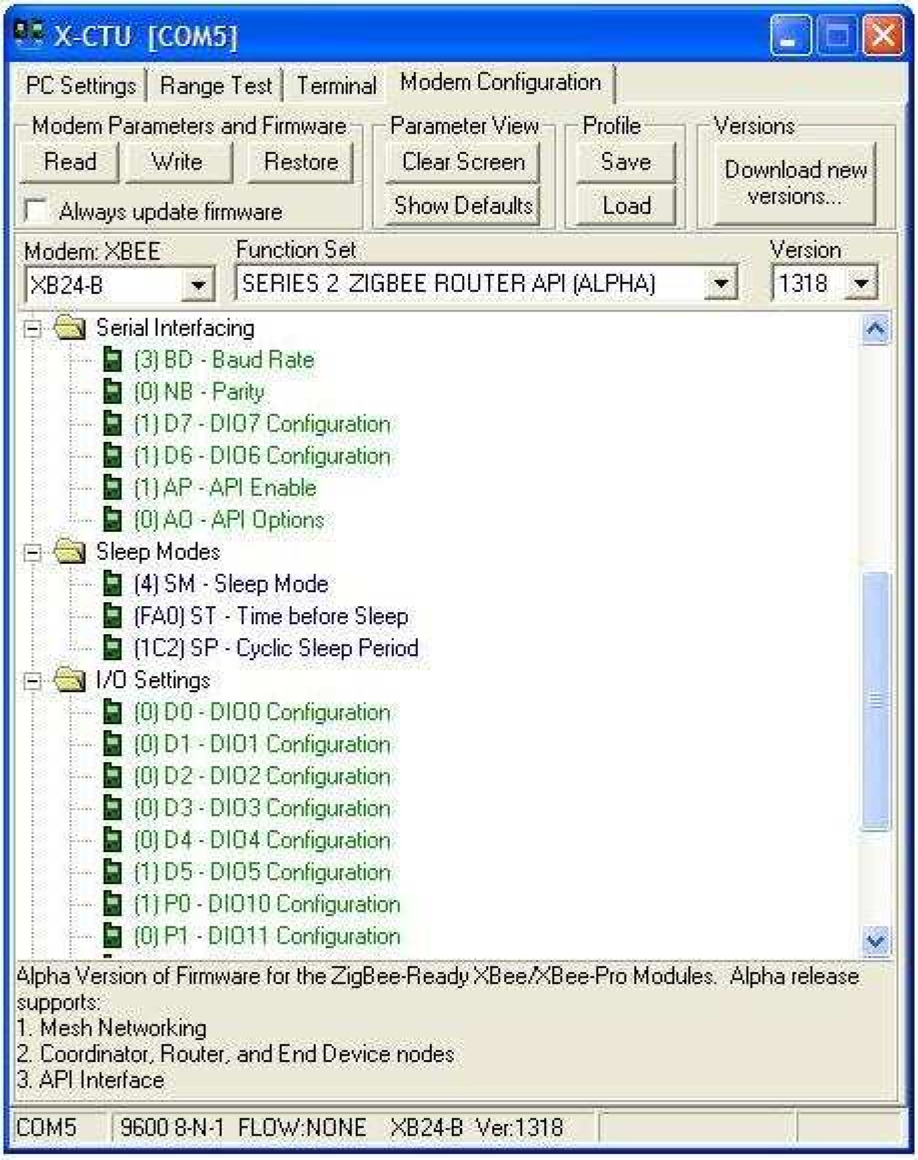
```
ZigBee Alpha Firmware
Networking
    (0) CH - Operating Channel
    (234) ID - PAN ID
    (FFFE) MY - 16-bit Network Address
    (13A200) SH - Serial Number High
    (400A00C8) SL - Serial Number Low
    (1FFE) SC - Scan Channels
    (3) SD - Scan Duration
    (0) JN - Join Notification
    (FF) NJ - Node Join Time
    ( ) NI - Node Identifier
    (3C) NT - Node Discovery Timeout
    (FF) AR - Aggregation Route Broadcast Time
RF Interfacing
    (4) PL - Power Level
    (1) PM - Power Mode
Serial Interfacing
    (3) BD - Baud Rate
    (0) NB - Parity
```

Alpha Version of Firmware for the ZigBee-Ready XBee/XBee-Pro Modules. Alpha release supports:

1. Mesh Networking
2. Coordinator, Router, and End Device nodes
3. API Interface

COM5 | 9600 8-N-1 FLOW:NONE XB24-B Ver:1318

FIGURE 4-9 : X-CTU Modem Configuration Snapshot-1



Modem: XBEE
XB24-B

Function Set
SERIES 2 ZIGBEE ROUTER API (ALPHA)

Version
1318

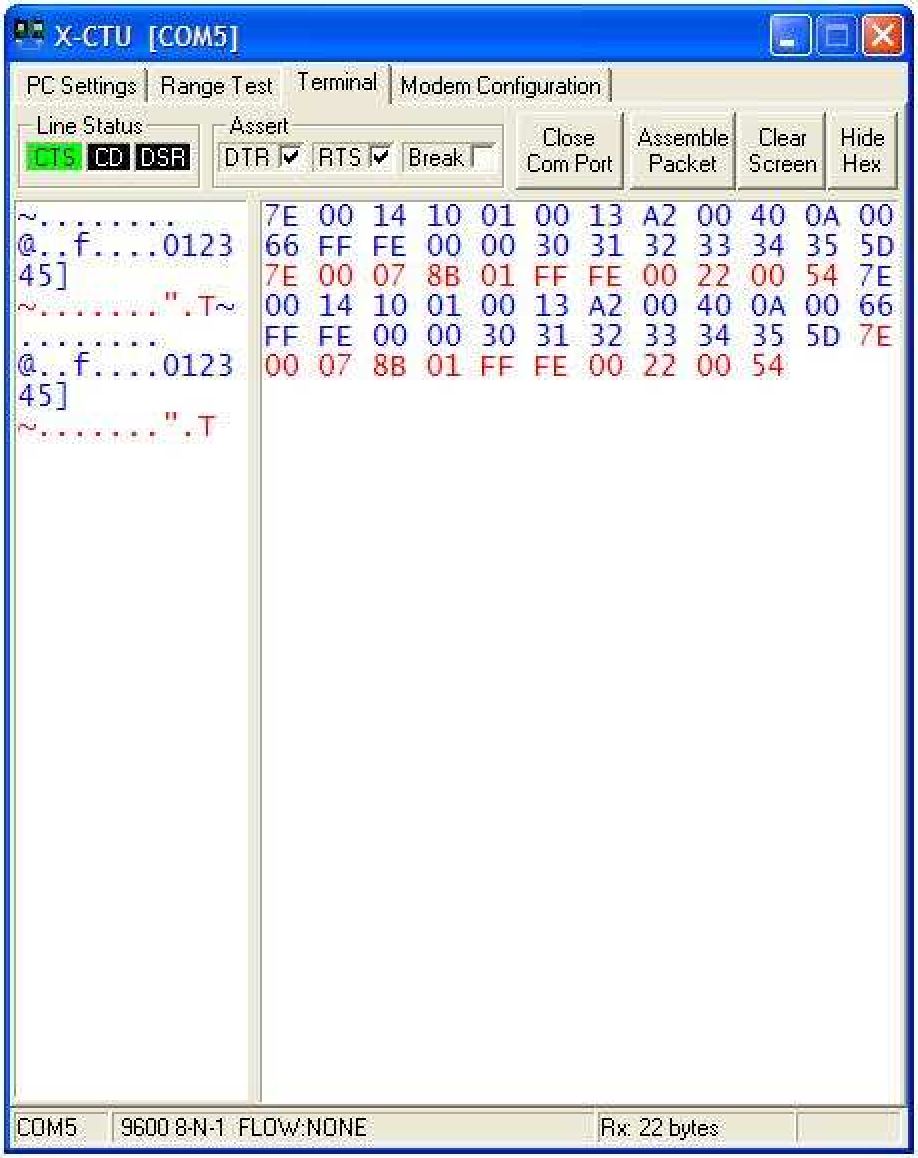
- Serial Interfacing
  - (3) BD - Baud Rate
  - (0) NB - Parity
  - (1) D7 - DIO7 Configuration
  - (1) D6 - DIO6 Configuration
  - (1) AP - API Enable
  - (0) AO - API Options
- Sleep Modes
  - (4) SM - Sleep Mode
  - (FA0) ST - Time before Sleep
  - (1C2) SP - Cyclic Sleep Period
- I/O Settings
  - (0) D0 - DIO0 Configuration
  - (0) D1 - DIO1 Configuration
  - (0) D2 - DIO2 Configuration
  - (0) D3 - DIO3 Configuration
  - (0) D4 - DIO4 Configuration
  - (1) D5 - DIO5 Configuration
  - (1) P0 - DIO10 Configuration
  - (0) P1 - DIO11 Configuration

Alpha Version of Firmware for the ZigBee-Ready XBee/XBee-Pro Modules. Alpha release supports:
1. Mesh Networking
2. Coordinator, Router, and End Device nodes
3. API Interface

COM5 9600 8-N-1 FLOW:NONE XB24-B Ver:1318

FIGURE 4-10 : X-CTU Modem Configuration Snapshot-2

The next Figure 4-11 shows the 24-byte packet transmitted from the node (blue text), while the red text shows the status of the transmitted message. The message sent/received and its status can be observed on the terminal tab in the X-CTU window.



DTR ☑ RTS ☑ Break ☐

```
~........            7E 00 14 10 01 00 13 A2 00 40 0A 00
@..f....0123         66 FF FE 00 00 30 31 32 33 34 35 5D
45]                  7E 00 07 8B 01 FF FE 00 22 00 54 7E
~.......".T~         00 14 10 01 00 13 A2 00 40 0A 00 66
........             FF FE 00 00 30 31 32 33 34 35 5D 7E
@..f....0123         00 07 8B 01 FF FE 00 22 00 54
45]
~.......".T
```

COM5 | 9600 8-N-1 FLOW:NONE | Rx: 22 bytes

FIGURE 4-11 : X-CTU Modem Terminal Window Snapshot -3

Note: Refer Chapter 5 for example data packets used for the experiment.

# CHAPTER 5: EMPIRICAL RESULTS

Zigbee applications typically have 0.1 to 1 percent duty cycle or even lesser.

Following duty cycle is considered for all experimental measurements:

$T_{on}$ = 250 msec

$T_{off}$ = 24750 msec

Period = T = 25000 msec

$$\text{Duty Cycle} = \frac{\text{Ton}}{\text{Ton} + \text{Toff}} \qquad \text{EQUATION 5-1}$$

Hence, Duty Cycle = 1%

Operating voltage for the experiment = 3.3 Volts

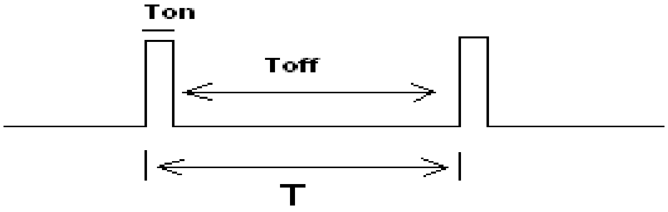


FIGURE 5-1: Duty Cycle

Average current over the entire period is calculated in the following way

Let, I = Average current over the entire period T

$I_1$= Average current over the $T_{off}$ period

$I_2$= Average current over the $T_{on}$ period

Hence,

$$I = \frac{(\frac{Toff}{Ton} * I_1) + I_2}{\left(\frac{Toff}{Ton}\right) + 1} \qquad \text{EQUATION 5-2}$$

Note:

- In the cyclic sleep mode the node device probes the parent every 100ms and checks for the available data.
- If there is pending data to be sent then it will send the data packet, when node wakes up from sleep.
- The transience observed, when the device wakes up, is specific to the chipset used (It includes the first probe made to the parent).
- The current characteristics are obtained by recording the current drawn by the chipset at a sampling rate of 0.5msec. (i.e. ~2000samples/sec)
- The battery under consideration is Energizer AA alkaline battery

  Datasheet [27]

  Date 30th July, 2007.

## 5.1 Brief Summary

TABLE 5-1: Brief Summary of Results

| Transmission Type | Packet Size (Bytes) | Calculated Battery Life (Days) |
|---|---|---|
| No Transmission | - | 1099.23 |
| End Device to Parent | 24 | 458.42 |
| End Device to Parent | 48 | 446.28 |
| End Device to Parent | 72 | 433.1 |
| End Device to End Device(Recipient of Data) | 24 | 798.5 |
| End Device to End Device(Recipient of Data) | 48 | 774.71 |
| End Device to End Device(Recipient of Data) | 72 | 707.62 |
| End Device to End Device(Transmitter of Data) | 24 | 535.86 |
| End Device to End Device(Transmitter of Data) | 48 | 501.39 |
| 1 Retry from End Device to Parent (Unsuccessful) | 24 | 244.87 |
| 1 Retry from End Device to Parent (Successful) | 24 | 235.07 |

The work consists of empirical measurements of current consumption of the battery powered end device for various types of transmissions and estimating the battery life by calculations based on real data.

The column 1 describes the type of data transmission in the network, which include

- End Device transmitting data to its parent

- The End Device transmitting data to another End Device wherein device under measurement is
    - § Transmitter of data
    - § Recipient of data
- End Device transmits to its parent on single retry
    - § Successful data transmission on retry
    - § Unsuccessful data transmission on retry

Column 2 shows the data packet size transmitted over the air for different transmissions. The data packet size is a parameter for performance metrics.

Column 3 shows the battery life of the node based on the power consumption for the chosen duty cycle.

## 5.2 End Device Transmits Data to the Parent

- § This case discusses the End Device to parent data transmission.
- § The graphs shows the current characteristics when, 24 bytes, 48 bytes and 72 bytes of data are sent over the air.
- § A comparison of its effect on battery life is seen in the last graph.

### 5.2.1 No Data Packet Transmitted Over the Air

X – Axis: Time stamps (sec)

Y – Axis: Current (A)

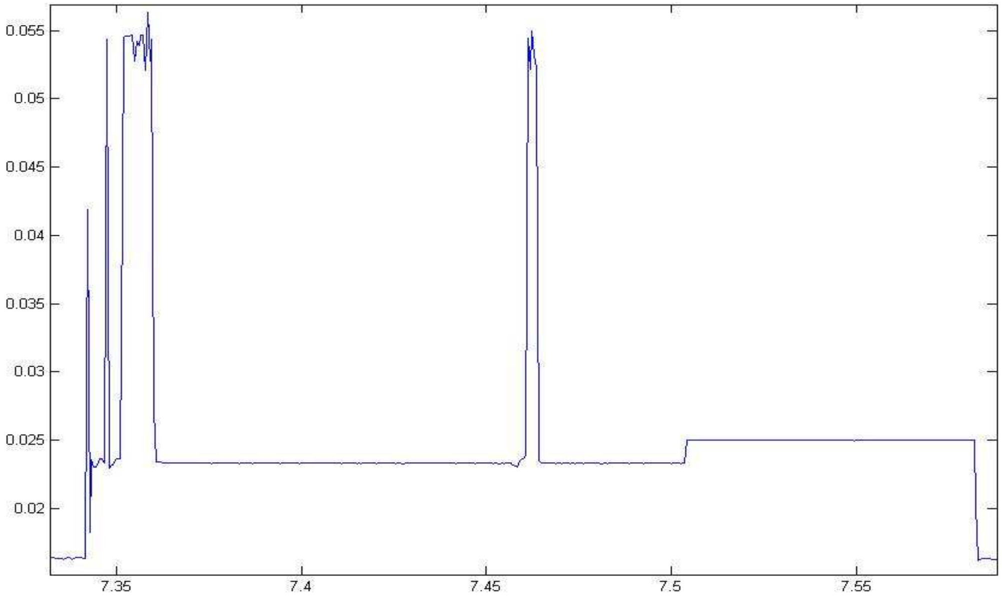


FIGURE 5-2 : Current Profile, No Data Transmitted over the Air

TABLE 5-2: 0 Bytes of Data Transmitted from End Device to Parent

| | |
|---|---|
| Sender | End Device (Reduced function device) |
| Receiver | Parent (Coordinator/Router) |
| Packet/Data size (bytes) | 0 (No data sent/received) |
| Number of hops | 1 |
| Average current over the ON part of duty cycle (mA) | 8.922 |
| Average current over the power down part of duty cycle (mA) | 0.019 |
| Average current over the entire duty cycle (mA) | 0.10803 |

| | |
|---|---|
| Average power consumed over the ON part of duty cycle (W) | 0.0294426 |
| Average power consumed over the power down part of duty cycle (W) | 0.0000627 |
| Estimated battery life (days) | 1099.23 |

Observations [Fig. 5-2]

1. Figure 5-2 shows the behavior of current when no data packet is exchanged over the air.
2. The end device probes its parent for the data. If no data available, then it goes back to idle mode.
3. The receiver is turned on every 100msec to probe for the data.

### 5.2.2 24 Bytes Data Packet Transmitted Over the Air

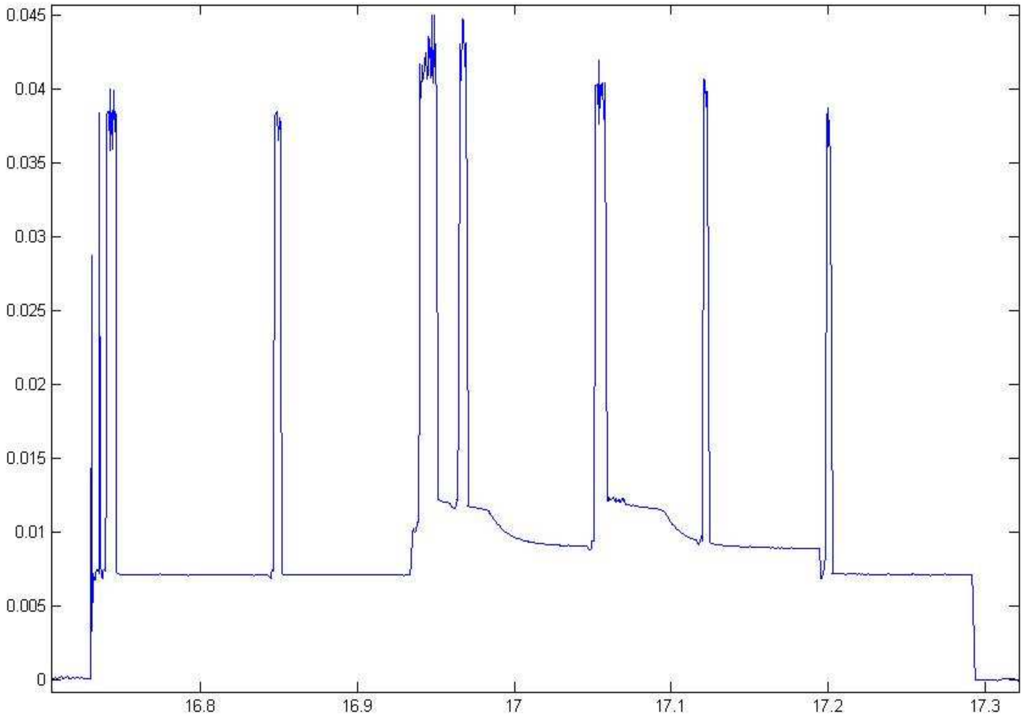


FIGURE 5-3: Current Profile, 24 Data Transmitted over the Air

TABLE 5-3: 24 Bytes of Data Transmitted from End Device to Parent

| | |
|---|---|
| Sender | End Device (Reduced function device) |
| Receiver | Parent (Coordinator/Router) |
| Packet/Data size (bytes) | 24 |
| Number of hops | 1 |
| Average current over the ON part of duty cycle (mA) | 10.82 |
| Average current over the power down part of duty cycle (mA) | 0.019 |
| Average current over the entire duty cycle (mA) | 0.259038 |
| Average power consumed over the ON part | 0.035706 |

| | |
|---|---|
| of duty cycle (W) | |
| Average power consumed over the power down part of duty cycle (W) | 0.0000627 |
| Transmitter ON time (msec) | 22 |
| Receiver ON time (msec) | 7 |
| Average current when transmitter ON | 37.42 |
| Average current when receiver ON | 41.22 |
| Estimated battery life (days) | 458.42 |

Observations

1. It approximately takes 4 msec to switch from transmitter mode to receiver mode
2. The average ON time increases when data transmitted/received
3. Average receiver current is higher than average transmitter current
4. Node probes for data at every 100msec interval (when awake)
5. Acknowledgement received on successful data delivery

### 5.2.3 48 Bytes Data Packet Transmitted Over the Air

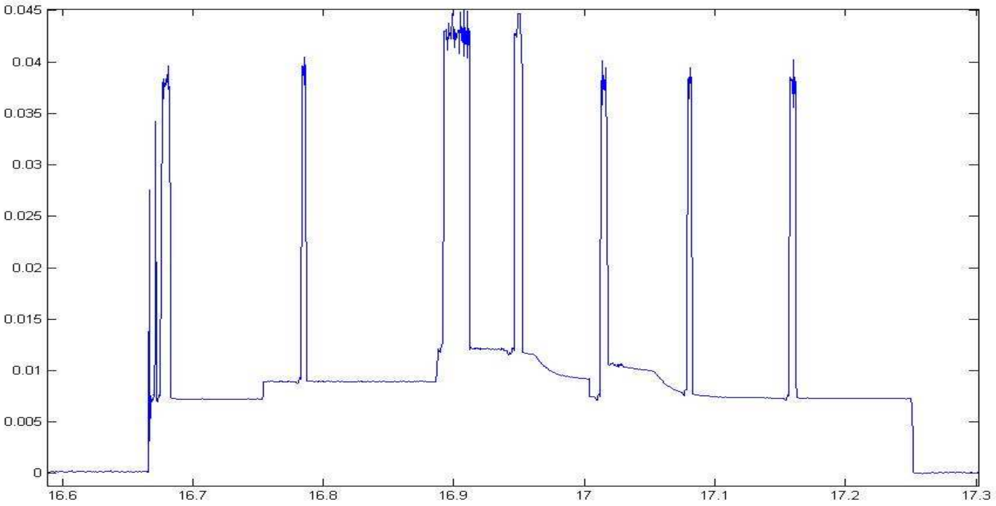


FIGURE 5-4: Current Profile, 48 Data Transmitted over the Air

Average ON period = 573 msec

TABLE 5-4: 48 Bytes of Data Transmitted from End Device to Parent

| | |
|---|---|
| Sender | End Device (Reduced function device) |
| Receiver | Parent (Coordinator/Router) |
| Packet/Data size (bytes) | 48 |
| Number of hops | 1 |
| Average current over the ON part of duty cycle (mA) | 10.925 |
| Average current over the power down part of duty cycle (mA) | 0.019 |
| Average current over the entire duty cycle (mA) | 0.26596 |
| Average power consumed over the ON part of duty cycle (W) | 0.0360525 |
| Average power consumed over the power down part of duty cycle (W) | 0.0000627 |

| | |
|---|---|
| Transmitter ON time (msec) | 23 |
| Receiver ON time (msec) | 7 |
| Average current when transmitter ON | 37.42 |
| Average current when receiver ON | 41.22 |
| Estimated battery life (days) | 446.28 |

Observations

1. Current consumed for transmitting 48 bytes of data is more than current consumed for 24bytes data
2. The transmitter remains On for longer duration
3. The battery power consumption increases

### 5.2.4 72 Bytes Data Packet Transmitted Over the Air

Acknowledgement received on successful data delivery

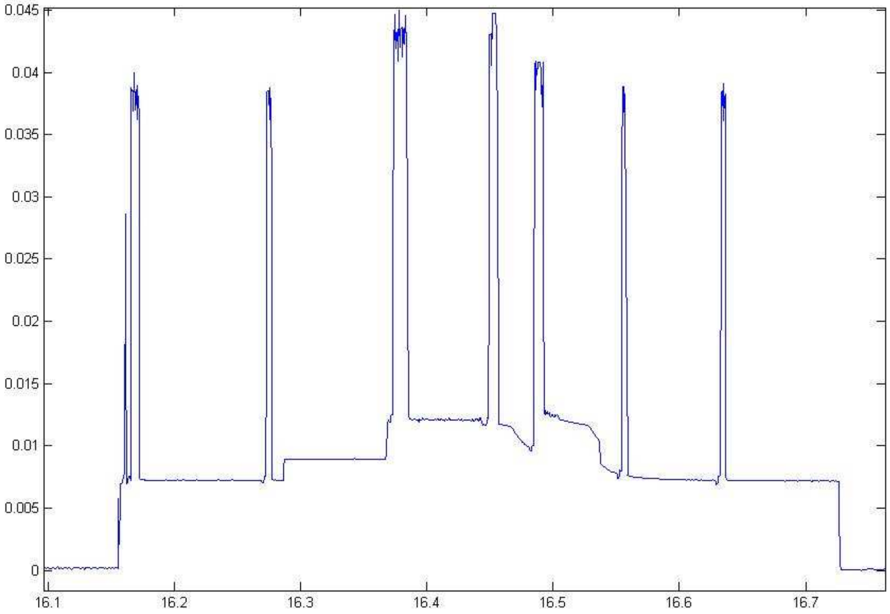


FIGURE 5-5: Current Profile, 72 Data Transmitted over the Air

Average ON period changes to = 577msec

TABLE 5-5: 72 Bytes of Data Transmitted from End Device to Parent

| | |
|---|---|
| Sender | End Device (Reduced function device) |
| Receiver | Parent (Coordinator/Router) |
| Packet/Data size (bytes) | 72 |
| Number of hops | 1 |
| Average current over the ON part of duty cycle (mA) | 11.22 |
| Average current over the power down part of duty cycle (mA) | 0.019 |
| Average current over the entire duty cycle (mA) | 0.274183 |
| Average power consumed over the ON part of duty cycle (W) | 0.037026 |
| Average power consumed over the power down part of duty cycle (W) | 0.0000627 |
| Transmitter ON time (msec) | 22 |
| Receiver ON time (msec) | 7 |
| Average current when transmitter ON | 37.42 |
| Average current when receiver ON | 41.22 |
| Estimated battery life (days) | 433.1 |

Observations

1. The transmitter ON period does not change considerably. Distribution of current changes the average current over the ON period of duty cycle
2. The battery life is affected by the size of data transmitted
3. Figure 5-5 shows the distribution of current when 72 bytes data transmitted

Plot of Battery capacity vs. time (days) for the transmission of data packets of different size

Key:

Blue: No packet transmitted

Green: 24 bytes packet transmitted

Red: 48 bytes packet transmitted

Marine Blue: 72 bytes packet transmitted

Log Scale

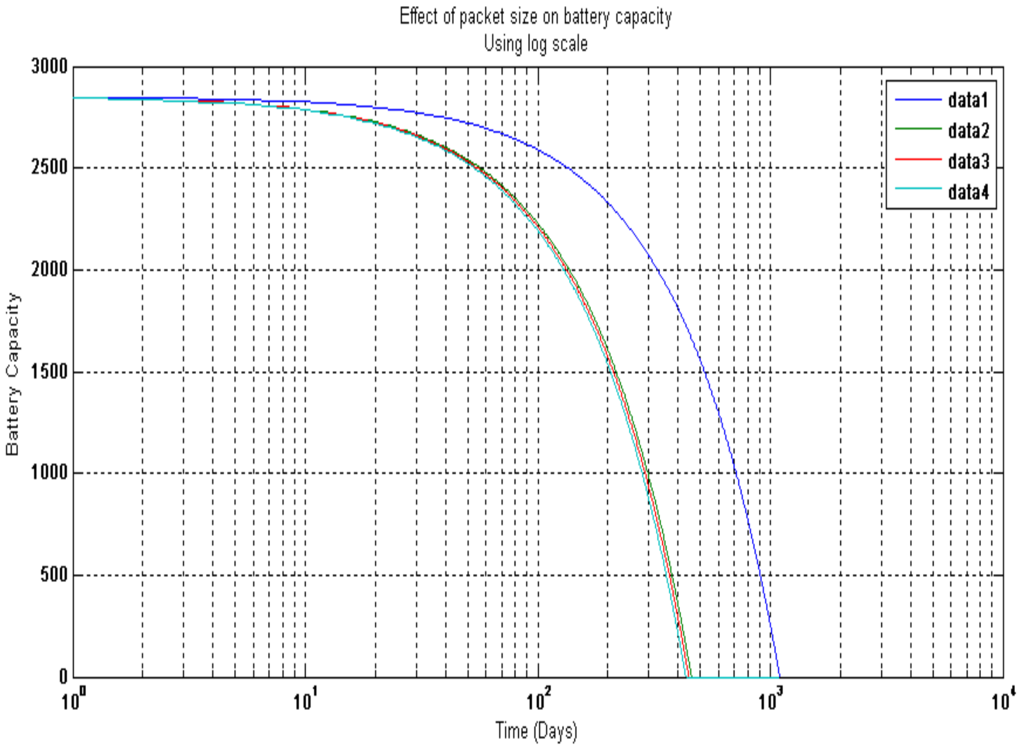


FIGURE 5-6: Effect of Packet Size on Battery Life of End Device (Data transmitted from End Device to Parent over the Air) on Log Scale

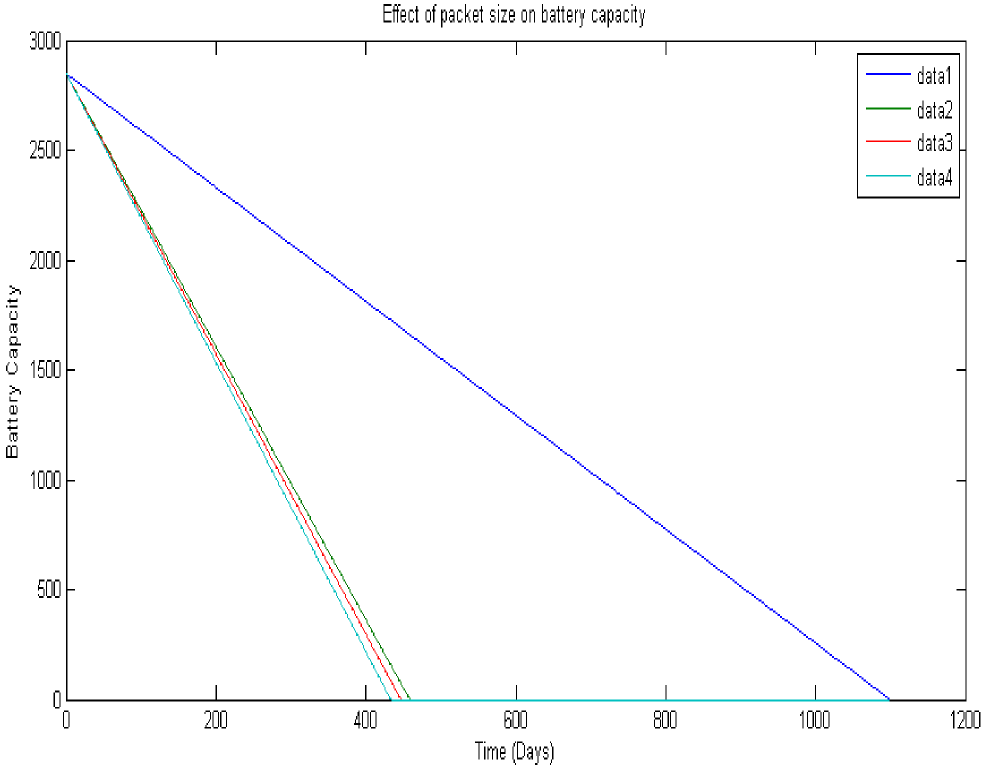


FIGURE 5-7: Effect of Packet Size on Battery Life of End Device (Data transmitted from End Device to Parent over the Air) on Linear Scale

Observations

1. The battery life is affected by the size of data packet being transmitted
2. The battery life can be extended by changing the period and duty cycle

## 5.3 End Device transmits data to other End device

### 5.3.1 The End Device Under Measurement is the Recipient of Data

§ In this case the end device receives the data send by the other end device

§ The device probes the parent for the data and the data is received at that instance.

- The graphs shows the current characteristics when 24 bytes, 48 bytes and 72 bytes of data are received over the air.
- A comparison of its effect on battery capacity can be seen in the last graph

#### 5.3.1.1 24 Bytes of Data Received by End Device from End Device

Average ON time duration changed to = 318msec

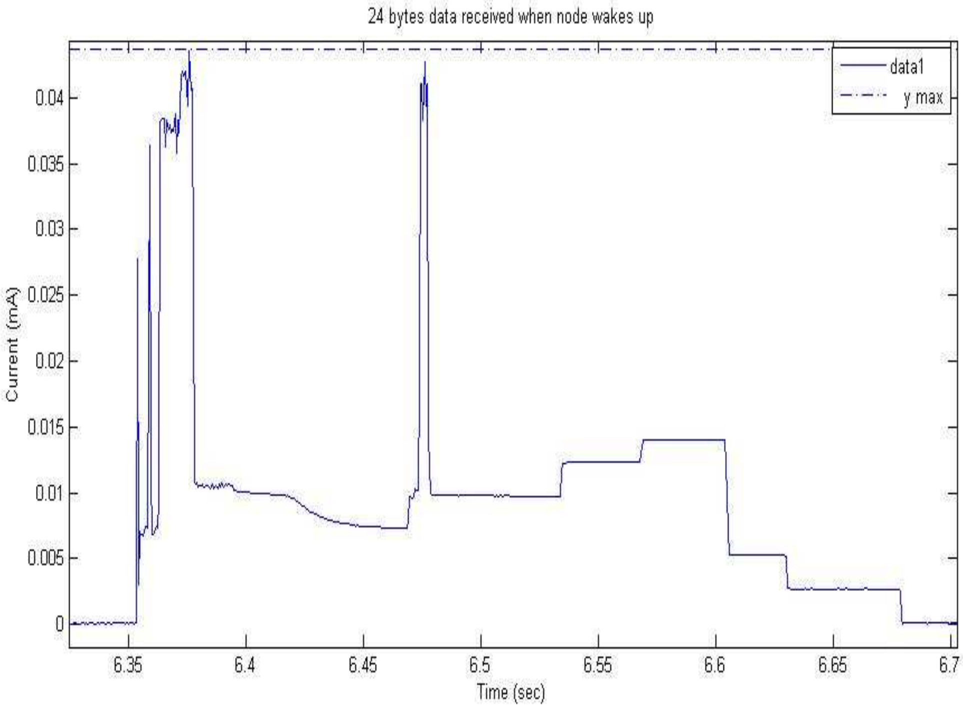


FIGURE 5-8 : Current Profile, 24 Bytes of Data Received over the Air

TABLE 5-6: 24 Bytes of Data Received by End Device from End Device

| | |
|---|---|
| Sender | End Device (Reduced function device) |
| Receiver | End Device (Reduced function device) |
| Packet/Data size (bytes) | 24 |
| Number of hops | 2 |
| Average current over the ON part of duty | 10.4 |

| | |
|---|---|
| cycle (mA) | |
| Average current over the power down part of duty cycle (mA) | 0.019 |
| Average current over the entire duty cycle (mA) | 0.150688 |
| Average power consumed over the ON part of duty cycle (W) | 0.037026 |
| Average power consumed over the power down part of duty cycle (W) | 0.0000627 |
| Receiver ON time (msec) | 16 |
| Average current when receiver ON | 38.9 |
| Estimated battery life (days) | 798.5 |

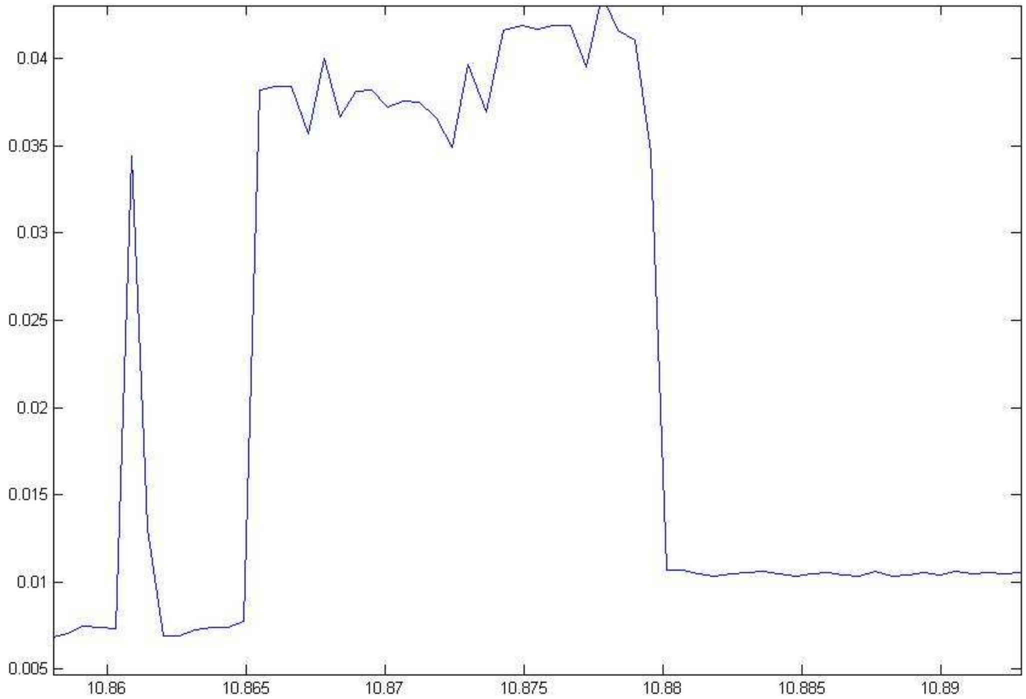


FIGURE 5-9 : Current Profile, 48 Bytes of Data Received over the Air

Observations

1. The node probes for data when it comes out of power down mode.

2. The data is received from the parent (Coordinator/Router)
3. If data is ready, then it is received during the first probe to the parent.

#### 5.3.1.2 48 Bytes of Data Received by End Device from End Device

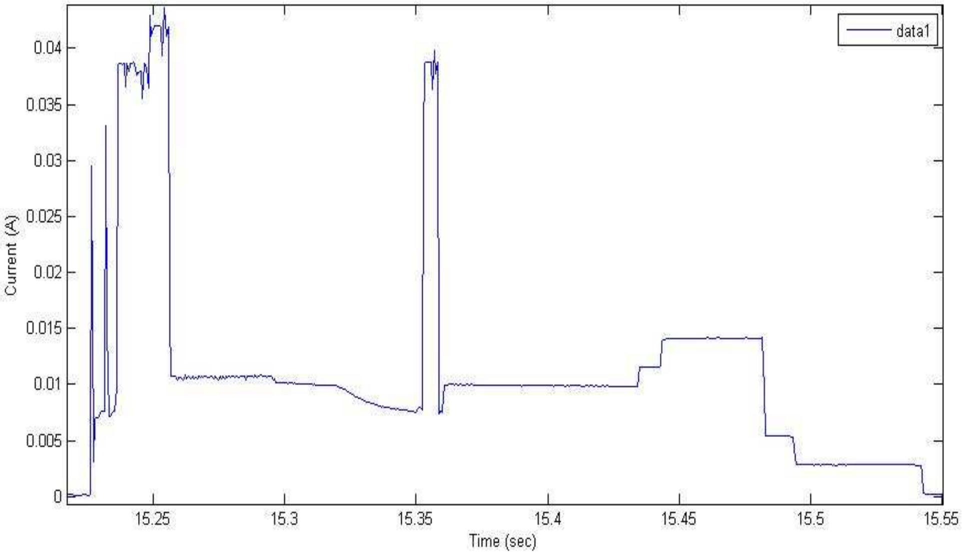


FIGURE 5-10 : Current Profile, 48 Bytes of Data Received over the Air

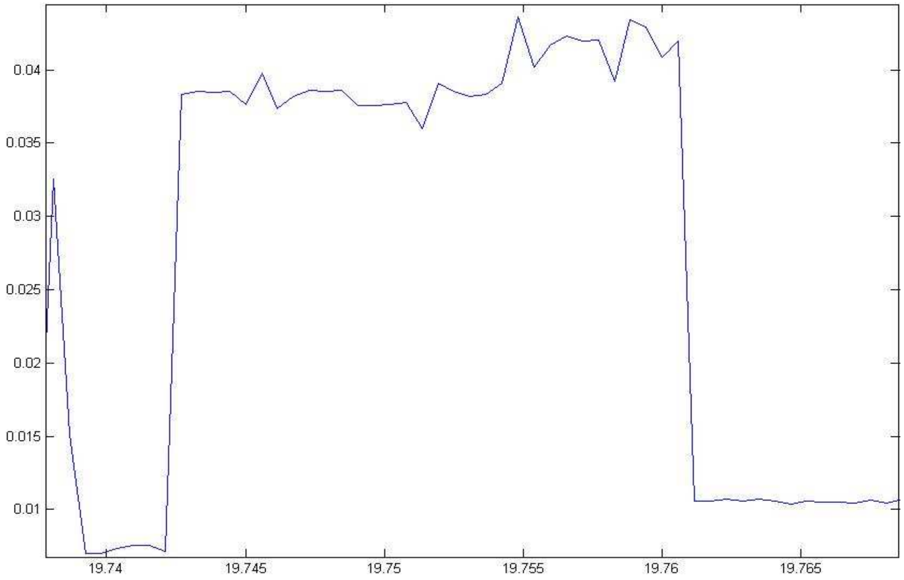


FIGURE 5-11 : Current Profile, Receiver Current

TABLE 5-7: 48 Bytes of Data Received by End Device from End Device

| | |
|---|---|
| Sender | End Device (Reduced function device) |
| Receiver | End Device (Reduced function device) |
| Packet/Data size (bytes) | 48 |
| Number of hops | 2 |
| Average current over the ON part of duty cycle (mA) | 11.16 |
| Average current over the power down part of duty cycle (mA) | 0.019 |
| Average current over the entire duty cycle (mA) | 0.159457 |
| Average power consumed over the ON part of duty cycle (W) | 0.036828 |
| Average power consumed over the power down part of duty cycle (W) | 0.0000627 |
| Receiver ON time (msec) | 19 |
| Average current when receiver ON | 38.9 |
| Estimated battery life (days) | 774.71 |

Observations

1. The receiver remains ON for longer duration to receive 48bytes of data

### 5.3.1.3 72 Bytes of Data Received by End Device from End Device

Average ON time duration changed to = 325 msec

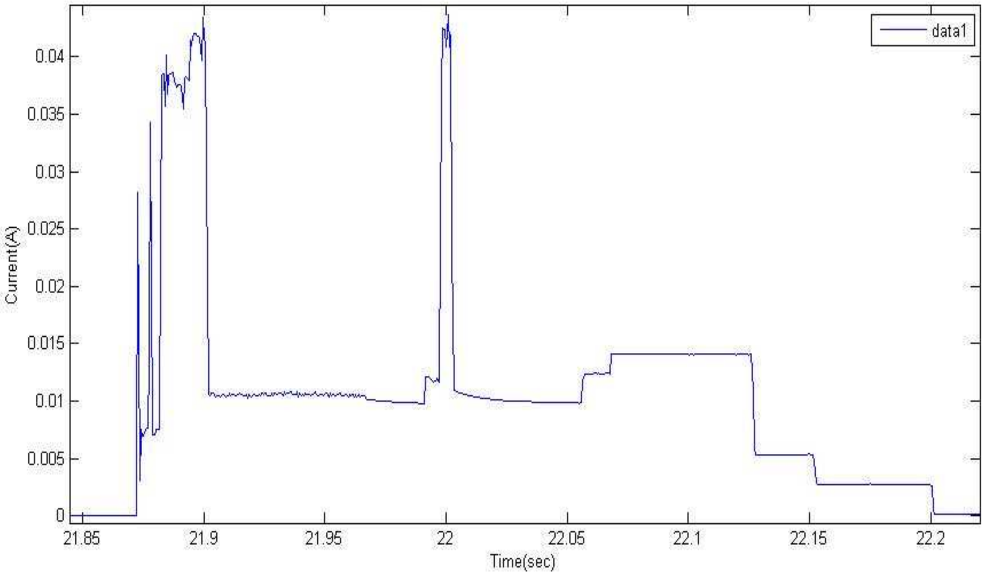


FIGURE 5-12 : Current Profile, 48 Bytes of Data Received over the Air

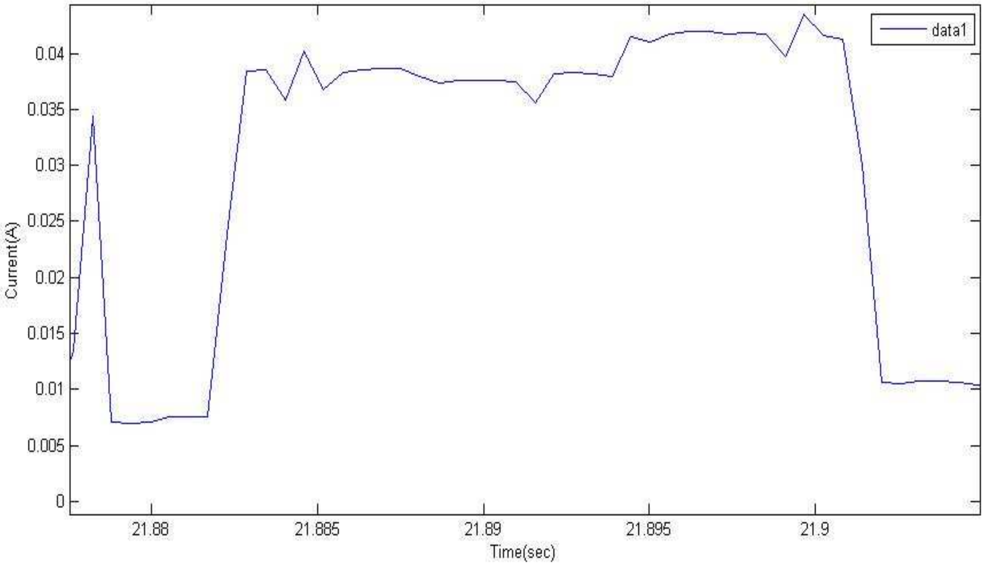


FIGURE 5-13: Current Profile, Receiver Current for 72 Bytes Data

TABLE 5-8: 72 Bytes of Data Received by End Device from End Device

| | |
|---|---|
| Sender | End Device (Reduced function device) |
| Receiver | End Device (Reduced function device) |
| Packet/Data size (bytes) | 72 |
| Number of hops | 2 |

| | |
|---|---|
| Average current over the ON part of duty cycle (mA) | 11.5 |
| Average current over the power down part of duty cycle (mA) | 0.019 |
| Average current over the entire duty cycle (mA) | 0.167814 |
| Average power consumed over the ON part of duty cycle (W) | 0.03795 |
| Average power consumed over the power down part of duty cycle (W) | 0.0000627 |
| Receiver ON time (msec) | 20 |
| Average current when receiver ON | 38.9 |
| Estimated battery life (days) | 707.62 |

Observations

1. Receiver remains ON for long duration compared to 24 and 48 bytes data

Plot of Battery capacity vs. time (days) for the reception of data packets of different size

Red: 72 bytes packet received

Green: 48 bytes packet received

Blue: 24 bytes packet received

Log Scale

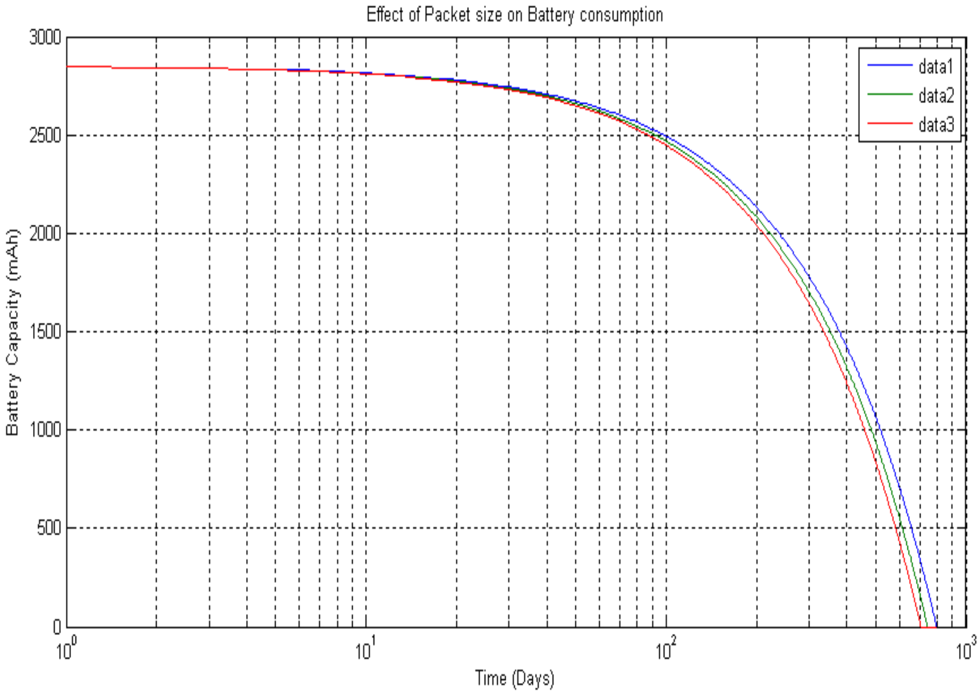


FIGURE 5-14: Effect of Packet Size on Battery Life of End Device (Data received from another End Device over the Air) on Log Scale

Linear Scale

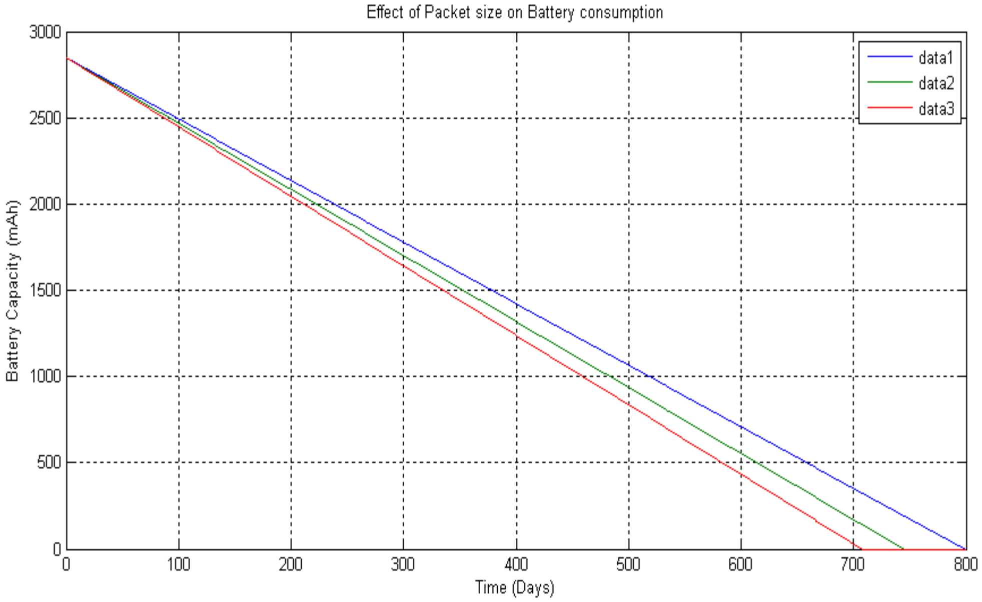


FIGURE 5-15: Effect of Packet Size on Battery Life of End Device (Data received from another End Device over the Air) on Linear Scale

Observations

1. The battery lasts longer when receiving data compared to sending the data
2. The battery consumption increases with the increase in data packet size received

### 5.3.2 The End device Under Measurement is the Sender of the Data

§ In this case the end device sends the data and receives ack from the other end device

§ The device also probes the parent for the incoming data it any.

§ The graphs shows the current characteristics when 24 bytes, 48 bytes and of data are sent over the air.

§ A comparison of its effect on battery capacity can be seen in the last graph

#### 5.3.2.1 24 Bytes of Data Transmitted by End Device to End Device

Average ON time duration changed to = 464 msec

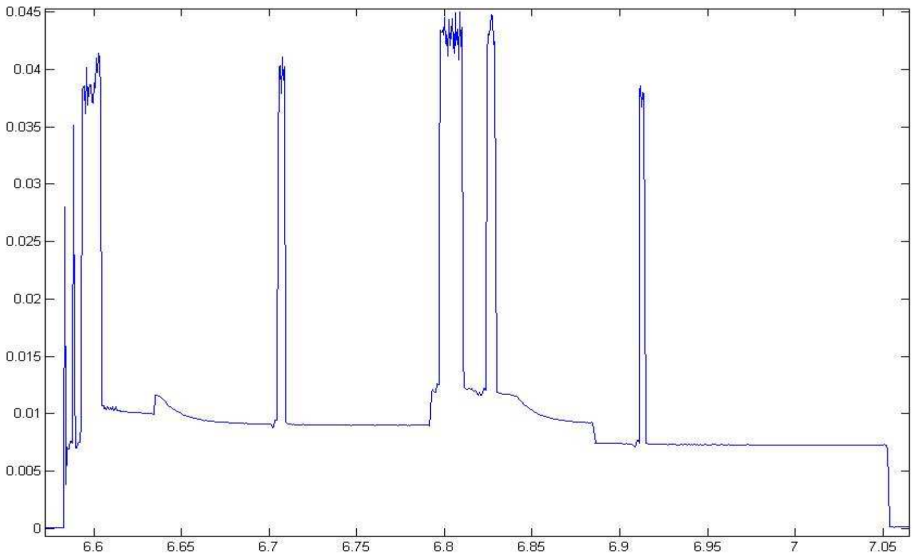


FIGURE 5-16: Current Profile, 24 Bytes of Data Transmitted over the Air (To other End Device)

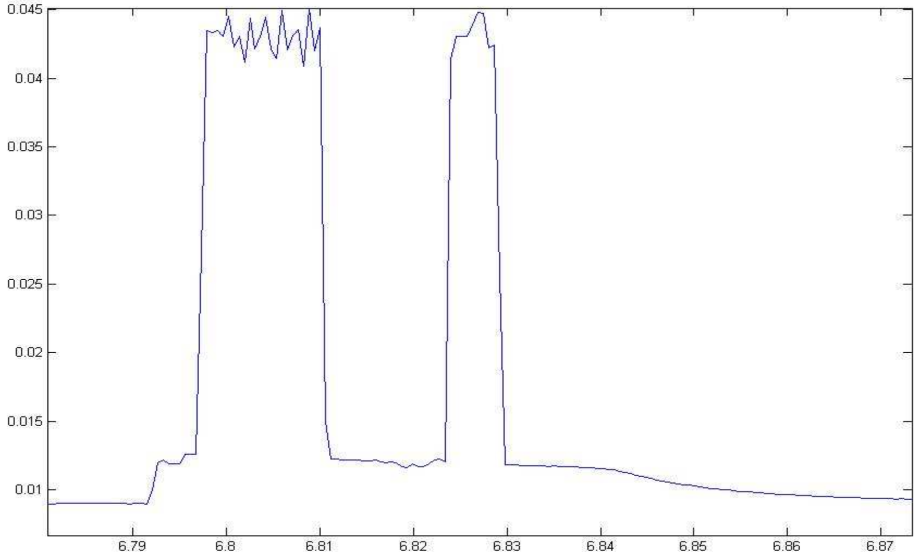


FIGURE 5-17: Current Profile, Transmitter and Receiver Current for 24 Bytes Data

TABLE 5-9: 24 Bytes of Data Transmitted from End Device to End Device

| | |
|---|---|
| Sender | End Device (Reduced function device) |
| Receiver | End Device (Reduced function device) |
| Packet/Data size (bytes) | 24 |
| Number of hops | 2 |
| Average current over the ON part of duty cycle (mA) | 11.25 |
| Average current over the power down part of duty cycle (mA) | 0.019 |
| Average current over the entire duty cycle (mA) | 0.221602 |
| Average power consumed over the ON part of duty cycle (W) | 0.037125 |
| Average power consumed over the power down part of duty cycle (W) | 0.0000627 |
| Receiver ON time (msec) | 19 |

| | |
|---|---|
| Average current when receiver ON | 38.8 |
| Estimated battery life (days) | 535.86 |

Observations

1. The behavior is not very deterministic, as environment and the behavior of other nodes affect the performance on the node under test.

### 5.3.2.2 48 Bytes of Data Transmitted by End Device to End Device

Average ON time duration changed to = 508 msec.

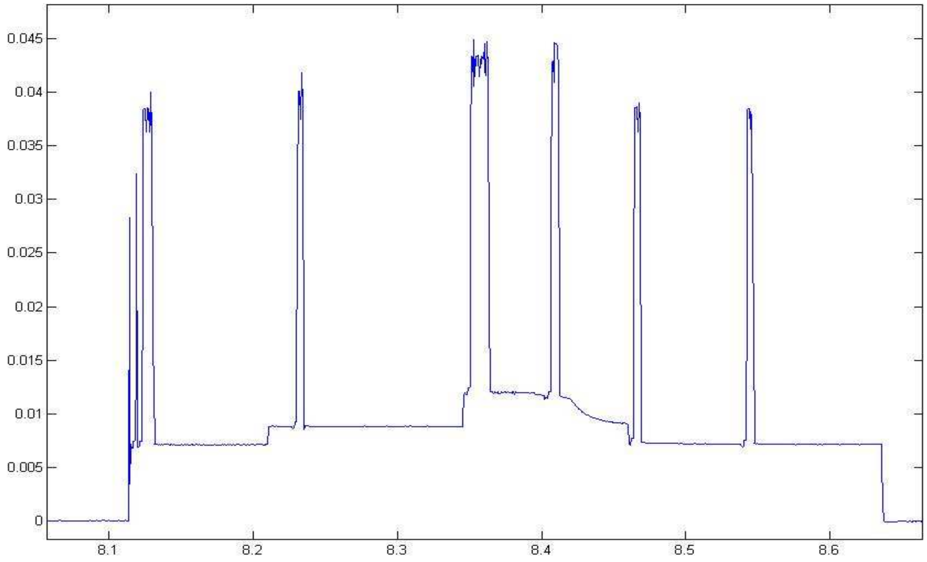


FIGURE 5-18: Current Profile, 48 Bytes of Data Transmitted over the Air (To other End Device)

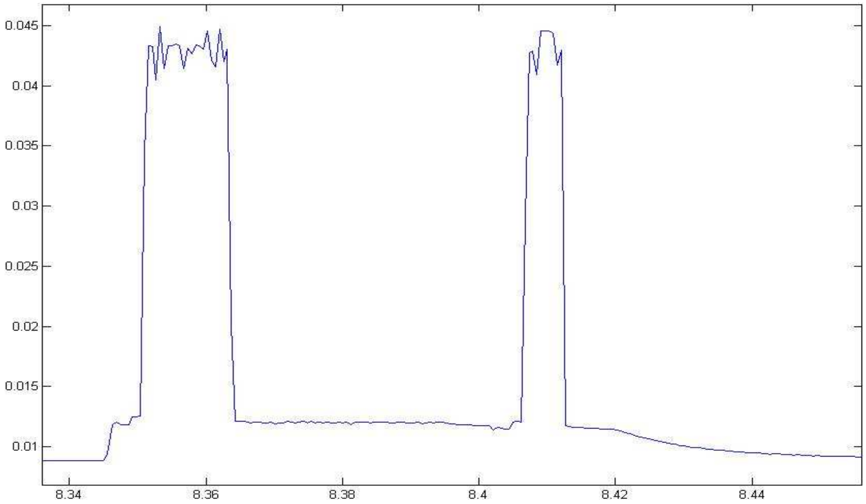


FIGURE 5-19: Current Profile, Transmitter and Receiver Current for 48 Bytes Data

TABLE 5-10: 48 Bytes of Data Transmitted from End Device to End Device

| | |
|---|---|
| Sender | End Device (Reduced function device) |
| Receiver | End Device (Reduced function device) |
| Packet/Data size (bytes) | 48 |
| Number of hops | 2 |
| Average current over the ON part of duty cycle (mA) | 10.85 |
| Average current over the power down part of duty cycle (mA) | 0.019 |
| Average current over the entire duty cycle (mA) | 0.236838 |
| Average power consumed over the ON part of duty cycle (W) | 0.035805 |
| Average power consumed over the power down part of duty cycle (W) | 0.0000627 |
| Receiver ON time (msec) | 19 |
| Average current when receiver ON | 38.8 |
| Estimated battery life (days) | 501.39 |

Observations

1. The delay between sending of data and reception of data changes for different transmissions
2. The network traffic, topology and environmental conditions affect the ON time of the node

## 5.4 Estimation of Effect of Retries on Battery Power Consumption

The retries are introduced in the system to increase the probability of true data transmission. If the node fails to communicate on the first try, then it tries again. The number of retries can be controlled by the firmware (not to exceed 3) and the selection of the number is done depending on the application and network environment.

When a device transmits a data packet, it waits for network level acknowledgement that it should receive from its parent. If end device does not receive the acknowledgement from its parent, it will retransmit the data. However, the end device must poll the parent to check for available data, in order to receive the acknowledgement. The probe is made every 100msec.

The constants that define the characteristics of the APS sub-layer is

apscAckWaitDuration

The maximum number of seconds to wait for an acknowledgement to a transmitted frame:

$0.05 * (2*nwkcMaxDepth) + (\text{security encrypt/decrypt delay})$, where the (security encrypt/ decrypt delay) = 0.1

Hence, $T_i = 0.05 * (2*1) + 0.1$

Ti = 200 msec

If there is no acknowledgement in 200msec, it tries to send data again.

The effect of current consumption will be estimated in the following way:

For End device sending data to the parent, will receive the acknowledgement through the parent.

The formula for current consumption estimation due to retries can be stated as follows:

Let,

I = Average current over the entire cycle

Ir = Average current consumed when the node receives the ack

Tr= Average amount of time the receiver remains ON when the node receives an ack

Ip = Average current consumed when the node probes its parent for data

Tp= Average amount of time the receiver remains ON when the node probes its parent

It = Average current consumed when the node transmits the data to its parent

Tt = Average amount of time the transmitter remains ON when it sends 24 bytes of data

Ii  = Average current consumed when the node is idle

Ti = Average amount of time the node remains in idle state when is waiting for an ack

I = Average current over the entire cycle

For 1 unsuccessful retry the Average current over the ON period will be

$$I1 = \frac{It.Tt+2Ip.Tp+Ii.Ti-Ir.Tr}{Ton} \qquad \text{EQUATION 5-3}$$

For 1 successful retry the Average current over the ON period will be

$$I1 = \frac{It.Tt + Ip.Tp + Ii.Ti + Ir.Tr}{Ton}$$ EQUATION 5-4

Using the above formula for following set:

Using the measurements from Table 5-3, the formula from above and the behavior of node under cyclic sleep period.

End Device transmits data to its parent

- In this case the End Device sends the data to its parent and waits for an acknowledgement
- A comparison of its effect on battery capacity can be seen in figure 5-6

### 5.4.1 The Device does Single Retry but Unsuccessful to Receive the Acknowledgement

Using Equation 5-3 and using the readings from the Table 5-3

TABLE 5-11: Parameters for equation 5-3 and 5-4

| | |
|---|---|
| It (mA) | 37.42 |
| Ip (mA) | 44.2 |
| Ii (mA) | 8.93 |
| Ir (mA) | 44.22 |
| Tt (msec) | 22 |
| Tp (msec) | 5 |
| Ti (msec) | 195 |
| Tr (msec) | 7 |

Ion = 10.82mA

Hence, using equation 5-3, we get

$I_1$ = 4.799 mA

Hence total ON current = Ion + $I_1$ = 15.619mA

ON period changes to = 562 + 200 = 762msec

Hence average current over the entire cycle = 0.484949mA

Hence current can be approximated to be continuous discharge of 0.484949 mA from the battery.

If the battery capacity is 2200mAh then the ideal battery life would be

= 2850/0.484949

= 244.87 days

### 5.4.2 The Device does Single Retry and Successfully Receives the Acknowledgement on Retry

Ion = 10.82mA

Hence, using the values from table 4-10 and equation 4-4, we get

Hence, I1 = 5.4755mA

Hence total ON current = Ion + I1 = 16.2955mA

ON period changes to = 562 + 200 = 762msec

Hence average current over the entire cycle = 0.505156mA

Hence current can be approximated to be continuous discharge of 0.505156 mA from the battery.

If the battery capacity is 2200mAh then the ideal battery life would be

= 2850/0.505156

= 235.07 days

Using the calculations from 5.3.1 and 5.3.2 we plot the graph of time the battery lasts versus the battery capacity,

Green: Unsuccessful Retry

Blue: Successful Retry

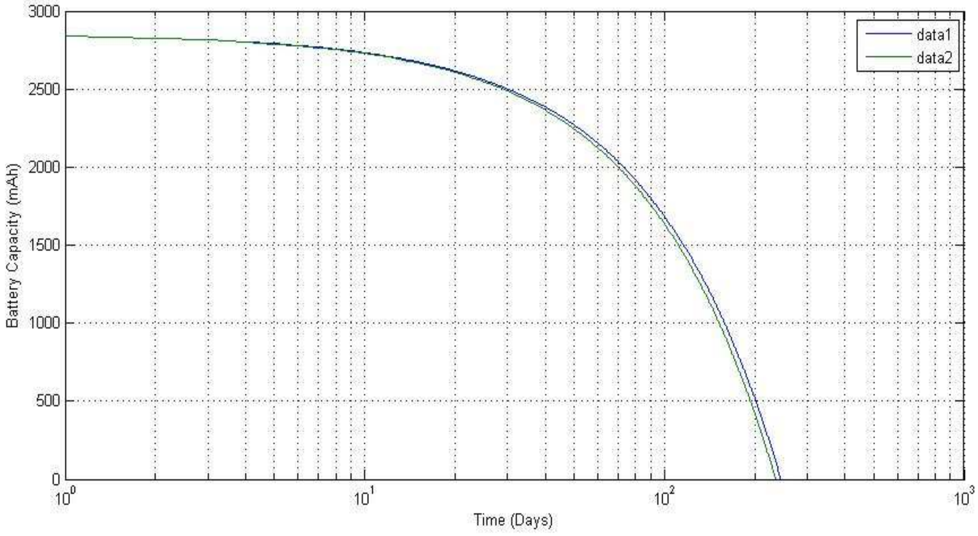


FIGURE 5-20: Effect of Packet Size on Battery Life of End Device for Unsuccessful and Successful Retry (24 bytes data transmitted) on Log Scale

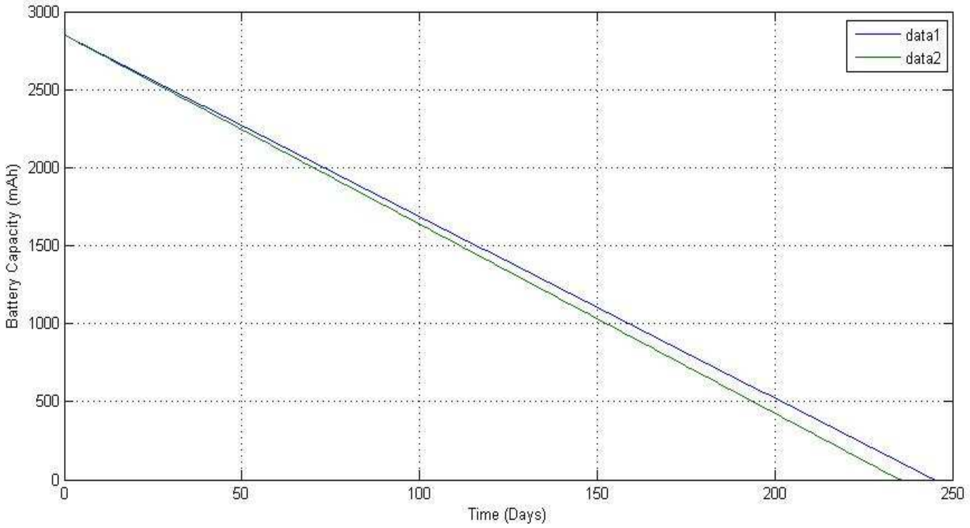


FIGURE 5-21: Effect of Packet Size on Battery Life of End Device for Unsuccessful and Successful Retry (24 bytes data transmitted) on Linear Scale

Observations

1. Retries affect the system adversely bringing the average life of the node down by approximately 45 percent.
2. The node will remain ON for longer duration of time, affecting the battery power consumption

The retries are very beneficial for the system to assure the higher probability of data transmission in the network. But, the trade-off, continual retry for every transmission can bring the battery life of the system down by ~45%. Hence in such cases the network size and density can be altered to avoid repeated retries.

# CHAPTER 6: CONCLUSION

Battery power consumption is the most important performance metric in the ZigBee networking system. The proposed work is the step to provide the effect of various transmission conditions on battery life of the node in the ZigBee Mesh networking system. This work is completely based on empirical data measurements, thus making it close to the real life behavior of the system.

From the observations we conclude that:

1. The packet size transmitted or received over the air affects the battery life of a system. viz. The battery life comes down by 5.24% for a 72 bytes packet versus 24bytes packet
2. The power consumption depends on the function of the node. Viz. If the node is recipient of the data then it is expected to last approximately 63% more than the node, which transmits 24 bytes of data.
3. The transmission retries are expected to affect the Zigbee devices severely as they can bring down the battery life by almost 45% (for a retry on every transmission).

The will prove useful in following ways:

1. Comparison can be made between the theoretical and experimental data by the application developers.

2. It will help the developers to make a decision over the size and density of the network, keeping in mind the effect of packet size and transmission retries.
3. It will help compare the protocol with other comparable technologies in future.
4. It will help select the right duty cycle for the device thus the device life and in turn network life can be estimated.

## Future Work

1. The research can be extended for the scaled network having large number of End Nodes. The battery power consumption of an End Device can be examined in a large mesh network.

2. The measurements can be validated by duplicating the work using 900MHz radios. As 2.4GHz frequency band is rather congested, the 900MHz band is gaining popularity.

3. The power consumption of routers can be monitored by introducing sleep modes in routers.

# REFERENCES

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[3] Howitt, I. Neto, R. Jing Wang Conrad, J.M.; “Extended energy model for the low rate WPAN” appears in Mobile Adhoc and Sensor Systems Conference, 2005. IEEE International Conference

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