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XBee Module Characteristics

And XBee Transmission Ranges

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Bee Module Characteristics and XBee Transition Ranges

Abstract:
As the needs of wireless grows and everything becomes more depending on wireless communications, this projects comes to find out the Power Consumption, Covering Range and some other critical issues. XBee is a particular brand of Zigbee compliant radios made by Digi International. It is supposed to be Zigbee compatible but as some enhancements in the software stack made to simplify the usage of the modules but it makes them not exactly Zigbee compatible. The project is to figure out the Electrical Characteristics/Power Consumption in different modes, and Coverage Range and the effect of the environments on the quality of the communications.

Keywords:
XBee, Zigbee; Arduino; Oscilloscope; Multimeter; Power Consumption; Range Test; EMC; FCC; Wireless communication.

Language:
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Approved by:

PhD in Computer Science Daniel Einarson **Date**
Examiner

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Mariwan Jalal
Malmö, 2012-08-21

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1 INTRODUCTION

In this chapter the aim of the project, the structure and the background of the will be introduced.

1.1 BACKGROUND

Technology in the last twenty years has made significant steps forward. One of the most important aspects is the wireless and mobile technology. Everything becoming mobile and uses wireless communication. In the early of 90th, Internet made a big revolution. Nowadays, in general, the communications and mobile communications or wireless communications becoming the most noticeable technology. As the needs of wireless communications are growing, the requirements will also grow and changes.

Many protocols and devices have invented. Generally, wireless communications made using radio frequency in different ranges. Some uses low frequency and other high frequency as Infrared. Each protocol and each wireless communications has their advantage and disadvantage.

The needs of wireless communications of peripherals with computers were the motivation behind effort to find out more and more way of communications between these devices and the computer. Infrared and Bluetooth is one of the most famous that replaces the cable in connecting different devices to computer like phones, mice, keyboard...etc.

This project is a research based on XBee module to determine and acknowledge the characteristics, hardware properties, Mode of operations and its effect on the power consumptions. The research will try to find out the best condition for running the modules, and the advantage – disadvantage in using XBee as a product of Digi international.

1.2 STRUCTURE

The report starts with a brief detail about the aim of this project. Chapter 2 is a short history about the Zigbee and XBee modules and other hardware that is not XBee but Zigbee compatible. Chapter 3 is about the documentation and tests done by the producer to get mandatory certificates as CE and its input to our research. Chapter 4 is for the equipments used in the research.

From Chapter 5 the research starts with describing the test setup and configurations used in the research and different scenario used in the research. Chapter 6 contains collected results from the tests made during the different project parts.
Chapter 7 will summarize the results, and clarify some results with graph. Then comes chapter 8 which contains some suggestions and future works might be required in the same field. And last chapter will be chapter 9 which is the conclusions obtained in the project.

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1.5 PROJECT AIM

The aim of the research is to find out facts about XBee power consumption and range of usage. The project will also try to find out the facts about XBee as a low power communication device how it can be used in a trusted way. There are some issues that are not clear how it affect the XBee. The research will try to find out these facts, advantage and disadvantage of each mode of running the XBee. Two subjects are the aim of this project, the electrical characteristic of the XBee device and the Signal strength Range of the module and Max range could be achieved.

2 HISTORY

In this chapter, history of Zigbee protocol and the need of the protocol will be described in brief. Internal hardware and configuration attributes of XBee module, which is a Zigbee compatible module, will be the subject of the capital. Some facts about XBee module as hardware will be mentioned also.

2.1 ZIGBEE

Zigbee Alliance established in 2002. The aim of the Zigbee Alliance is for setting standards for energy efficient Control Networks.
Zigbee as name comes from the zigzag path of bees that form mesh networks between flowers. As the name, the Zigbee is a networking protocol based on the IEEE 802.15.4 standard. This type of networking became convincing when engineers and companies realized the fact that Bluetooth or WI-FI will fail to provide network services in a variety application when low power consumption and battery powered devices will be come a requirement for future devices and technologies. The aim of Zigbee protocol is not to provide faster communication channels, rather than creating a standard for control and sensor networking. It means that Zigbee is not a replacement for Wi-Fi. Both standards will work parallel in different applications.

2.2 XBEE MODULE

XBee is the trade name from Digi international for radio modules with some compatibility form. The module originally owned by MaxStream brand in 2005. These radio communication modules based on IEEE 802.15.4-2003 protocol. It aimed to provide point-to-point, point to multi point, and multipoint to multi point communications. Digi International acquired MaxStream 2006.

Initially there were two modules introduced with low cost and low power consumptions. The first one called XBee with 1 mW power transmission and the other called XBee Pro with 100 mW power transmissions that allows larger range. They are compatible in pin layout and each of them possible to replace with the other type whenever needed. Care must be taken when XBee is replaced XBee Pro as XBee Pro has higher power consumption and higher power transmission. XBee Pro is slightly more sensitive in reception also.
Some members of XBee: (XBee® Wi-Fi, XBee® 802.15.4, XBee-PRO® 802.15.4, XBee-PRO® 900, XBee-PRO® XSC, XBee-PRO® 868, . XBee ® ZB SMT, XBee-PRO® ZB SMT, XBee® ZB, XBee-PRO® ZB, XBee ® SE, XBee-PRO® SE, XBee-PRO® DigiMesh® 900, XBee® DigiMesh® 2.4, XBee-PRO® ® DigiMesh® 2.4, XTend). This large range of XBee is because of the needs of different communications. It starts from low power transceiver to high power transceiver with small range to large communications range. However, in this research we are interested to XBee® ZB that has hardware S2.

XBee module has different type of configuration, which determines the property of the communication. The complexity will be also different depending on the property of each configuration. Looking to the X-CUT these different configurations are possible (see Figure 2-1):

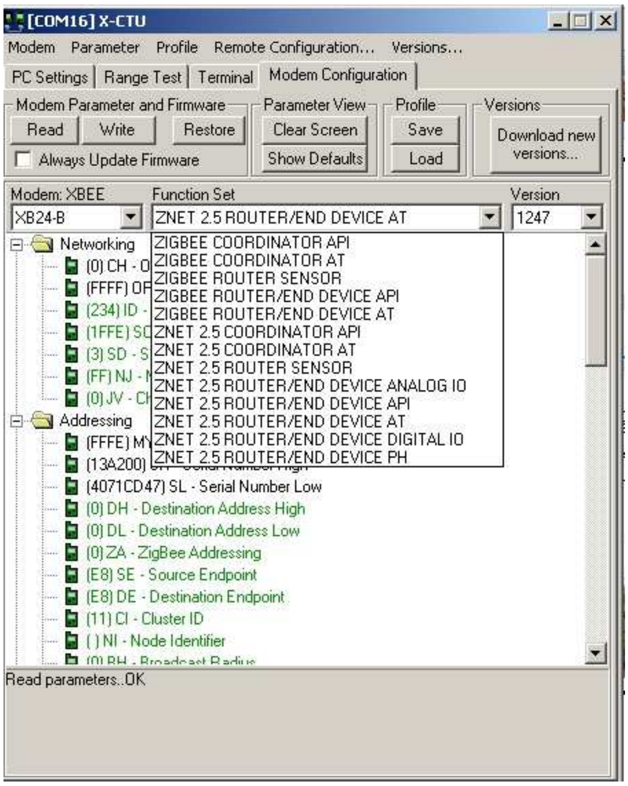


Figure 2-1A X-CTU

Note:
The research will mention only attributes that changes during the tests, the rest of the attributes are as the default values, which could be retrieved, using, restore from X-CTU. The following is a list of the possible configurations for the XBee module:

1. ZIGBEE AT MODE
   a. COORDINATOR
   b. ROUTER/END DEVICE

2. ZIGBEE API MODE
   a. COORDINATOR
   b. ROUTER/END DEVICE

3. ZNET 2.5 AT MODE
   a. COORDINATOR
   b. ROUTER / END DEVICE
4. ZNET 2.5 API MODE
   a. COORDINATOR
   b. ROUTER / END DEVICE

5. ZNET 2.5
   a. ROUTER SENSOR
   b. ROUTER / END DEVICE ANALOG IO
   c. ROUTER /END DEVICE DIGITAL IO
   d. ROUTER /END DEVICE PH

There are two major different modes. The first mode is ZIGBEE and the other is ZNET 2.5. Each mode has different sub mode and under each sub mode, there are different configurations. Before we describe how the configurations should be, some other attributes needs some clarifications.
Under each Function set that X-CTU provides, there are 6 major area of configurations each XBee needs to get before the communication could be started. Here I will mention and select only attributes that we need to modify for our network to works.

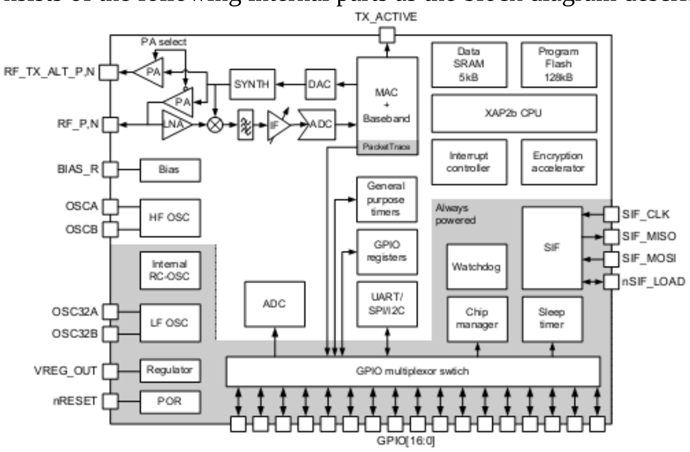
- **NETWORKING**: Determine the configuration of the networks parts.
    - CH – Operation channel: the Coordinator determines this, which coordinate all communications. If the value =0 it means that the device is not joined to any network.
    - PAN ID: This is the most important value, which all devices in the network should have it.
    - **DH – Destination address** - extended (64-bit) address: This should be determined when the XBee module wants to send a message to another XBee module.
    - **DL – Destination address** – extended (64-bit) address: This should be determined when the XBee module wants to send a message to another XBee module.
    - MY – 16 bit address for the XBee module (unique)
    - SH – 64 bit address for the XBee module (unique)
    - SL– 64 bit address for the XBee module (unique)
- **RF INTERFACING**
    - BD- Baud rate. Communication speed between the XBee modules and connected devices (microcontroller).
    - **D7 : CTS FLOW CONTROL**
    - **D6 : RTS FLOW CONTROL**
- **SERIAL INTERFACING**
- **SLEEP MODES**
    - SM : Sleep Mode - Determine if the XBee module goes to sleep mode or not.
    - ST : Time before sleep . Applicable for cyclic sleep end devices only.
- **I/O SETTING**
- Diagnostics Commands

2.3 XBEE® SERIES 2

This research uses XBee® Series module as shown in Fig 2-1B.

Figure 2-1B XBee Series Top and Bottom view

This XBee module has S2 hardware. The Top side got only the antenna chip, which replaces the regular antenna. In the left side, there is a place for a little antenna when the antenna chip is not used. Generally, the XBee module consists of the following internal parts as the block diagram describe.



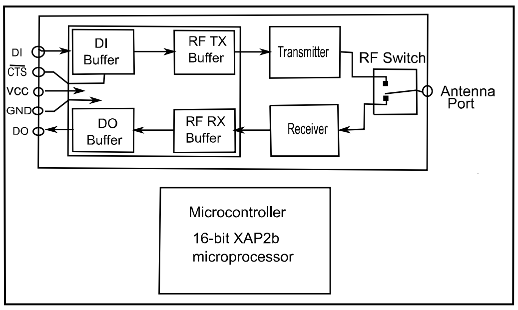


Figure 2-2 XBee Internal Block diagram

A 16-bit Microcontroller with all parts that any 16 – bit microcontroller could have (ADC, Timer, Watchdog, Sleep timer, UART, General-purpose I/O port, 128kB of Flash , 5kB of SRAM …etc.). Beside the Microcontroller, some other parts are for communication. The microcontroller designed by Cambridge Consultants Ltd. The Microcontroller runs on a 12 MHz clock speed. A hardware AES encryption engine is included also in the EM250. [19]

Table 2-1 XBee specification for Series 2 [07]

	XBee Series 2
Indoor/Urban range	up to 133 ft. (40m)
Outdoor RF line-of-sight range	up to 400 ft. (120m)
Transmit Power Output	2 mW (+3dbm)
RF Data Rate	250 Kbps
Receiver Sensitivity	-98dbm (1% PER)
Supply Voltage	2.8 - 3.6 V
Transmit Current (typical)	40 mA (@ 3.3 V)
Idle/Receive Current (typical)	40 mA (@ 3.3 V)
Power-down Current	1 uA
Frequency	ISM 2.4 GHz
Dimensions	0.0960" x 1.087"
Operating Temperature	-40 to 85 C
Antenna Options	Chip, Integrated Whip, U.FL, RPSMA
Network Topologies	Point to point, Star, Mesh
Number of Channels	16 Direct Sequence Channels
Filtration Options	PAN ID, Channel & Source/Destination

This was a brief internal view of the XBee module.

CARRIER FREQUENCY

Here we can take benefit of FCC documentations and test they made for the XBee. We can borrow their diagram for the spectrum analyzes as we by ourselves does not have any spectrum analyzes and we are forced to use their tests.

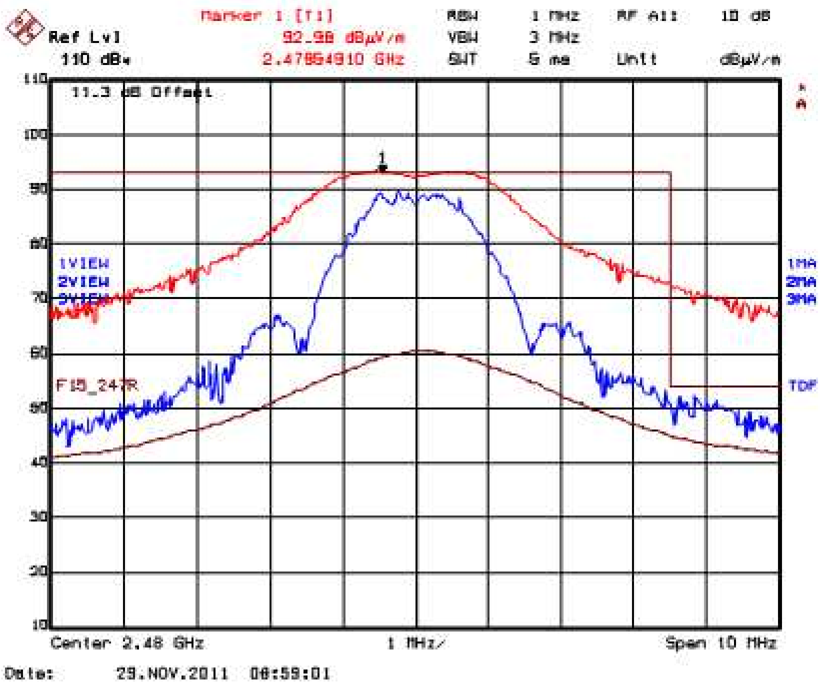


Figure 2-3 XBee-Band-Edge RF Radiated Emissions, Vertical Polarization Upper End of Frequency Band Transmitter Frequency: 2480 MHz

TRANSMITTER	
Equipment Type:	• Mobile • Base Station (fixed use)
Intended Operating Environment:	• Commercial, industrial or business • Residential
Power Supply Requirement:	2.8 – 3.4 VDC
RF Output Power Rating:	1mW (0 dBm)
Operating Frequency Range:	2405 – 2480 MHz
RF Output Impedance:	50 Ohms
Channel Spacing:	5 MHz
Duty Cycle:	100%
6 dB bandwidth:	1.61 MHz
Modulation Type:	O-QPSK
Oscillator Frequencies:	16 MHz
New Antenna Type:	External Phantom Antenna Make: Laird Gain: 3.0 dBi Part No.: A24-H3UF

Figure 2-4: some measurements from FCC final report shows the most important parameters.

The data packets modulate over the carrier signal using the O-QPSK (Offset Quadrate Phase-shift keying).

A QPSK means that each element represents more than one bit and it is as below:

$$S(t)=\begin{cases} A\cos\left(2\pi f_c t+\frac{\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t+\frac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t-\frac{\pi}{4}\right) & 10 \\ A\cos\left(2\pi f_c t-\frac{3\pi}{4}\right) & 11 \end{cases}$$

There is a difference between O-QPSK and QPSK. In O-QPSK, the data streams are offset in time by half the symbol period after S/P conversion, avoiding simultaneous transitions in waveforms at node A and B. The phase can change only for 90° every Ts.[25]

2.4 Other Zigbee Compatible Modules

There are many other modules admit to be Zigbee compatible also. These modules have too many shapes. Some of these modules made as USB – Dongle. It is possible to use them with any computer without needs of any other hardware. Others come with RS-232 convertor. There are also some other modules that likes the XBee from Digi international. Searching for Zigbee Modules in http://www.alibaba.com/ will result in 1,967 Products found. Unfortunately, it was not possible to get any other Zigbee compatible module from the University to make a comparison between what Digi international produce and other manufactures. This may be the subject for future research.

Some examples: CC2530-L Zigbee Modules, VT-CC2530-M1, cc2531 Zigbee wireless transceiver module USB dongle

2.5 Hardware and Software

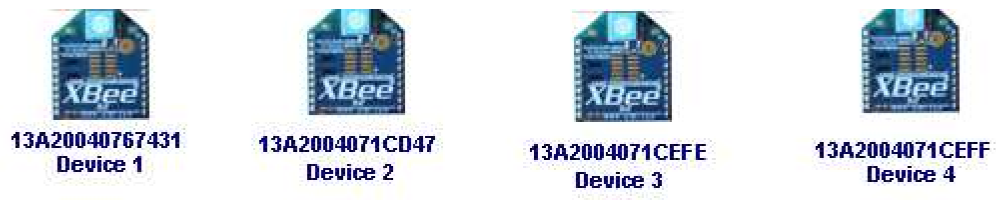


Figure 2-5 : XBee modules with their addresses used in the research

The power supply of the XBee modules is 3.3 Volts. This means that the signal from the XBee is also between 0 and 3.3 Volts theoretically. Connecting any Microcontroller which have a 5Volt power supply directly to XBee modules could cause problems as their signal voltage level are not the same [20].
For commercial application, care is necessary in converting the signals-voltage-level, to make sure that, errors are avoided and the XBee will run in safe conditions.

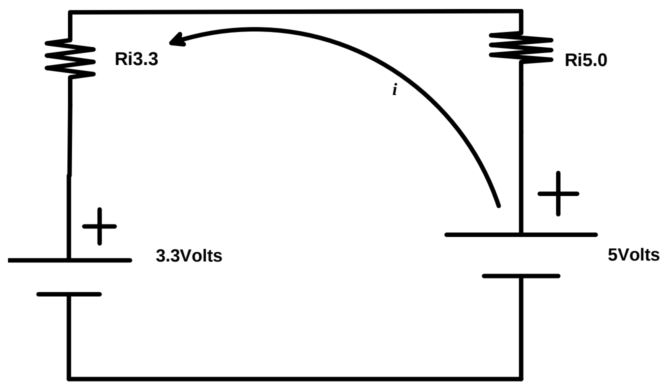


Figure 2-6 Different logical level results in unwanted current flow between Microcontroller and XBee

Theoretically, we can calculate the current is going from the Logical 1 from microcontroller which is 5 Volts, to logical 1 from the XBee which is 3.3 Volts. There will be a current flow from the Microcontroller to the XBee module as symbolized in figure 2-6. The internal resistance of each part (microcontroller and the XBee will decide the actual current, but theoretically is as bellow:

$$i = \frac{5-3.3}{Ri_{3.3}+Ri_{5.0}} = \frac{1.7}{Ri_{3.3}+Ri_{5.0}}$$

Using Multimeter I measured the current that flow to the XBee module and it was equal to 20.7 mA (this is when Arduino external power supply was equal to 8 Volts and the Logical voltage output was 4.95 (see figure 4-4)

We can calculate the $Ri_{3.3}+Ri_{5.0}= \frac{1,7}{0,0207} \approx 82\Omega$

Soon or late, the extra voltage will damage the XBee module.
For configuring XBee modules, there is a program, which called X-CTU. Digi international made the program and it is downloadable from their home site.

X-CTU gives user a variety of choices to make different test. In the research, two Laptops and two Arduino will be used in testing the XBee modules and for communicating between different XBee's in different conditions. Generally, Device 1 will be as Coordinator, special device that other wants to send message to. By this we make it easy to determine the address which is important.

3 CE

In this part we briefly talk about the CE certificate and it's effect on any product produces in the world. The importance of the certificate and what information could be achieved by this certificate will be described in the following parts.

3.1 WHY CE

CE stands for Conformité Européenne. It is a mandatory mark for certain product groups that confirm the essential health and safety requirement put by European Directives. CE is not to confirm the quality as much as the health safety. Any product consists of many chemical substances that may be health hazardous chemicals or emission as in radio frequency emitter. The CE certificate has several goals as bellow:

1. Simplify and unify regulation of customer and industrial for all EU members in single regulation and in one certificate
2. Reduce the cost while CE becomes mandatory to reduce the overall cost of the product that will help the producer to accept the marketing.
3. Ensure and enhance the safety of the products
4. Define and documenting procedures taken when each product tests that it is possible to recheck and reproduce the reports by other member of the EU.

CE certificate is to protect environment, customer and countries from hazardous products, any kind of products that may harm customers. The regulation is much harder when products are targeting children. Each group of products gets its own sub certificate that must be fulfilled before the product can be allowed to see the EU markets.
Noter: CE is not about the quality of the product itself. Products gets CE is not by default perfect in the quality. The CE is only for providing safe products, for human and for environment.

3.2 XBEE AND CE

Why do we talk about CE for a module that is a small product and runs only on 3.3 volts?
There is a special requirement that low voltage product should fulfill before it gets their CE certificate. Two major certificates will be required

1. Low Voltage Directive (LVD) (limit is 50V AC or 75V DC) [01].
2. Electromagnetic Compatibility Directive (EMC)

In simple words, the product must be safe to use and didn't harm our environment, and electromagnetic capabilities of the product should be under the acceptance level.
XBee has got the CE certificate, which means that the product have been under several kind of tests, and it has fulfilled the requirement puts on such a product that works on low level voltage and emit electromagnetic waveform.

Two kind of electromagnetic waveform is available ionizing radiation and non-ionizing radiation. In general, all ionizing radiation, even at low levels, are dangerous, but the non-ionizing radiation could be safe if they are not in at very high levels [22]. Ionizing radiation can cause damage in DNA and permanent damage to them is possible. Ionizing radiation generally is caring high level of energy.

The non-ionizing radio nation is what we are about and XBee has this kind of radiation. Simply, the radiation is safe if it does not pass levels made for each group of frequencies. High-energy electromagnetic emission can cause burning and other serious problems. In the other hand even if the energy emitted is not so much, but the continuity of emitting could be the other factor that may cause the problem.
WI-FI or Bluetooth is using the same range of frequency that some XBee uses. Each device is not emitting so much energy if we compare it with any mobile phone. However, having 20 to 30 laptops in an area of 30 square meter means that the level of the electromagnetic emitted will be more than what nay mobile phone could emit. The same is true for the XBee modules. There are no evidence that having many WI-FI devices will be harmful but there are no evidence either that they will not cause problem.. [23]

Definitely, we need more research in this field. We need to take the problem seriously before it becomes late. The concern is bigger with XBee as we may have many products emitting signal in a small environment which cause to rise the level of the emitted energy in that environment which children may be apart of it. If an XBee is emitting only 10 to 63 mw, 100 XBee devices that could be reasonable in some environment will emit a mount of energy that is equal to 6,3W that is a lot.

RF emissions limits:
There are standards that describe the limits of allowed EMF. EN 550XX series that are some of the standards, have harmonized limit levels for conducted and radiated emission. Here are some graphs that show the limits

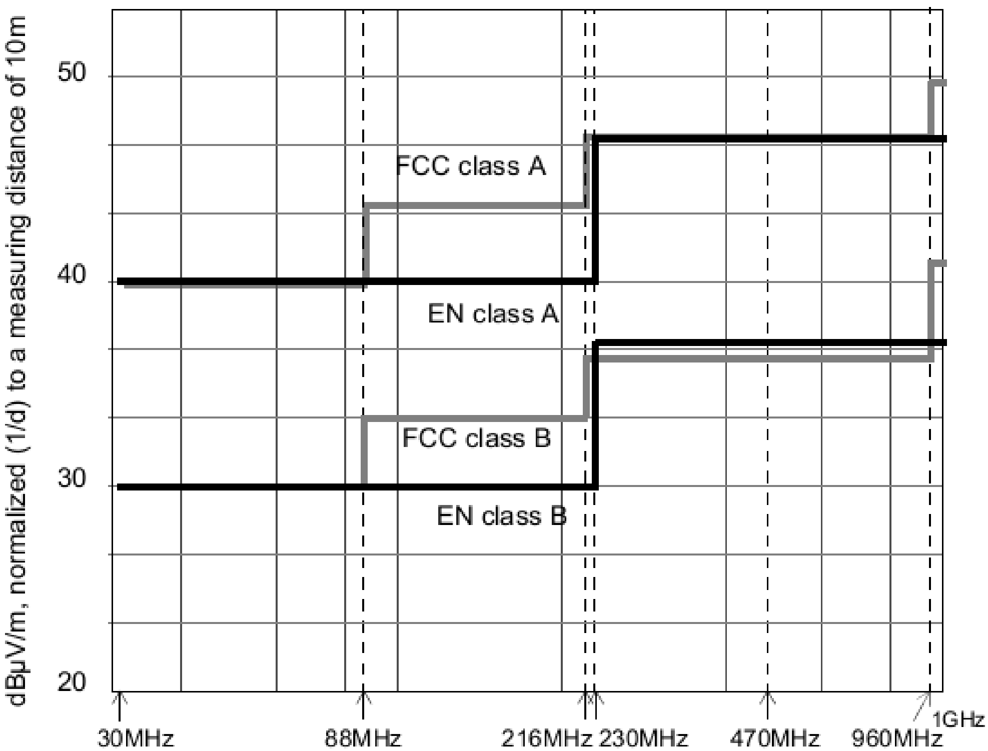


Figure 3-1 Radiated emission limits [1]

This document [24] put the max limit of the power that transmits by any product with different frequency jumping possibilities; the power limit for this group of products is as below

Class of transmitter	Permitted operating frequency band (MHz) (lower limit exclusive, upper limit inclusive)	Maximum EIRP	Limitations
Frequency hopping transmitters	2400–2483.5	500 mW	A minimum of 15 hopping frequencies must be used.

Our XBee module that uses in the research has also the same power emitting level.

3.3 FCC:

FCC[16] is abbreviation of The Federal Communications Commission, which is an s an independent United States government agency. The FCC established by the Communications Act of 1934. The FCC has the duty to regulate interstate and international communications by radio, television, wire, satellite and cable. The FCC's jurisdiction covers the 50 states, the District of Columbia, and U.S. possessions. They have the following functionalities:

- Executes on-scene investigations, inspections and audits.
- Immediately responds to safety of life issues.
- Investigates and resolves interference.
- Investigates violations in all communications services

The reason we are talking about FCC is that there are documentations were registered and saved there. The CE certificate, the internal hardware of the XBee, EMC certificate..etc. There is much good information that could help in understanding the XBee modules. Any product tests by FCC will be registered and get an FCC number that is possible to search for in their database. Hereby I bring some picture of their documents describing important information about XBee.

ANNEX 1 - TEST SETUP PHOTOS

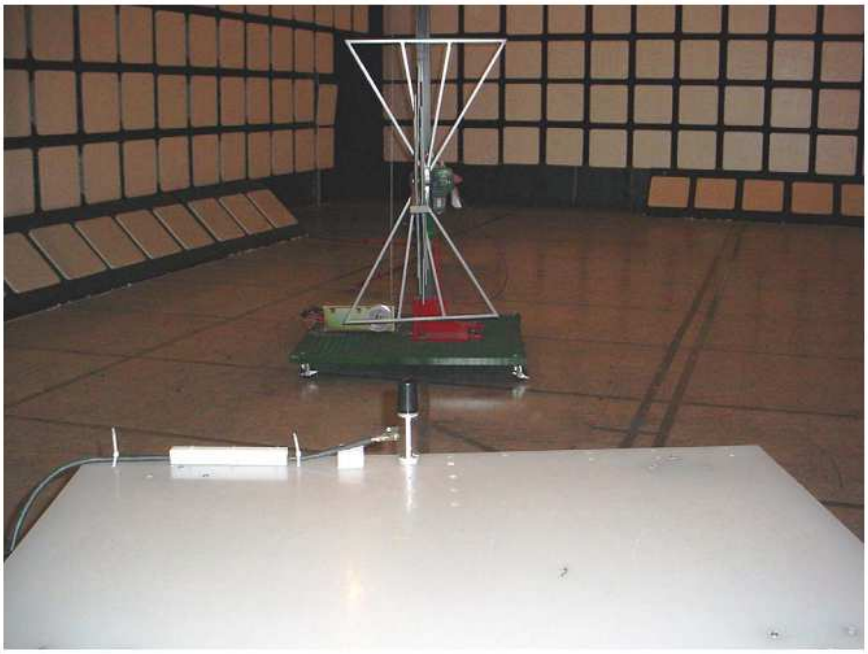
(Orthogonal Position 2)

MaxStream, Inc.
XBee, Model XB24
FCC ID: OUR-XBEE
IC: 4214A-XBEE

A1 - 3

Figure 3-2 Test equipment - EMC

ANNEX 1 - TEST SETUP PHOTOS



(Orthogonal Position 1)

MaxStream, Inc.
XBee, Model XB24
FCC ID: OUR-XBEE
IC: 4214A-XBEE

A1 - 2

Figure 3-3 Test equipment - EMC

3.4 SUMMARY

This section was to describe some information about the CE certificate and documentations that could give researcher better understanding of the XBee modules. In the FCC part, we described that there are documentation of tests made by FCC that contains different tests and detailed specification for these modules. It is important to know that any product will need to get a new CE and FCC certificate if any change made in their hardware. Each CE or FCC is for the product sent for the test, any modification in the hardware results in a new product and needs new CE certificate. To minimize the money losses, designer needs to be certain when they require certificate for their product as it costs them money each time they make modification to the product.
This documentation cannot be included in this report, as it is large and unnecessary; however, the goal was to give an idea about this source of information for other researcher.

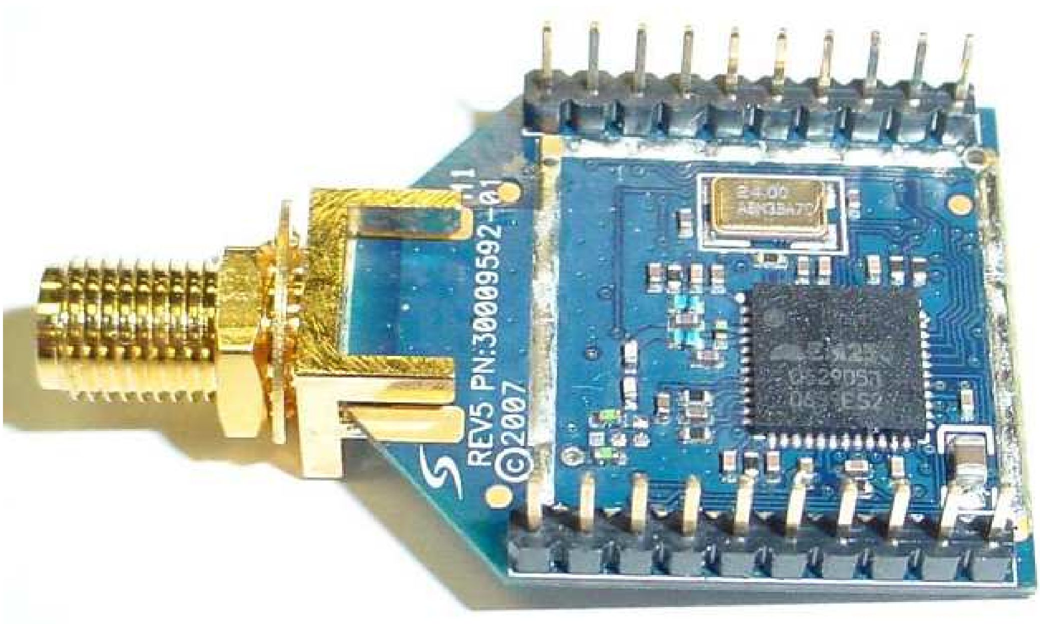


Figure 3-4 internal view of an XBee module from FCC documentation

4. EQUIPMENTS

The electric characteristics of XBee modules are one of the goals of the research. In the research we need some different measuring equipment. Two different Multimeters will be used in measuring the current, voltage and power consumption by XBee modules. To figure out the Waveform of received signal and sent signal an oscilloscope with screen capture possibility will be used. The oscilloscope will be used also to measure different parameters like current and voltage where it is not possible to measure them using Multimeter. I will explain later.
Here is a list of the equipments uses in the research:

1. Oscilloscope (Type Tektronix TDS 2001C 50MHZ 500MS/S)
2. Oscilloscope (Type UTD2102CEL)
3. TENMA 72-7755 Multimeter (Measure only average – not RMS)
4. MY-68 Multimeter (Measure only average - not RMS)

4.1 ARDUINO

Arduino board UNO is used in many application, or projects done by students in different levels. I faced too much trouble using the Arduino with XBee in the past. Many people thinks are not as supposed to and needs to be clarified in this research so other researcher will not get confused in their measurement and unwanted behavior.

I. The 3.3 Volts should be able to give max 40mA. No more current is possible to load from the 3.3 Volt. This is only true if recommendations described in point 2 is fulfilled.
II. Many people, as I did by myself also, think that the external power source should be 5 volt as it should be possible to use the Arduino using an usb-cable to power up the Arduino module. This is a false expectation, as the Arduino needs at least 7.5 Volts external power and will never be safe using only a USB-cable or 5 Volts. When the input power voltage source is less than 7.5 (let we say it is 5 volt), the five Volts on the board is not giving 5 Volts. In fact, it will deliver only 3.4 Volts. You get the same result whatever you use to give the power voltage to the Arduino, when the input voltage is only 5Volts. Figure 4-1 shows the input voltage and the Vcc on the ATMEGA microcontroller, which is the same voltage on the 5 Volt female contact on the Arduino board. The problem could occur on the current, as the input voltage source is not enough, the current cannot either be as enough. I consider This as a bad design for Arduino and bad component (regulator) used in Arduino also for the reasons below:
    a. The power, which is coming form the USB port, should be trusted and it does not need regulating through the regulator. That is the case and the power from the USB is taken to the regulator for further regulating which will fail.
    b. The regulator cannot pass 5 volts when it is really 5 volts; this is also a bad choice of a regulator that cannot work when the voltage source is equal to 5 Volts.

Figure 4-1 Left side is the Voltage supplied to the ATMEGA microcontroller at pin 7. Rights side is the external power voltage supplied to the Arduino

III. Using a 7.5 – 12 Volts external power supply to power up the Arduino, it gives a correct voltage to the ATMEGA microcontroller and to the

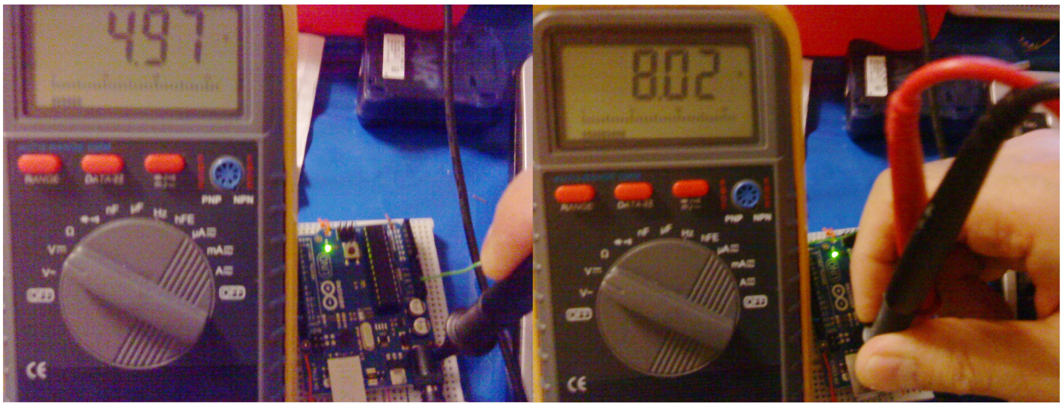


Figure 4-2 Left side is the Voltage supplied to the ATMEGA microcontroller at pin 7. Rights side is the power supplied to the Arduino

IV. As the ATMEGA gets 5 volts as power supply to the Vcc, pulses comes out from the ATMEGA microcontroller is depending on that voltage. In Figure 4-3 can we see clearly that the output signal from the Arduino at the TX has 0 to 5 volt p-p.

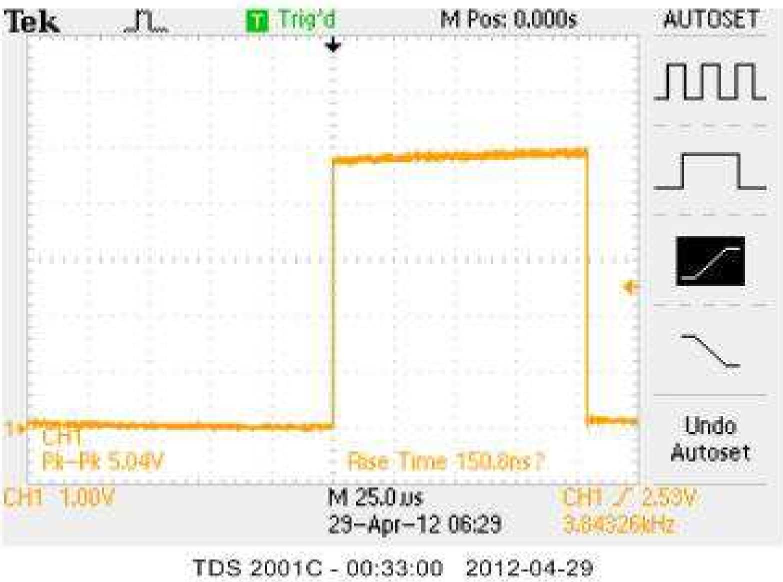


Figure 4-3 ATMEGA microcontroller is getting 5 Volts at Vcc and the generated signal from the TX is between 0 and 5 volt. p-p

1. Referring to point four, I connected the XBee module to the Arduino. Figure 4-4 clarifies that the ATMEGA microcontroller must get down with its voltage level to a lower voltage level as the XBee module connects to the Arduino. It is clear that the TX is loaded with some load, which pushes down the signal level to 4 volts p-p. This is not good and XBee module soon or later will damage. See figure 4-4

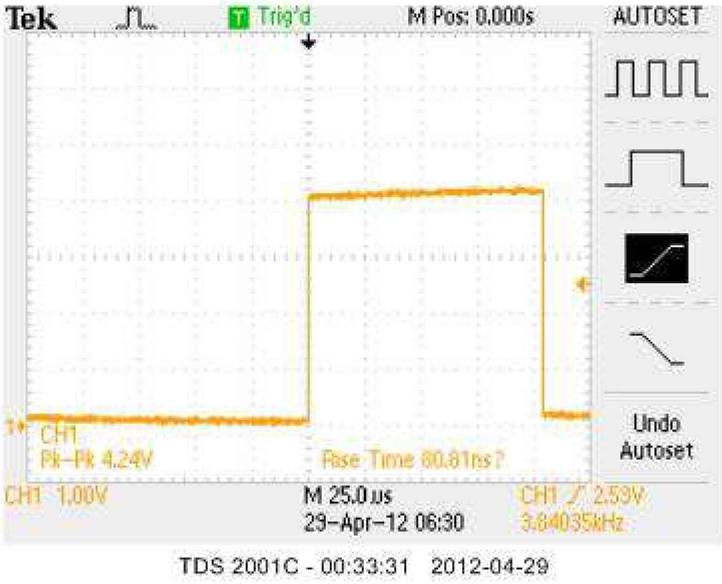


Figure 4-4 ATMEGA microcontroller has 5 Volts logical level but when it is connected to XBee it goes down to about 3.8 Volts

4.2 OSCILLOSCOPE

The oscilloscope used in the research is Tektronix TDS 2001C. It has an USB port that, which gives the possibility to connect to computer, and there is software that import screen capture from the Oscilloscope. The Oscilloscope will be useful in capturing the power consumption and other waveform in the research.

4.3 MULTIMETER

Two different kinds of Multimeter were used in this research. The first one is 72-TFNMA 7755 and the second one is called MY-68. These Multimeters are not claiming a measurement of true RMS, which means that they use average measurements.

4.4 OTHERS

- At least two computers is necessary in this research as it will be used during the "range test" of the XBee modules in AT mode or API mode networking.

- A regulator needed to produce 5 volts as a power supply to the Arduino to make the Arduino mobile. The regulator will get power supply from a 9Volts battery and will be stepped down to 5 Volts as we do the test in this range.

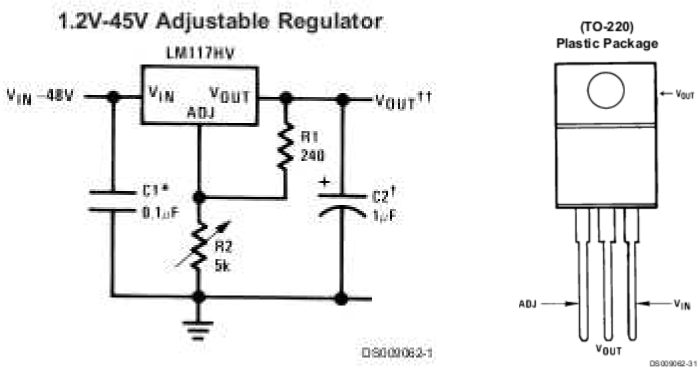


Figure 4-5 regulating of 9Volts battery to 5 volts be suitable for Arduino

Actually, I discovered later that no regulator would be needed as the Arduino could get 9 Volt as power supply voltage. This fact discovered during week 2 in the research while testing the characteristic of the output waveform of the XBee.

5 SETUP & CONFIGURATIONS

In this chapter, configurations were used in the research for each part of the project will be described. Results shown in the result chapter needs to come back to this part to know what configuration was selected what connections are used. There are two major parts, Range test and Power consumption and Electrical characteristics of the XBee modules.

5.1 Electrical Characteristics and Power Consumption

Power consumption for the different types of modes and states will be the subject of this part. It is necessary for every designer to know how the power is consumed by the XBee and how the XBee is acting during different time and different situations or modes. We use two (ROUTER/END DEVICE): s AT Mode to measure the power consumption.

A. Power Supply Setup:

In this section, the voltage supply and requirement of the power supply to XBee module are the aim of the research. The power supply voltage of the XBee should be in-between 2.8 to 3.4 volts as the documentations say. It is important to have a very stable power supply to the XBee modules as ripple could result in unwanted XBee behavior. At the input, a 0.1 µF 10 Volts capacitor is required and at the output of the regulator a 1 µF 10 Volts Capacitor needs and an 8.2pf (Figure 5-1). This is what the documentations suggest to use with regulator power suppliers.
In our project, we use the regulator to step down the 9 battery voltage to 5 volt. This power will be used with the Arduino to provide the mobility of the module. Figure 5-1 shows the regulator circuit.

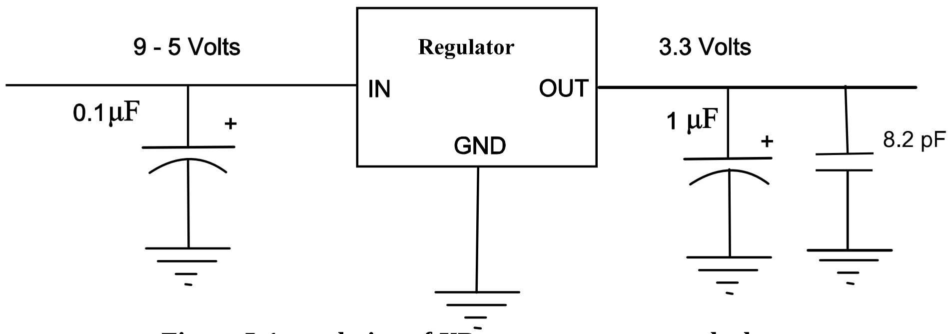


Figure 5-1 regulating of XBee power source needs three capacitors

B. Current Measurements:

Before starting the measurements, we need to mention that the power supply voltage of our XBee module using the XBee USB-Module card is 3.3 Volts. There will be no need to mention this voltage in the research parts, as that will be the pre-known, unchanged voltage for all parts of the research. When power consumption is calculated this voltage will be used.

The current supply to the XBee modules varies as the condition of the XBee module itself varies from a state to another. Generally, we can say that the current consumption is not DC. It could be difficult to calculate exactly how much each module consumes during each kind of configuration as the current consumed varies per configuration and state. However, we will put some facts here and measurements.
To capture the current waveform, an Oscilloscope will be used. However, Oscilloscopes have no possibility to show current waveform directly. To show the current flow waveform we need to convert the current to voltage by using a very small resistor. Waveforms in this section is captured by using 3 resistors having values of 22 Ω and connected in parallel and they will be connected in series with the XBee power supplier.

Resistor in parallel = $\dfrac{1}{\dfrac{1}{R1}+\dfrac{1}{R2}+\dfrac{1}{R3}} = \dfrac{1}{0.045+0.045+0.045} = 7.3\Omega$

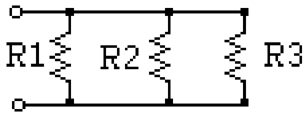


Figure 5-2A Resistors in parallel

Since the current consumption is related to the power consumption. Here we described how these waveforms are captured and how we can convert them to current consumption and later to power consumption. We know already the voltage power supply to the XBee modules to be 3.3

In order to get a DC equivalent voltage, current and power consumption from the pulses or different shaped waveform, there are two ways of calculating the DC equivalent:

1. The effective voltage/current/power (which is called also RMS): This is the correct way in calculating the effective power consumed by any device gets its inputs source in different shaped waveform.
2. The average voltage/current/power: Most of the Multimeter uses the average measurements. This measurement will not be correct always and it will fail if the input waveform is not a pure sinusoidal. I this project I will write down both measurements for reference comparison.

Note:
All tests done in the research are based on using the 5 Voltage from the Arduino as power supply and using the USB shield (adapter) for connecting the XBee to power supply and connecting the D-IN/D-OUT. To be mentioned here also, the adapter consume 9.9 mA ~ 12 mA when it is connected to the USB-Port of my Laptop.

5.1.1 AT MODE

Starting with AT mode configuration, electrical characteristics and power consumption will be the subject of this part. Under AT Mode there are many other sub modes. The following section is the detailed modes.

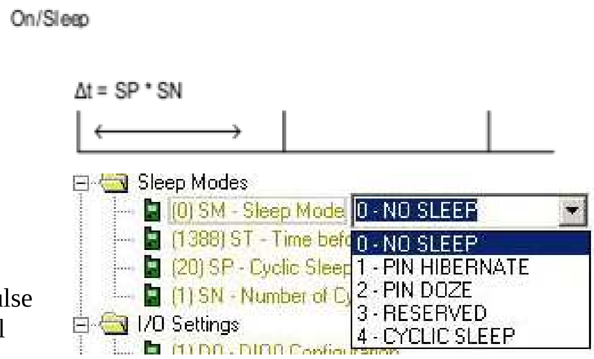
5.1.1.1 AT STANDBY

It is important to know that when there is only one XBee in the area got powered ON. Such setup cannot be called "STANDBY" as the XBee is trying to make contact to another device in the surrounding. In order to show the difference we will make our setup in two different states: This is why there is a big difference between the following figures (Look at figure 6-4 and 6-8):

There are different standby states:
1- Only one XBee is powered ON
2- More than one XBee is powered ON.

5.1.1.2 AT SLEEP MODE

In this research only the cyclic sleep mode will be used. It is impossible to use all other options as the research will be too big. The XBee documentation (page 90) describes the roll of these configuration bytes as in this picture:



Having XBee configuration as below:

SM=4 :
ST=100
SP=100
SN=1
Δt = SP*SN= (100)*(1) =100 ms
This configuration gave us a 100ms cycle period with a 10ms pulse width (which is the minimum you can configure). [XBee manual page 89].

Even when we have sleep mode configuration, there will be two further options:
1- More than one XBee is powered ON:
2- Only one XBee is powered ON:
We have the same configuration as above, however we remove the second XBee module. But we will not switch OFF/ON the first Module. This could be the situation with any XBee module when it lefts alone after been working (battery down situation).

5.1.1.3 AT SENDING – NO SLEEP MODE
When XBee is in transmitting state, it is consuming more power compared with standby or sleep mode. The Arduino device will send a character-one byte (which is 'M') continuously. At the other side a computer uses X-CTU to receive and resend the "M" to the Arduino via the XBee modules. We will try even sending only one Character and capture the power consumption to determine the rise of power consumption for one byte.

5.1.1.4 AT RECEIVING
Here we have the same configuration and setup as for the sending.

5.1.2 API MODE
We have two XBee modules with one coordinator configured in API mode. All sends with full power and no sleep mode activated. Totally there will be 3 XBee modules. The power will be captured on one of the END Devices. They are all connected to a computer and X-CTU is used for sending receiving.
For continuous sending, I used the program that I made which is shown in figure 5-10 .

The packet that will be sending is containing a one byte data which is the symbol "+". Each 2.45 sec the byte will be sent and measurements will be recorded (7E000F10010013A2004071CEFEFFFE00002B94) which represent a "+" symbol.

5.2 AC CHARACTERISTICS / BAUD RATE CONFIGURATION

In this section, the AC characteristics of XBee modules are our goal. Baud rate or how many symbols transport in a second is a way of computing the speed of communication has a direct affect on the power consumption and the quality of the communication. Looking to the XBee modules, there are lists of baud rates that are allowed:
- 1200
- 2400
- 4800
- 9600
- 19200
- 38400
- 57600
- 115200

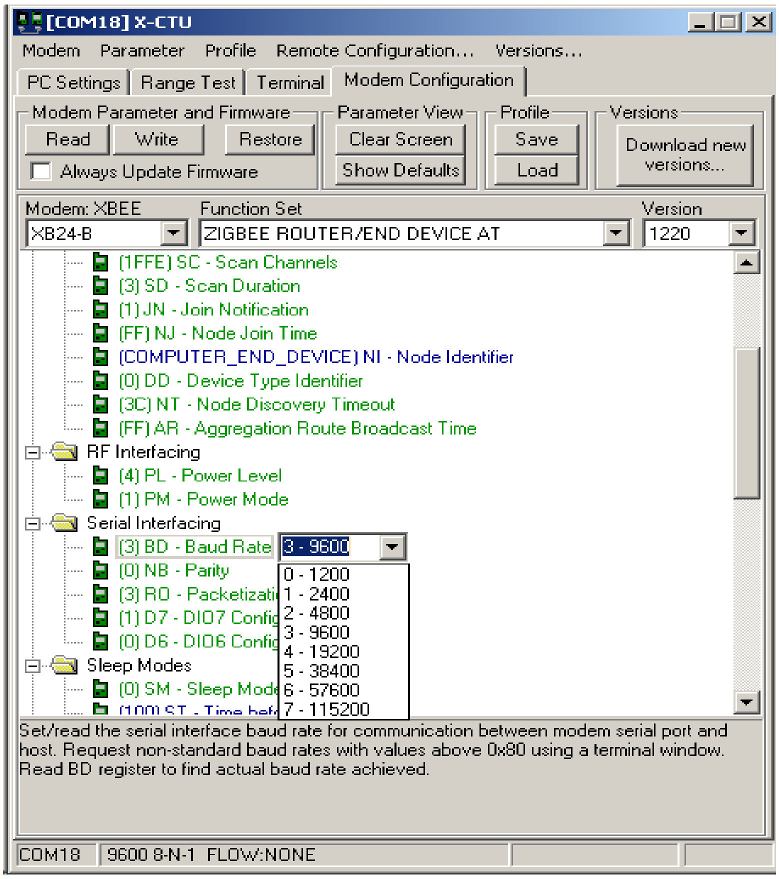


Figure 5-3 Baud rates available for XBee Modules

We use Arduino Uno with an ATMEGA microcontroller called ATMEGA 328P, which has a frequency clock at 16MHZ. to calculate correct baud rate we use this equation in our code:

Baud Rate= (CPU_CLOCK_SPEED/ 16 / BaudRate) – 1
As we can see, Microcontrollers clock speed divides always by 16. This division will not generate an integer numbers. In our case:

Baud Rate =(16000000/16/9600)-1= 103,1666666

The baud Rate calculated here to be used with the ATMEGA is =103 with an error factor of %0.2 since there is a reminder in the division of the microcontrollers clock speed.
Now if we choose another baud rate for the XBee let we take a faster baud rate and calculate what Arduino will get. Here is an example:
If we configure the XBee to have 115200

$$\text{Baud Rate Error} = \left(\frac{\text{BaudRate Closest Match}}{\text{BaudRate}} - 1\right) \times 100\%$$

$$= \left(\frac{125000}{115200} - 1\right) \times 100\% = \%8.5$$

Table 5-1 Baud Rate Table vs Error

ATMEGA clock frequency	Baud Rate (XBee)	Baud Rate calculated =clock freq/16/Baud rate	Integer	Nearest	Error
16 000 000	1 200	833,33	833	1200	0.0%
	2 400	416,67	416	2404	0.2%
	4 800	208,33	208	4808	0.2%
	9 600	104,17	104	9615	0.2%
	19 200	52,08	52	19231	0.2%
	38 400	26,04	26	38462	0.2%
	57 600	17,36	17	58824	2.1%
	115 200	8,68	8	125000	8.5%

As we can see from the table 6-1, when the baud rate increases, the error also increases also and reaches 8.5%. This could generate much trouble in the communication and packet may be lost more often when the sending speed from the microcontroller is mismatching the XBee.

What make the problem even worse, the Arduino does not use a real Crystal Oscillator for the Clock frequency of the ATMEGA 835P. The Arduino uses a 16 MHz ceramic resonator. It means that the frequency that generates is not accurate and may vary. All these could make unknown conditions and unknown errors for the XBee communications. Definitely it could affect the quality of service for the communications, especially when faster baud rate is chosen.

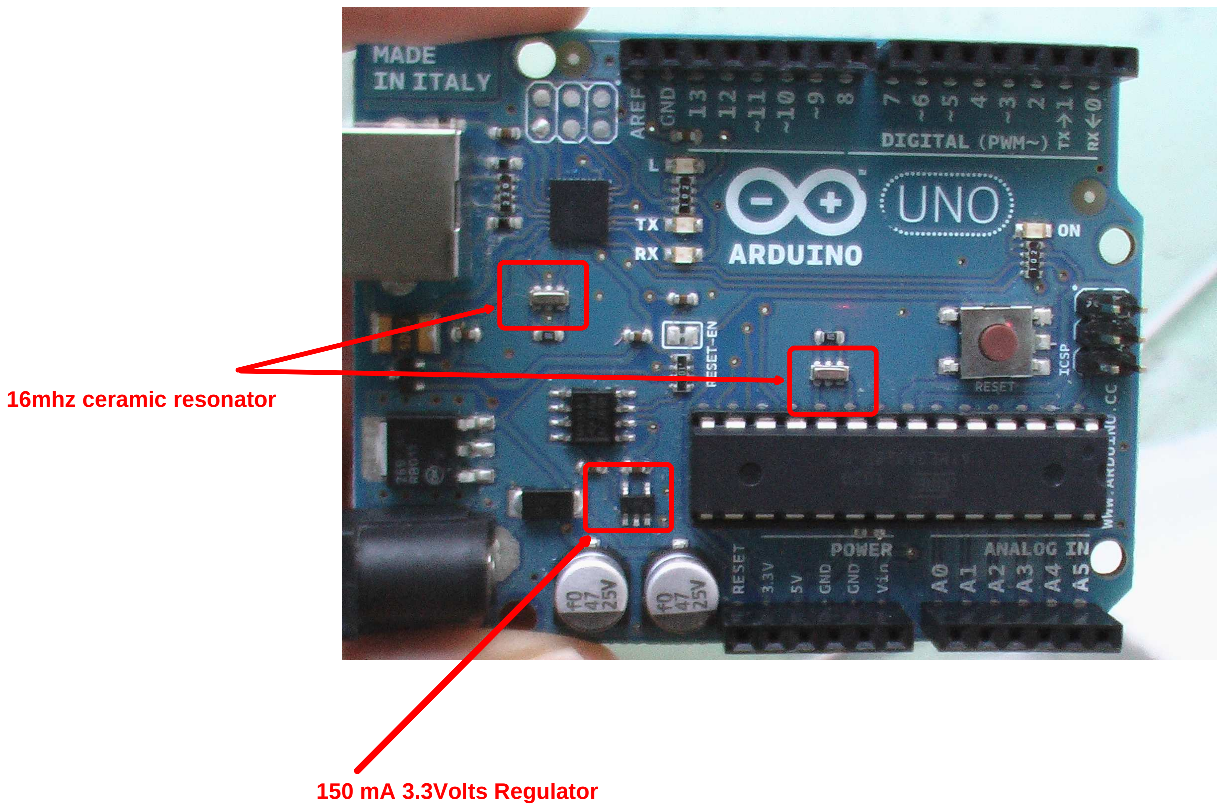


Figure 5-4 Arduino uses Ceramic resonator

5.3 Communication Ranges test

5.3.1 Introduction:

The range test consist of the effect of the distance, power emitted, disturbance effect of different electronic devices, and barriers on the reception of the XBee modules. Many instruments used in these tests. Some of the tests made more than one time to ensure the correctness of the results.

Tools used in testing the range are an Arduino –XBee module programmed to send back a messages that sends from a computer using X-CTU. Different configurations and different environment were chosen.

Before we start, This project has been done in three different location for different purposes. Figure 5-5A, 5-5B, 5-5C are maps of the apartment, ground floor - entry plan of H10 (Near to the restaurant), and Sal 83 in H10, these locations were selected to carry out the tests. Each location has different environment which make it suitable place to choose. The following is the reasons behind each selection:

1. The apartment is a normal home for any house automation could be proper to compare. XBee is supposed to be used in home automation.
2. Entry plan is a large location and has a wide area. It can be compared with any industry local. There are different devices, walls, other barriers which could affect the signal. It has a length of about 40 m
3. The last location was a normal classroom called SAL 83. In this room, there were also some devices and the XBee got different environment for the test. As a WI-FI router was in the room also, it was a perfect place to do the third test. The classroom is chosen as many projects at the university will be tested and done in normal classrooms. This part will be as a reference for them.

Apartment – Figure 5-5A:

This is a map of the apartment that I did some of the tests. There are locations on the map that are marked with red dots are places were test and measurements are recorded in the research. Some information about the apartment needs to be declared:

1. Largest distance (without barrier) is only 12 m. This is due to the size of the apartment.
2. The red points are places were the XBee modules are tested, and data were recorded in the research.

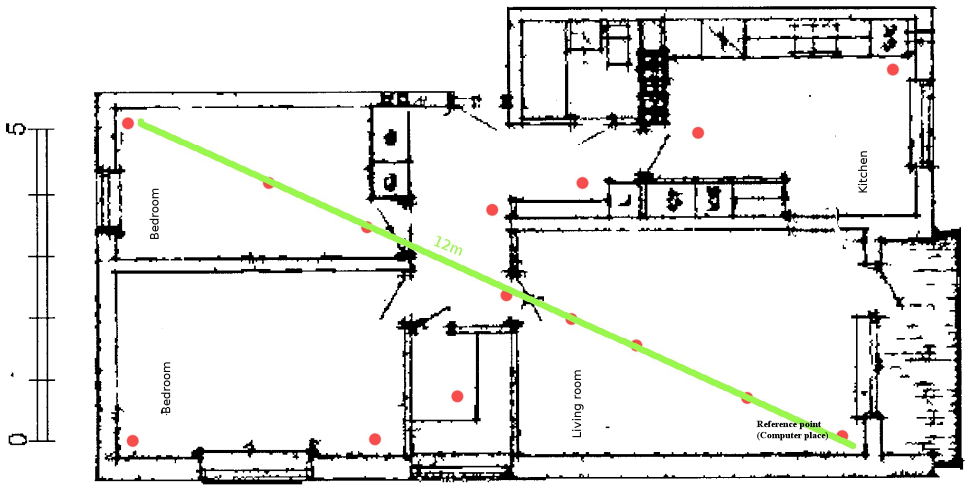


Figure 5-5A Map of apartment where testes took place

H10 – Ground floor– Figure 5-5B:

I selected this hall as it is big and there are many things that could affect the signal reception by the XBee.. There are walls, barrier, and many devices that emit electromagnetic waves. Kitchen machines, WI-FI, etc... are some of the objects that may affect the reception.

1. Largest distance (without barrier) is more than 40 m.
2. The red points are places that the XBee modules were tested, and data were recorded in the research.

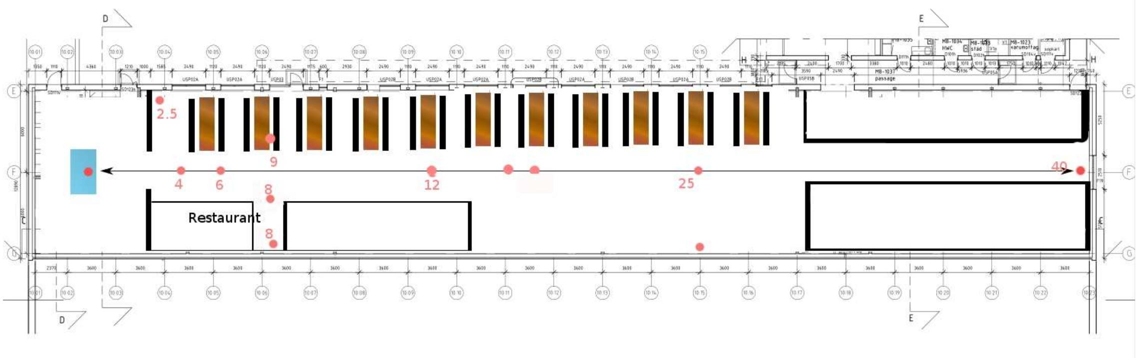


Figure 5-5B Map of Ground floor – H10

SAL 83 – Figure 5-5C:

This is a normal classroom with a big area. Many possible threats to the reception are included in the room, such as WI-FI router. It is perfect environment for testing the XBee range since we can see the effect of these devices on the reception.

3. Largest distance (without barrier) is about 18 m.
4. The red numbers represents places that the XBee modules were tested, and data were recorded in the research.

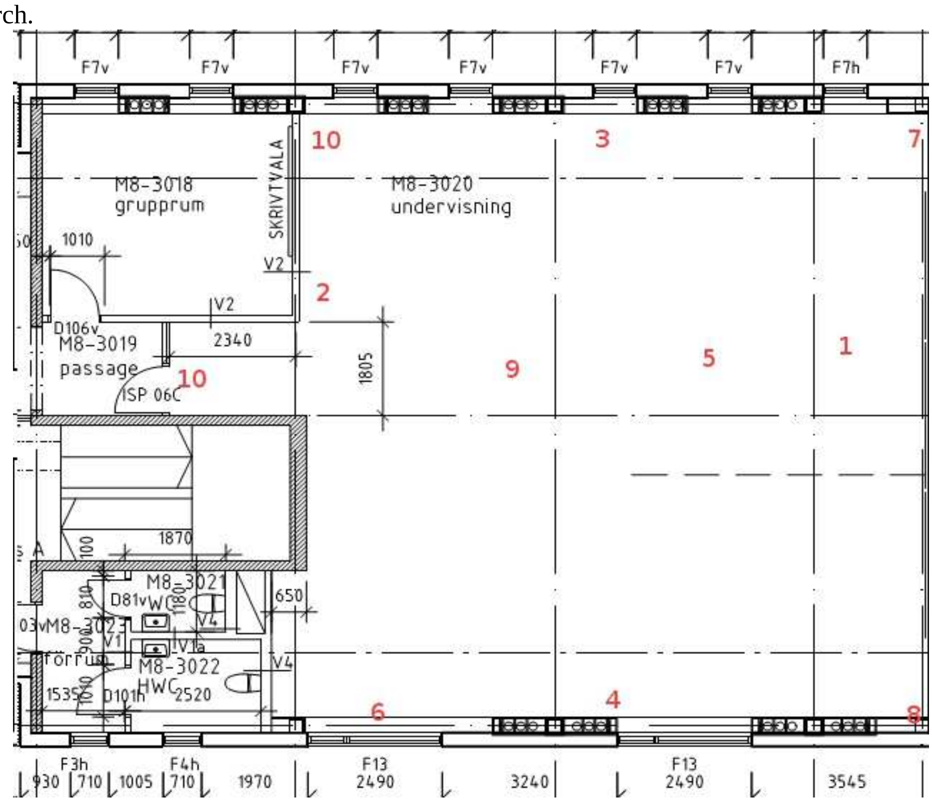


Figure 5-5C Map of the classroom - SAL83

5.3.2 ZIGBEE

In this part, different types of connections will be the target of the research. It is about determining the advantage and disadvantage of each type of network configuration. Which one is simple and what are the complex configurations. What are the attributes...and so on?

5.3.2.1 AT MODE

Even in AT mode there are some other sub modes (configurations). In this part these modes will explains in details. The explained connection will be used later in the other parts of the research. Configuration which is a part of the tests will should be one of these listed here in this part. Because of that, the other parts will point to this part.

5.3.2.1.1 ROUTER/END DEVICE

The simplest configuration is to use XBee modules in AT mode with sub mode called Router/End device. These configurations are tested and it works fine Figure (5-6).

Note:

The XBee modules I use in this project have got their names in the beginning of this report. These name will be used in the report every where.

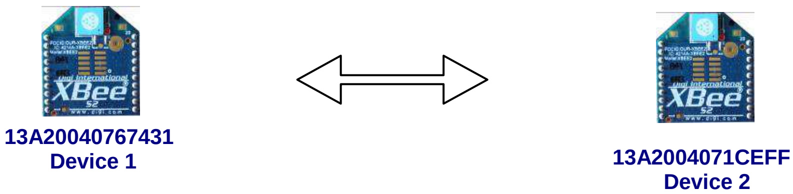


Figure 5-6 Two AT END DEVICE

To connect two XBee modules using AT modes these configurations are necessary:

1-Each device has an address for destination device. For example Device1 which has the address (**13A20040767431**) should have Device2 s address which is equal to (**13A2004071CEFF**) as destination. By writing, these configurations both devices simply can communicate with each other. Without doing this step it will not be possible to get communication between these devices. For this peer-to-peer communication, no coordinator or extra router needed as the communication is only between two devices.

2-If multiple devices need to communicate to one device, as shown in Figure 5-7. The same steps can be applied to these three devices. Every one of these devices (2, 3 and 4) should has Device 1's address but for device 1 it will not be possible to communicate with all of them in directly without changing the address of the destination whenever it needs to communicate to one of them (2,3 &4).

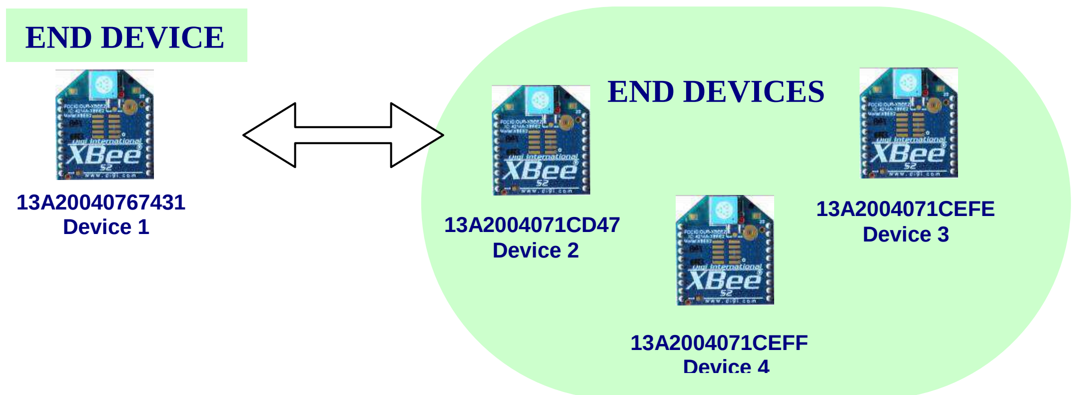


Figure 5-7: Multi points to one, AT- XBee network

5.3.2.1.2 COORDINATOR/ ROUTER/ END DEVICE

To establish a network using AT mode, an AT coordinator is an obligation. The coordinator is the master of the network; and must be the first module that get it's configuration and power.. No networking will work if the coordinator does not start first. This is the most important step in building any XBee network. It does not mater if the

networking is using AT mode or API. Missing or doing the steps in other order will cause malfunctioning of the XBee networks.
PAN ID is the Personal area network identification that will be common between all devices. Without having the same PAN ID, XBee modules cannot join a network. The coordinator could automatically decide PAN ID when the PAN ID will be equal to zero. We must remember that the communication channel should be the same for all XBee modules in the network or they cannot hear each other. The following is an AT network that 4 devices are participated in establishing the network.

Device 1 becomes a coordinator and Device 2 and Device 3 will communicate to each other as in the figure 5-8.

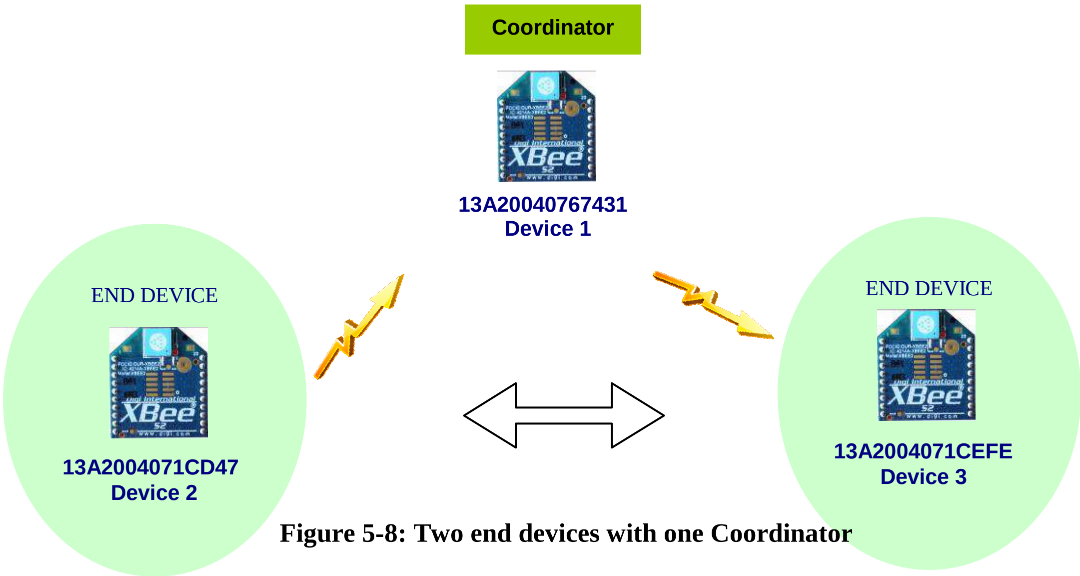


Figure 5-8: Two end devices with one Coordinator

Figure 5-6 shows the AT Mode peer-to-peer communication. Both modules must be configuring to have destinations of the other. Coordinator is not required. This is the simplest way to communicate between two XBee modules.

When configuration of Figure 5-7 is required where three XBee modules need to send message to another XBee module (3 End devices to one end device). The three modules need to configure the destination address to the XBee module in the right side. However, for XBee module in the right hand cannot send to all right side without changing the destination address. However, this is a possible scenario in communications.

For figure 5-8, it is important to program each module to get the same PAN and Channel of communication. Without having the same channel nothing will work, even the PAN address is the same. Documentations say that Coordinator will force Router and END DEVICE to join to the same channel. This is not working, as it should. Programmer should do this job by sending AT commands in the code. Unknown behavior will be faced if everything is not controlled by the code and confirmed.

5.3.2.2 API MODE

API mode is the configuration that allows establishing real networking with different complexity of the network. From very simple network, that consist of only one coordinator which supervise the members of the network that are END DEVICES to a very complex network that multiple mesh networks connected together. In this research, we are going to use four XBee devices, two of them as END DEVICES, one as a coordinator and the other is as a router.

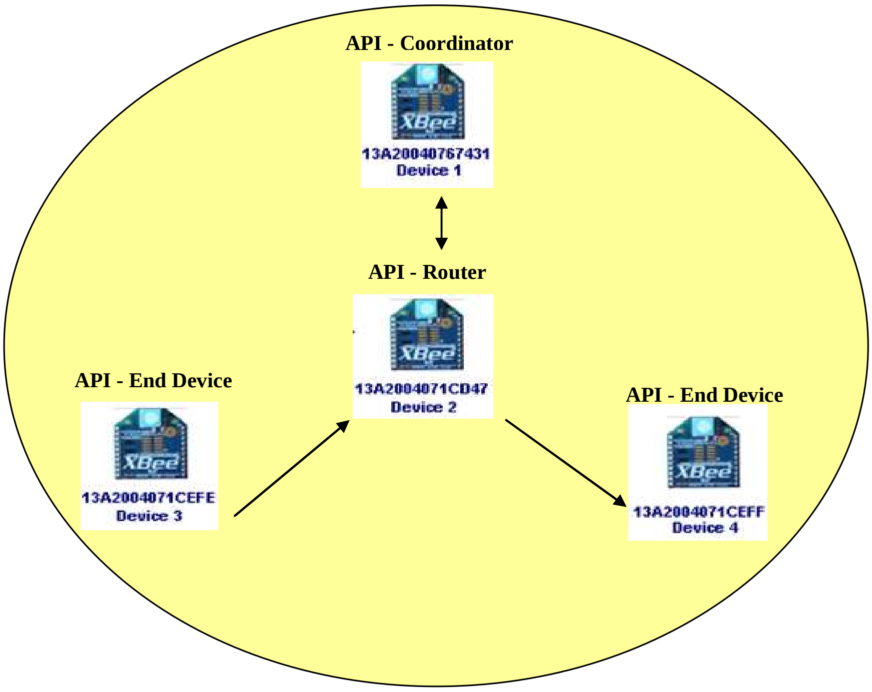


Figure 5-9: API MODE SYSTEM

In our XBee network, we have two end devices, and one coordinator. The coordinator is the responsible for many important things like channel selection and fore all members to choose the same channel, and both the Router and The coordinator can save a message for a limited time while one of the member of the network is not reacting to the message.

It is important to know that the number of symbols or bytes sends in this mode increase depending on the communication protocol. Never the data sends in this mode will be equal to the same size as it was for the AT mode. This means that power consumption is much more and increase dramatically. However, the AT mode is not giving the possibilities that API mode is giving that is why this mode is important. We will try to find out the differences in using this mode and how difficult is to establish simple communication between two END DEVICE XBee in API Modes.

Testing API mode is not the AT mode. Developing computer software is necessary. The program will send messages to the other XBee, which is connected, to the Arduino. Another program will use Arduino to receive the messages and send it back to the computer using the XBee in API mode. Loosing messages between the two parts will be noticed and calculated during a dedicated period to calculate the total packet lost in different environment as we did for the first part (Figure 5-10).

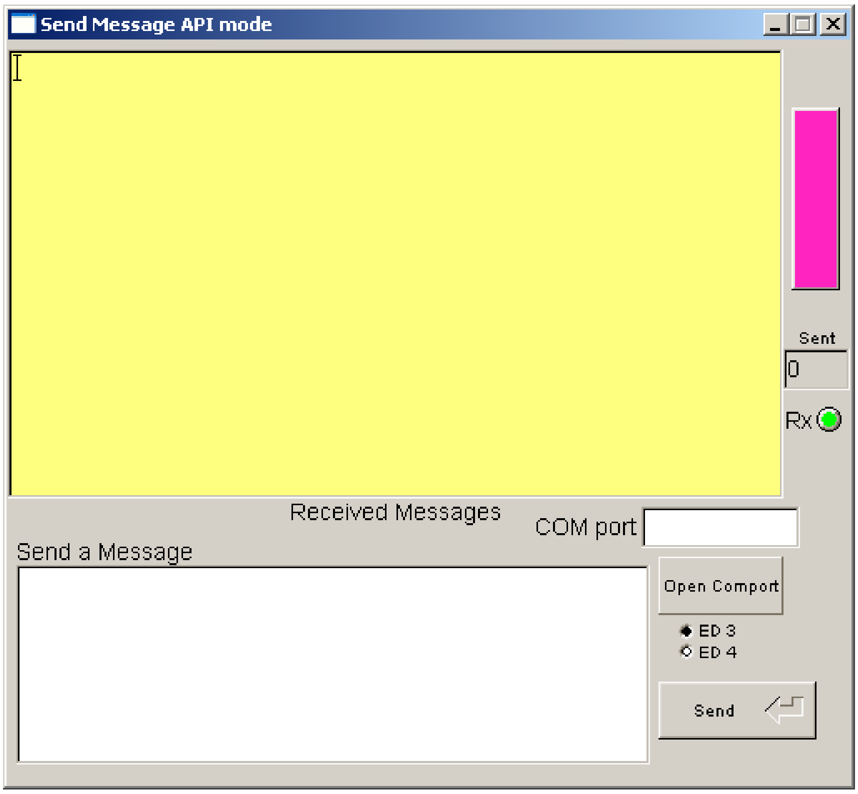


Figure 5-10: Computer software for communication in API mode

The program can send a single message or continues. In the white widget under “Send a Message”, can any message sends by pressing “Enter key”. Continues messages is possible to send by pressing the red colored button and the program starts to send cautious messages to the other XBee using com-port of the XBee module.

5.3.3 ZNET 2.5

This configuration is possible for this kind of XBee module which has the HD XB24-B. This research will not use this mode and it is mentioned here only for reference.

5.4 SUMMARY

In this chapter we described kind of tools, environment and configurations that will be used in the research. XBee modes, measurement sett and maps over the location selected were some of the information described here. In order to understand the result, reader needs to come back to this chapter and read about how things were configured.

6 RESULTS

The following observations were made as a result of experiments conducted by this research. Different section will represent different kind of test. Generally there are two major tests this research had as goal, the Electrical characteristics with power consumption measurement in different modes, and range test of XBee modules.

6.1 ELECTRICAL CHARACTERISTICS AND POWER CONSUMPTION

This also divides to different parts as follow:

6.1.1 USB Shield power consumption.

In order to get the power consumption for the XBee module itself without this module, user should subtract the amount of the power measured for this USB-module. A test of the USB model shows a current consumption of ~2.66 mA using the Multimeter, and the oscilloscope shows a 29.9v RMS over the 7.3 Ω see the following picture

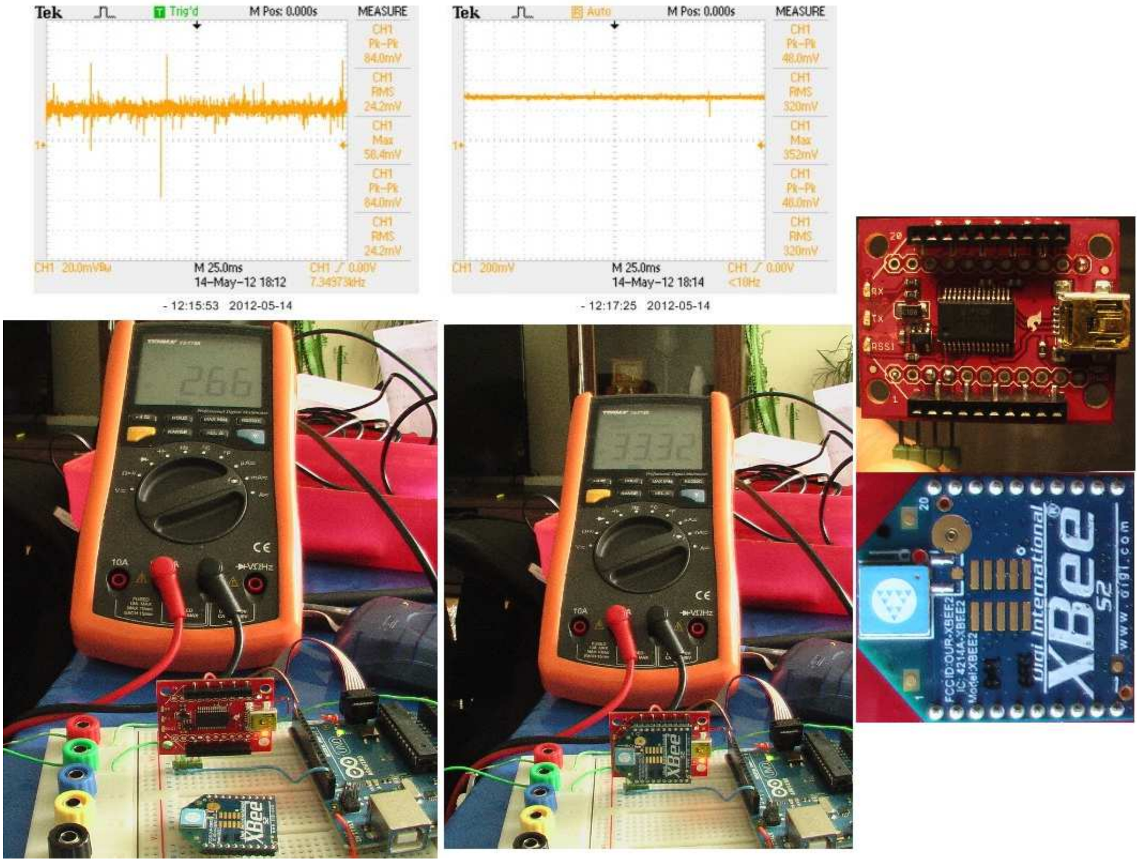


Figure 6-1 Power consumed by USB-module used for connecting the XBee

Calculating the consumed power by the USB module-using oscilloscope, which is shown in left part, is as follow:

$$I = \frac{29.9}{7.3} = 4mA$$

Power consumed by the USB-module (using oscilloscope)$_{rms}$ = 5volt * 4mA=20 mW
Power consumed by the USB-module = 5volt * 2.66mA=13.3 mW

There is an accuracy factor of 6 mW between the two measurements. The most accurate power consumption is the one measured by the Oscilloscope and the average consumption is about 20 mW.

Power consumed by the USB-module (when connected to computer port) = 5volt * 9.9 mA=49.5 mW

6.1.2 XBee Power Consumption

6.1.2.1 At Standby – One XBee Module

Only one XBee module in this section is switched ON, no further XBee modules is in the surrounding:

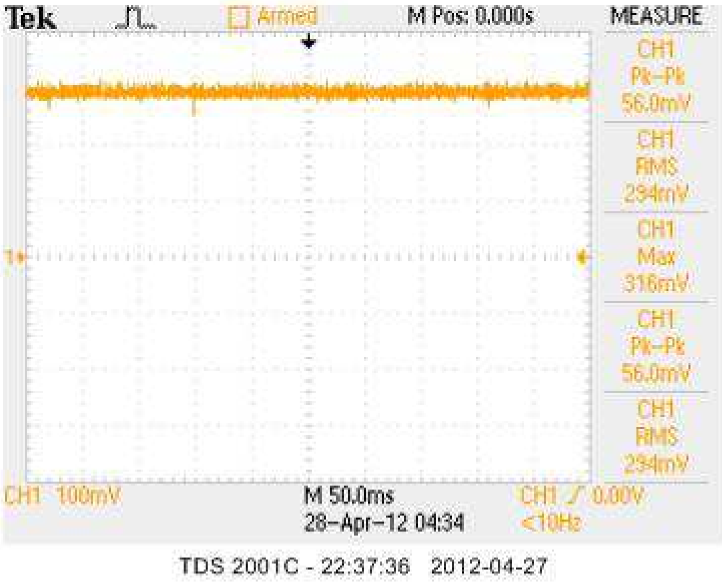


Figure 6-2 Current flow to the XBee - without sleep mode configuration – one XBee module

The RMS current will be equal = $\frac{294mV}{7.3\Omega} = 40.2$ mA

The Average voltage over the 7.3Ω will be equal = $\frac{316+288+260}{3} = 288mV$

The Average current = $\frac{288mV}{7.3\Omega} = 39.45$ mA

Consumed power $_{rms}$= 0.0402A*3.3V=0.13 w
Consumed power $_{avg}$ =0.3945A*3.3V=0.13 w

6.1.2.2 At Standby – Two XBee Module

More than One XBee modules are available in the network, but they are not communicating. The sleep mode is not either activated. We will calculate both average and rms power consumption as follow:

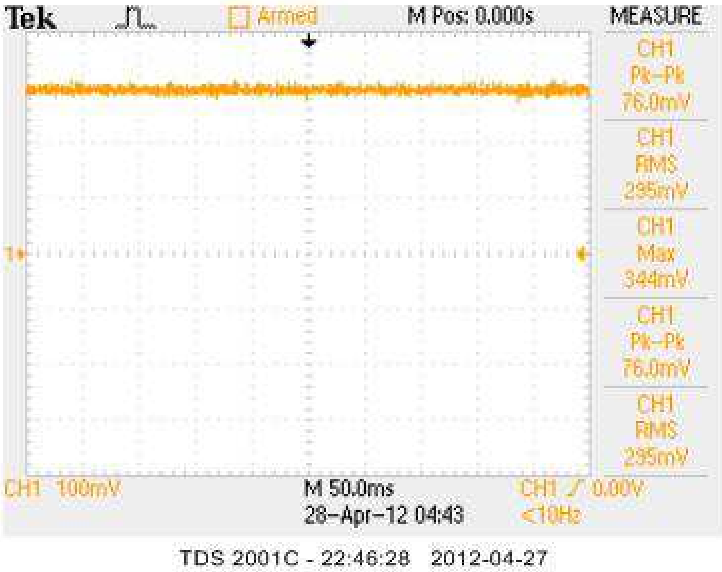


Figure 6-3 Current flow to the XBee - without sleep mode configuration – 2 XBee modules in the network

The required current $_{rms}$ = $\frac{295mV}{7.3\Omega}$ =40.41 mA
Consumed power $_{rms}$ = 0.04041A*3.3V=0.133 W

Now for the Average:
The Average supplied voltage = $\frac{295+333+262mV}{3}=296.6mV$
The required current $_{avg}$ = $\frac{296.6mV}{7.3\Omega}=40.630mA$
Power consumed $_{avg}$=0.0406mA*3.3V=0.134W

In order to be sure that we calculate the current correctly, I used even another Multimeter that has a com-port and there is software to capture the current/voltage. Figure 6-4 shows the same result as previously calculated by oscilloscope and three parallel resistances.
When the two X bee communicate the captured current consumption is as follow using the M-980T Multimeter:
Captured current = 0.053 A
Power consumed = $3.3V \times 0.053A$ =0.1749W

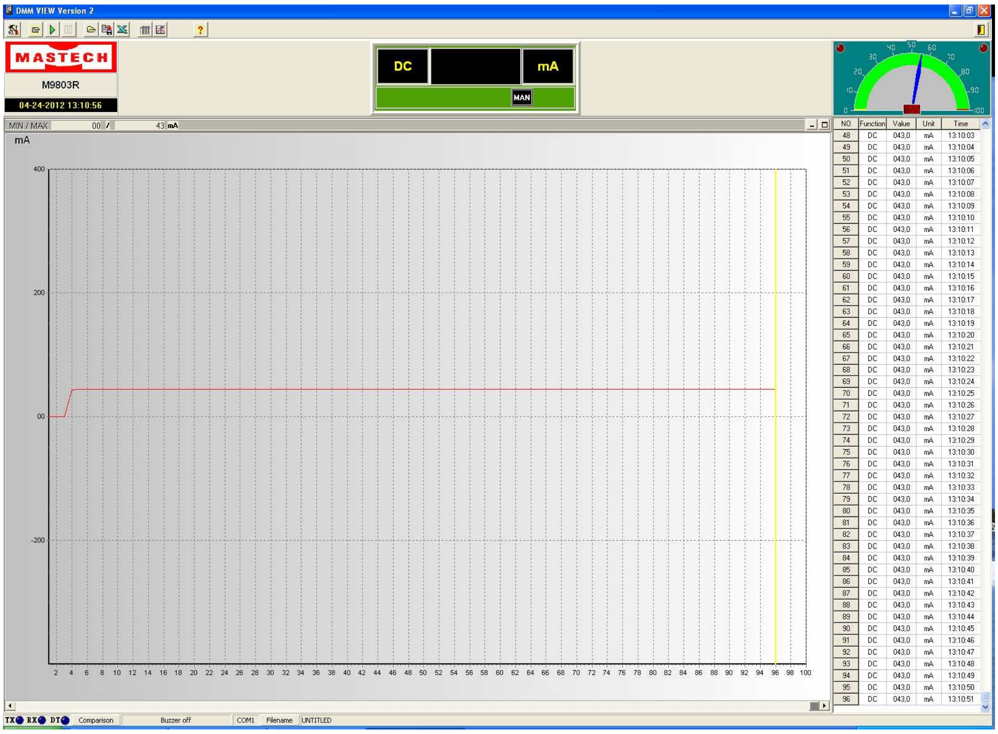


Figure 6-4 Current flow to the XBee module measured by special Multimeter connected to computer with no sleep mode

6.1.2.3 AT SLEEP MODE – ONE XBEE MODULE

Even when we have Sleep mode activate, but when there are no other XBee in the surrounding of this XBee the power consumption will be slightly higher.

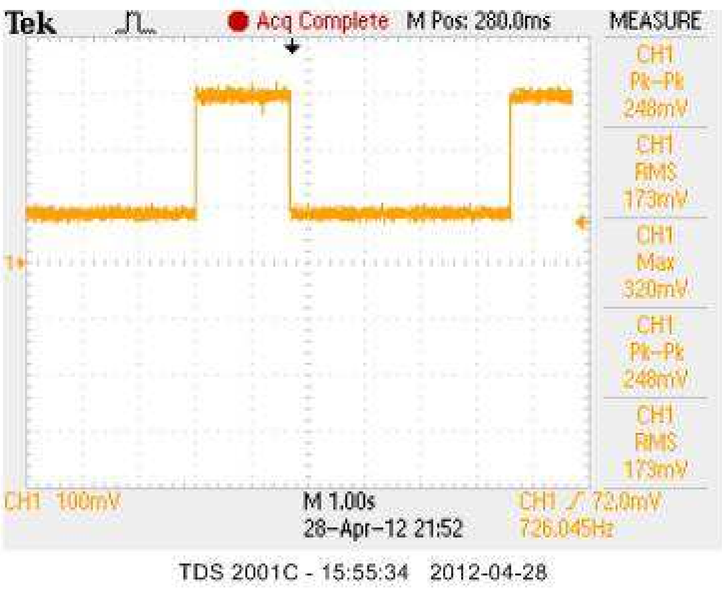


Figure 6-5 One-XBee Module Configured with Sleep Mode

Now we need to calculate the current consumed in this situation. The period is 6.5 squares - one second per square division. The Multimeter measures two different currents (9.40 mA and 32.08 mA). We will calculate the current also using the oscilloscope.

Consumed current during sleeping = $\frac{80mv}{7.3} = 10.95$ mA

T=5.6 sec
t_1=1.7 sec
Vp=300 mV

Consumed Current $_{rms}$= $\frac{200mv}{7.3}\sqrt{\frac{1.7}{5.6}}$ +10.95 mA=15.09+10.95 = 26.45 mA

Power consumed $_{rms}$ = 0.02645*3.3=0.0872 W

Now the Average power:

Consumed Current $_{avg}$= $\frac{200mv \times 1.7}{5.6} \times \frac{1}{7.3\Omega} + 10.95mA = 19.267$mA

Consumed Power $_{avg}$=19.267mA * 3.3V= 0. 06358 W

6.1.2.4 At Sleep Mode – Two XBee Module

The periodic current consumption is represented by figure 5-6. It wakes up each 100 ms for 10 ms. The current consumed is as follow:

Consumed current during sleeping = $\frac{80mv}{7.3}$ = 10.95 mA

The current waveform is a square pulses, the calculation of the current will be done using this equation

RMS equivalent of a square wave is [21] = $V_p \times \sqrt{\frac{t_1}{T}}$

Where V_p: is the peak voltage
t_1: is the Pulse width (Minimum allowed is 10ms)
T: is the cycle period

Total required current would be$_{rms}$ = $\frac{200mv}{7.3}\sqrt{\frac{10ms}{100ms}}$ +10.95= 19.61 mA

Consumed Power$_{rms}$ = 3.3*0.01961=0.0647 W

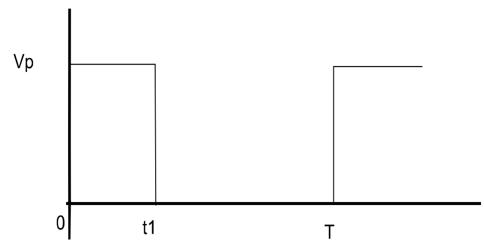


Figure 6-6A Pulse Waveforms

OR:

$$V_{average} = \frac{1}{T}\int_0^{t1} V_p dt = V_p \times \frac{t_1}{T} = 200\ mV\ \frac{10}{100} = 20\ mV$$

Consumed power $_{avg}$ = I*V =

$$\left(\frac{20\ mV}{7.3} + 10.95\ mA\right) \times 3.3V = 0.045176 \text{ W}$$

Consumed power during sleep mode is = 0.0361W
Consumed power at wake up zone = 0.045176W
This is the lowest power consumption that an XBee module consumes when sleep mode is activated. Looking to the diagram, it shows how the power consumption increases with the increase of the “wake-up” time to be full ON.
The minimum value for t_1 is actually is 10ms if you need to activate the sleep mode [Xbee manual page 89].

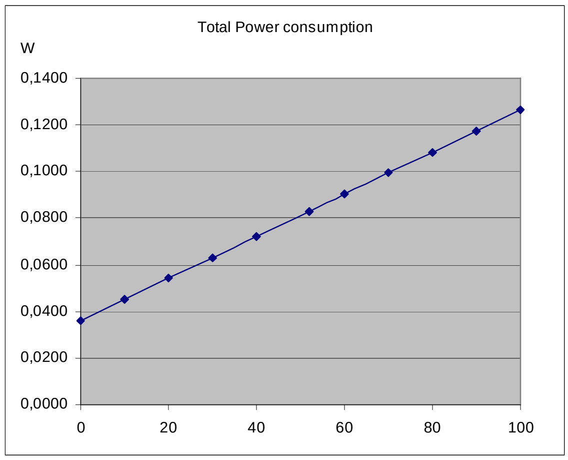


Figure 6-6B ST value affect on the power consumption

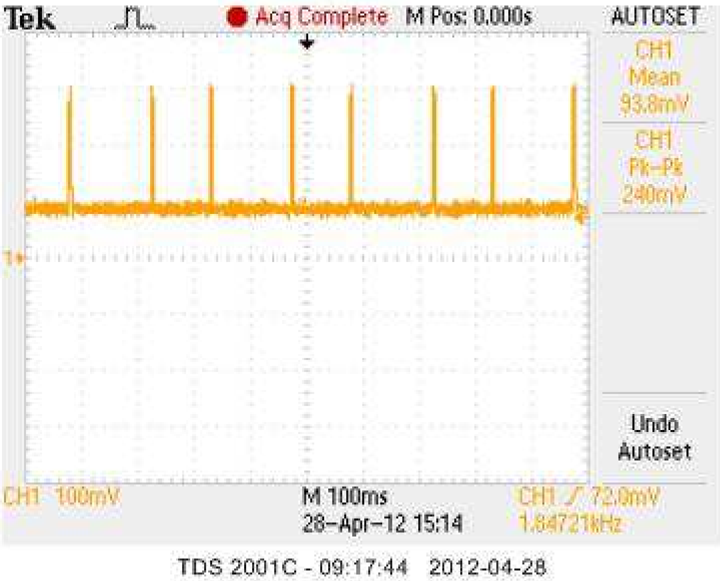


Figure 6-7 Two-XBee Module Configured with Sleep Mode Captured current waveform over the resistor

6.1.2.5 AT SENDING

The following is what we get when on XBee module sends one character (which is 'M') continuously.

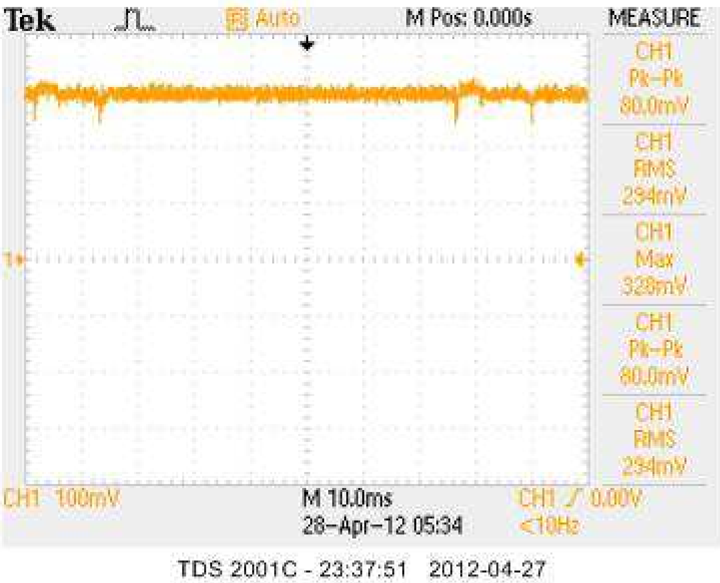


Figure 6-8 continuously sending a letter

The required current $_{rms}$ = $\frac{294mV}{7.3\Omega}$ = 40.2 mA

The power consumption $_{rms}$ = 0.0402*3.3=0.132 W

Now the required current $_{avg}$= $\frac{328+308+388mV}{3} \times \frac{1}{7.3\Omega} = 42.19mA$

Power consumption $_{avg}$ =0.04219 A*3.3 V= 0.1392 W

However, for sending only one letter we see that the current is jumping to the same as for the continuous sending but only for a short time, which is about 350 mSec of amount of 20mV.

The required current rms/avg = $\frac{20mV}{7.3} = 2.7397mA$

The Consumed power = 0.00273mA*3.3V=0.009041 W (During a time base of 350 mSec).

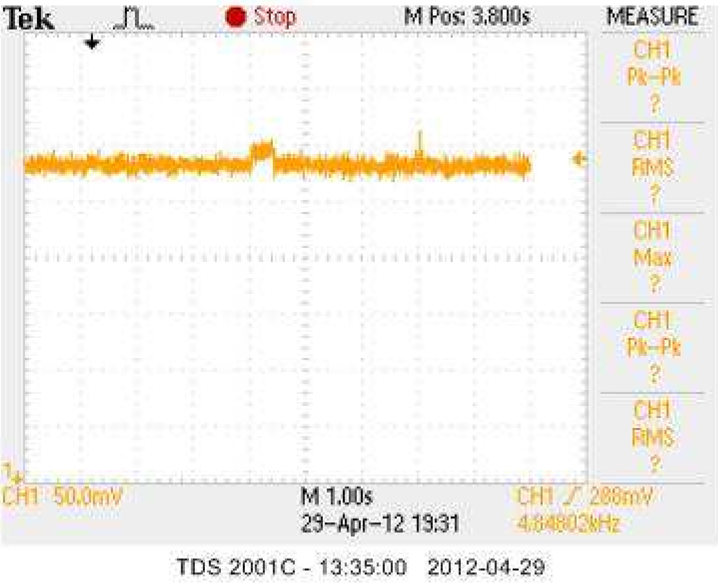


Figure 6-9 sending only one letter

To calculate the amount of power consumes in sending one letter:

15 mV the waveform rises up.

The required current $_{rms}$ = $\frac{15mV}{7.3\Omega} = 2.54$ mA

The power consumption $_{rms}$ = 0.00205479A*3.3V= 0.00678W

Now the required current $_{avg}$= $\frac{15+14.5+14mV}{3} \times \frac{1}{7.3\Omega} = 1.98mA$

Power consumption $_{avg\,=}$ 0.00198A*3.3 V= 0.00655W

6.1.2.6 AT RECEIVING

No big difference could be notice when the XBee Module is in listening and receiving state. The diagram blow shows the difference and we will calculate it.

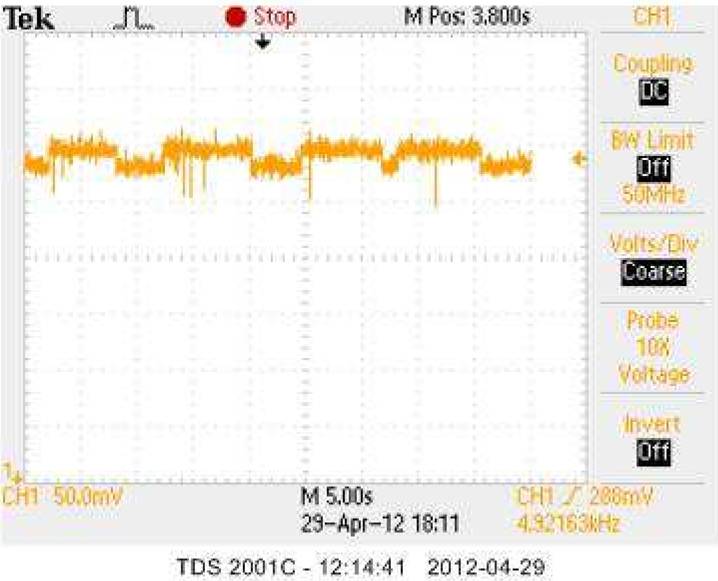


Figure 6-10 at irregular intervals receiving a letter

At receiving we see that the pulse has a value = $6\,\text{squares} \times 50.0\text{ mV}$ =300 mV

The current consumed is = $\dfrac{300mV}{7{,}3\Omega} = 41.09mA$

The consumed power is =0.04109 A*3.3 V=0.135 W

When nothing is sent and the XBee is not receiving any signal = $5.3\,\text{squares} \times 50.0\,\text{mV}$ =265 mV

The current consumed is = $\dfrac{265mV}{7{,}3\Omega} = 36.30mA$

The consumed power i=0.036 A* 3.3 =0.1188 W

The Multimeter is measuring as follow.

Figure 6-11 at irregular intervals receiving a letter measured by Multimeter

6.1.2.7 SENDING RECEIVING USING USB-SHIELD

Captured current requirement using a Multimeter connected to the com-port of a computer. As we mentioned before, it will be higher current since the USB-Shield itself needs power.

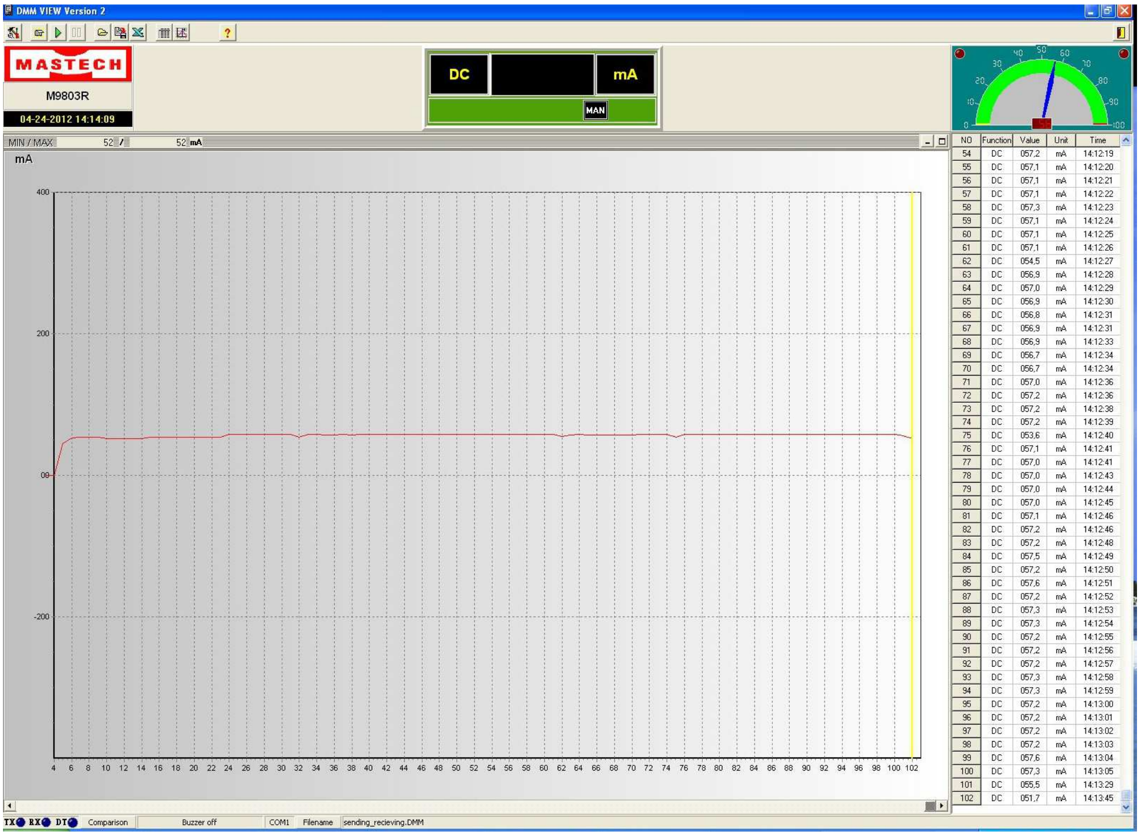


Figure 6-4 . Using X-CTU – Range test to measure the current consumption of the XBee module. The plot includes both sending and receiving

6.1.2.8 API MODE

We have a picture shows the waveform captured using API mode for sending-receiving a message. The packet contains only one real byte but as we know the actual packet is much bigger. It is too difficult to calculate the exact amount of power consumed as the shape is too complex.

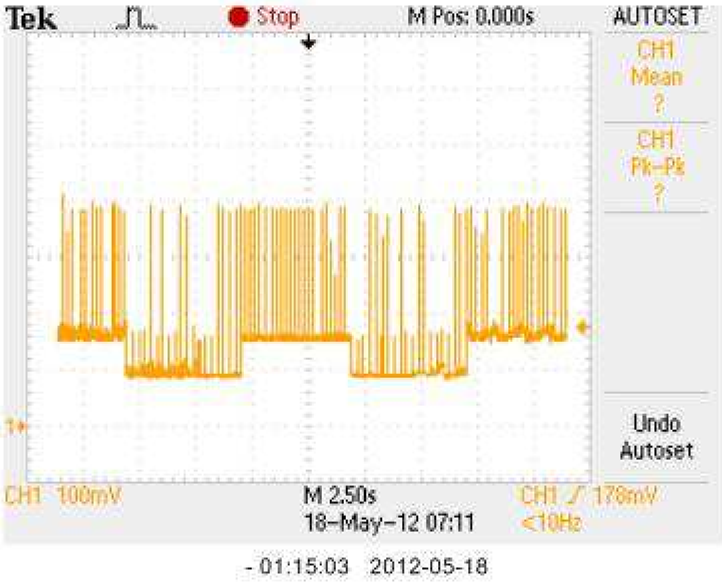


Figure 6-12: XBee in API mode receiving one char ("+") in a packet of 19 bytes and sending acknowledge of 11 bytes with sleep mode

6.1.3 UART Waveform Characteristic

This section is to figure out the characteristic of the waveform comes out by the communication pins of the XBee module. The waveform comes out from ATMEGA and XBee is inversed. The figure below shows receiving of some charterers by the XBee and sends to the Arduino. This means that if the Voltage level is not fixed there will be a constant current coming from the microcontroller to the XBee, as in the standby state it has ha high level which is 3.3 Volts for the XBee and 5 Volts for the Arduino.

Figure 6-13 Arduino connected to XBee and their waveform when they communicate via UART

6.2 RANGE TEST MEASUREMENTS

In this section, we write down the data collected in test done in different locations.

6.2.1 INSIDE THE APARTMENT – NO BARRIERS:

The tables below (6-1A & 6-1B) represent the same results, but in 6-1B the X-CTU is shown in the table.

Note:

1. The first six rows shows the range test for two XBee end devices with different distance between them when there were no Barriers in between them. As we see, it is safe only when the distance up to 800 cm, after that will be packet lose between the two XBee. This is true in normal apartments when at least one WI-FI router is active and two or more wireless portable devices active and sends signal.

2. The last two row is for the same XBee modules but one of them is put in a plastic box to make a physical Barriers between them, no directly effect was noticeable in this test. There will be no need for any diagram as the result is obvious.

Table 6-1A: Range test - AT Configurations

Module 1	Module 2	Distance (cm)	Baud rate	Packet lost module 1	Packet lost module 1	Duration	Barriers	Signal Strength
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	3	9600	0	0	1 min	no	100%
		100	9600	2	2	1 min	no	68%
		200	9600	4	2	1 min	no	67%
		400	9600	2	2	1 min	no	59%
		800	9600	8	2	1 min	no	50%
		1200	9600	46	40	1 min	no	22%
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END EVICE AT	3	9600	2	5	1 min	Yes One of the modules was inside a box	100%
		400	9600	6	2	1 min		63%

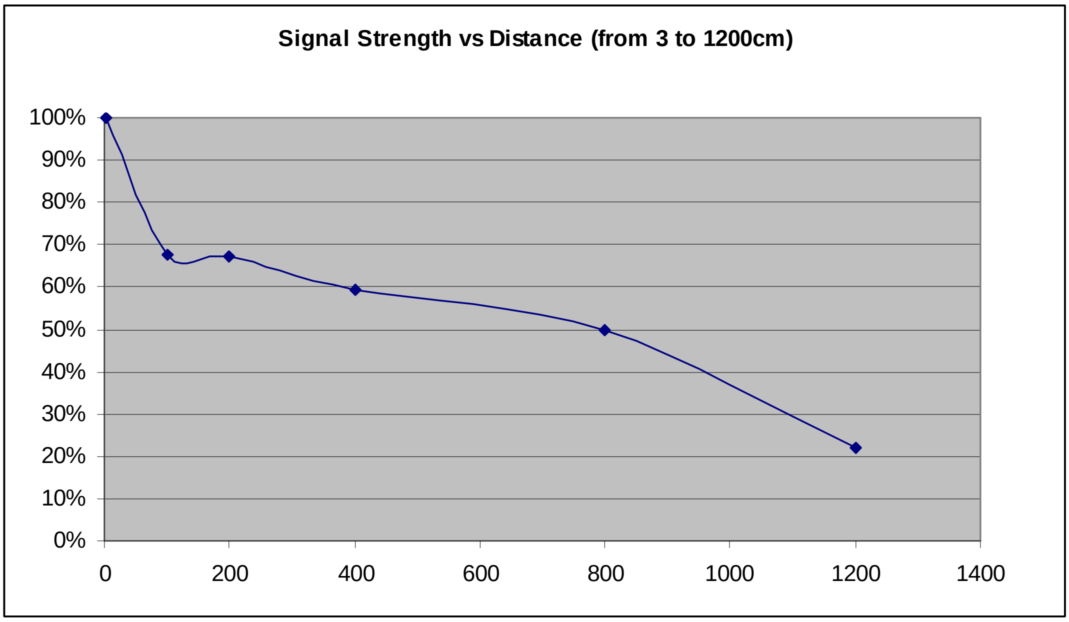
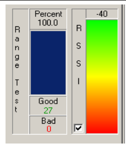
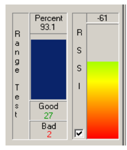
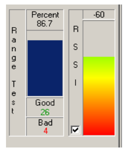
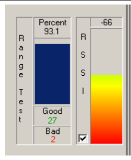
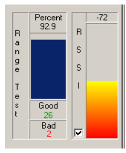
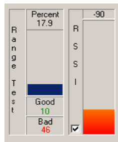
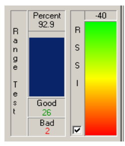
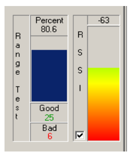


Figure 6-14: Signal Strength vs. Distance depending on table 6-1

Table 6-1B: Range test - AT Configurations

Module 1	Module 2	Distance	Baud rate	Packet lost module 1	Packet lost module 2	Duration	Barriers	Range
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	3 cm	9600	0	0	1 min	no	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	100cm	9600	2	2	1 min	no	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	200cm	9600	4	2	1 min	no	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	400cm	9600	2	2	1 min	no	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	800cm	9600	8	2	1 min	no	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	1200cm	9600	46	40	1 min	no	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	3 cm	9600	2	5	1 min	Yes One of the modules was inside a box	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	400 cm	9600	6	2	1 min	Yes One of the modules was inside a box	

6.2.2 INSIDE THE APARTMENT – WITH BARRIERS:

The tables below (6-2A & 6-2B) represent the same results, but in 6-1B the X-CTU is shown in the table.

Table 6-2A: Range test - AT Configurations – Barriers between the modules

Module 1	Module 2	Distance	Baud rate	Barriers	Signal Strength
ZIGBEE ROUTER / END DEVICE AT MODE	ZIGBEE ROUTER / END DEVICE AT MODE	500	9600	Wall	63%
		650	9600	Wall	52%
		900	9600	Wall	50%
		1400	9600	Wall and doors	45%

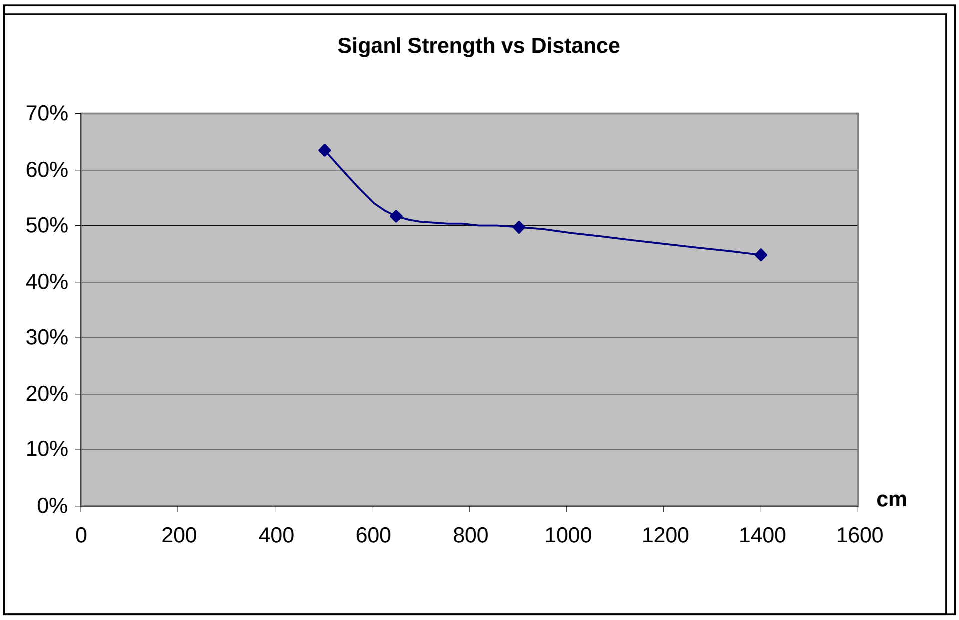
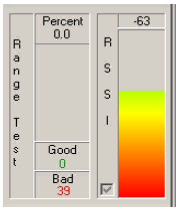
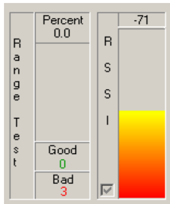
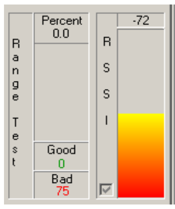
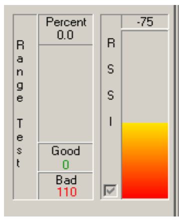


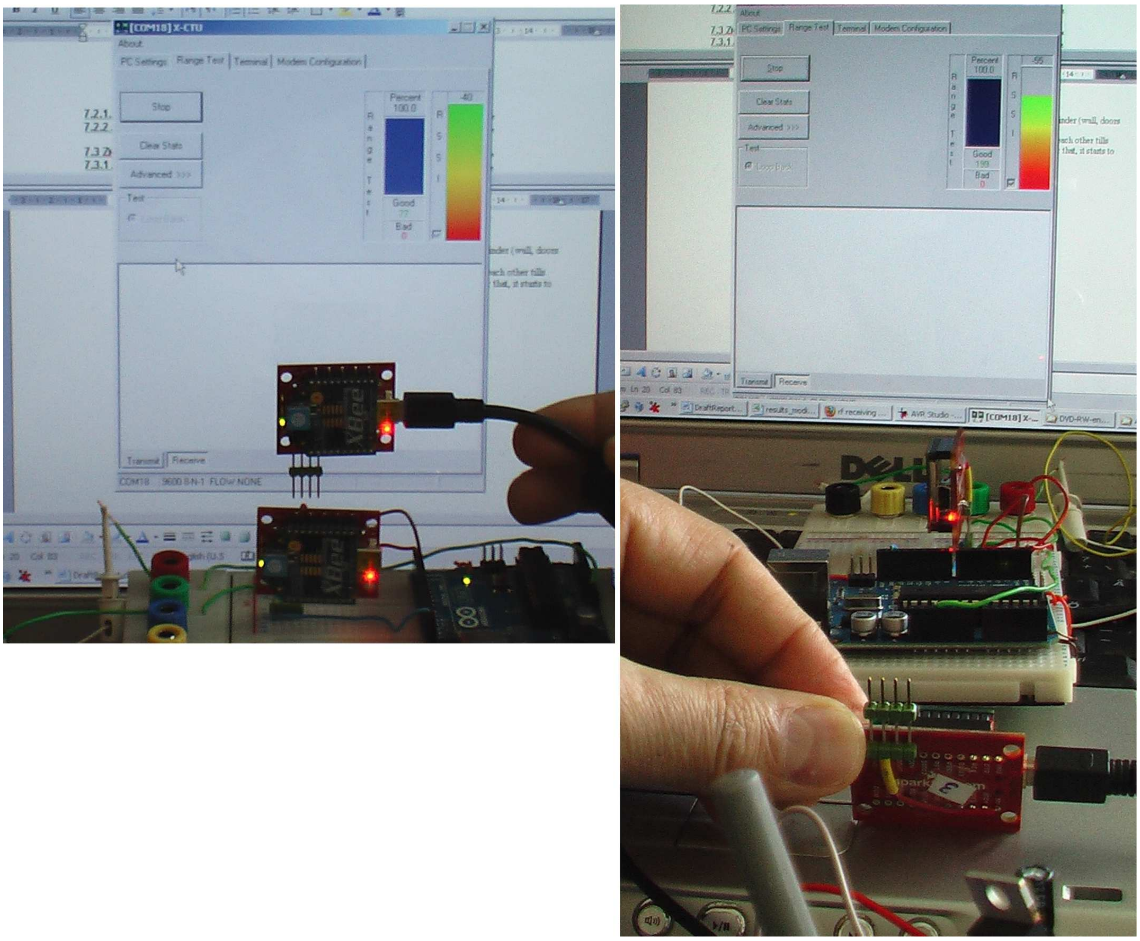
Figure 6-15: Signal Strength vs. Distance

Table 6-2B: Range test with Barriers between the two XBee - AT Configurations

Module 1	Module 2	Distance	Baud rate	Barriers	Range
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	500	9600	Wall	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	650	9600	Wall	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	900	9600	Wall	
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	1400	9600	Wall and doors	

6.2.3 ANGEL EFFECT ON RECEPTION

In this research, I found that XBee module are very sensitive for the angle they where sending. In two different tests in this section the result becomes obvious. The first part, both XBee have only some centimeter distance between them and the effect is obvious.. About 35% of the reception will be lost only by changing the angle of the module.



6-16 Range test between two XBee – Angel effect on reception

This effect becomes much clear when there is a bigger distance between the modules, for example 800 cm. See picture below Figure6-17

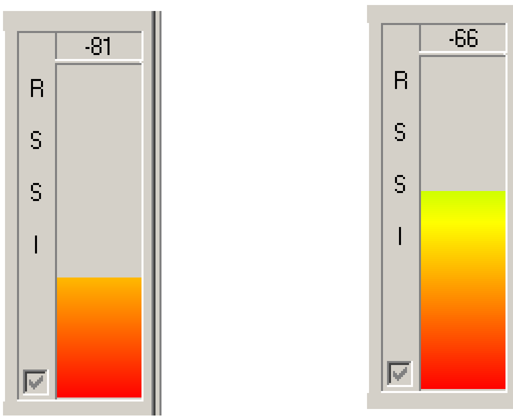


Figure 6-17 Range test between two XBee with the same distance of 800 cm But different angel - effect on reception

6.2.4 LOWEST POWER TRANSMISSION

When XBee configures as lowest power transmission, the reception and transmission becomes bad really. Figure 6-18 shows the reception level only after 200 cm. It will be totally useless after 2 m, no reception or sending will be possible.

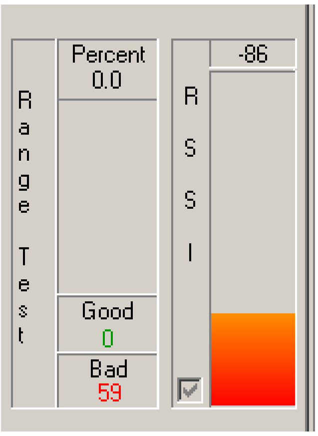


Figure 6-18 Range test between two XBee with distance of 200 cm Lowest power transmission

6.2.5 Inside H10 – Ground floor

In this location, we have longer distance between the XBee modules.

Table 6-3A Range test with Barriers between the two XBee - AT Configurations

Module 1	Module 2	Distance (m)	Baud rate	Barriers	Signal Strength
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	1.5	9600	No	60%
		4	9600	No	62%
		6	9600	No	50%
		8	9600	No	34%
		25	9600	No	36%
		40	9600	No	25%

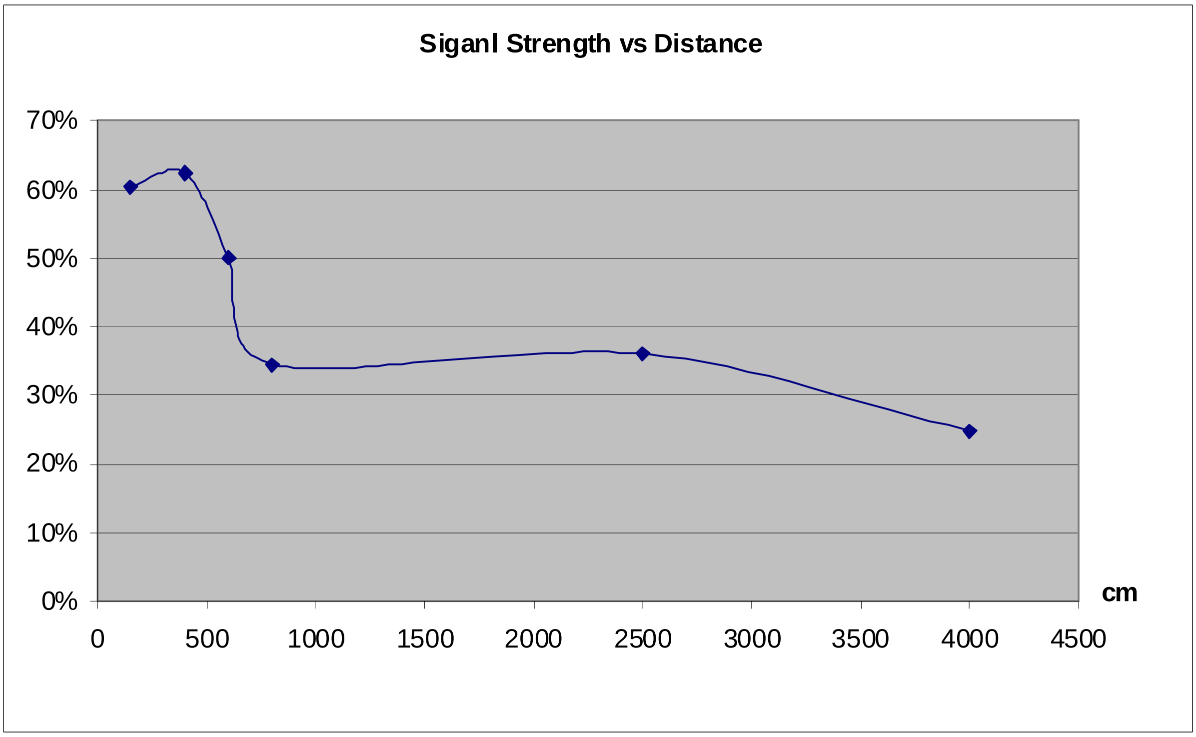
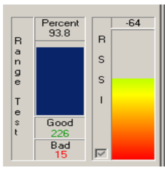
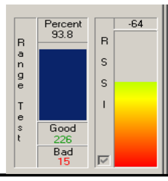
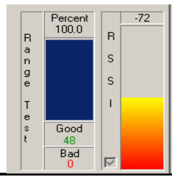
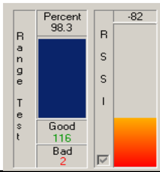
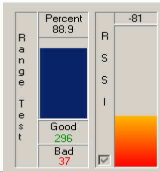
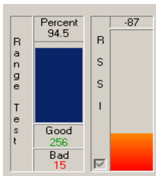


Figure 6-19: Signal Strength vs. Distance - H10 Ground Floor

Table 6-3B Range test with Barriers between the two XBee distance in meter - AT Configurations

Module 1	Module 2	Distance	Baud rate	Barriers	Range
ZIGBEE ROUTER / END DEVICE AT	ZIGBEE ROUTER / END DEVICE AT	1.5	9600	60%	
		4	9600	62%	
		6	9600	50%	
		8	9600	34%	
		25	9600	36%	
		40	9600	25%	

6.2.6 Inside the Classroom - SAL 83

Max distance for good reception in the classroom was 9m in some configuration. The table bellow shows the differences in reception while having different configurations.

Table 6-4 Range test with Barriers between the two XBee - AT Configurations (SAL83)

XBee 1	XBee 2	Distance(cm)	Condition	Signal Strength
2	5	900	XBee 1 on the table in X direction	17%
2	5	900	XBee 1's height changed to 30 cm while XBee 2 is in the same place (table)	55%
1	10	1400	XBee 2 on the ground at point 10 - No barrier	47%
1	10	1400	Arduino - XBee on a high place - Other on the table	50%
3	4	1200	Both near to the window – opposite sides	40%
1	10	1400	Searching for best reception	63%

The figure bellow shows the reception after 900 cm when all packet were lost (The picture is captured when it started to loose packet while before that the signal was good).

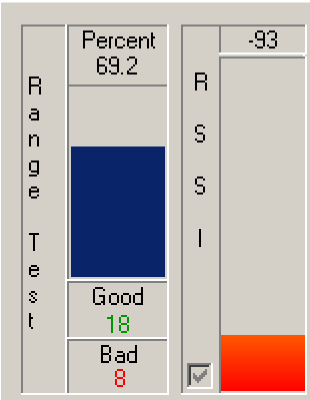


Figure 6-20: Signal Strength vs. Distance – SAL83

7 SUMMARY OF RESULTS

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This section will be divided in to two main parts, the Electrical Characteristics/Power Consumption of the XBee module and Range Test. Data input to this section will be from the previous section, section 6. With some other calculations and diagrams for the purpose of comparison, which the summary becomes more useful.

For the Range test, most of the collected data are based on AT mode. The API mode was not possible to use in the range test. The fact that the module's sender is consuming the same amount of power in sending one byte in different mode make it sure that results collected from AT mode could be used in understanding API Mode also. The sender hardware (modulator) is a separate part of the XBee that works always in the same way. There is only one configuration which makes a difference in sending, that configuration is the power sends by the module. The only different is when and how long the microcontroller inside the XBee module uses the sender (modulator) part of the XBee hardware.

7.1 ELECTRICAL CHARACTERISTICS AND POWER CONSUMPTION

This section will contain the results of power consumption and current requirements in different situations.

Table 7-1: Electrical Characteristics and Power Consumption of the XBee module

No	Descriptions	Average /RMS	Current (A)	Voltage supply (V)	(W)	Page
1	Single XBee module - no sleep mode	RMS	0.0395	3.3	0.1302	38
2	Single XBee module - no sleep mode	Avg.	0.0402	3.3	0.1327	38
3	Two XBee modules - no communications	Avg.	0.0406	3.3	0.1341	38-39
4	Two XBee modules - no communications	RMS	0.0404	3.3	0.1334	38-39
5	Two XBee modules - communicating (connected to computer)	Avg.	0.053	3.3	0.1749	39
6	Two-XBee Module Configured with Sleep Mode - no communications	Avg.	0.0123	3.3	0.0407	41
7	Two-XBee Module Configured with Sleep Mode - no communications	RMS	0.0137	3.3	0.0451	41
8	One-XBee Module Configured with Sleep Mode	Avg.	0.0193	3.3	0.0636	40
9	One-XBee Module Configured with Sleep Mode	RMS	0.0265	3.3	0.0873	40
10	Two XBee - One of them sends continuously	Avg.	0.0402	3.3	0.1327	42
11	Two XBee - One of them sends continuously	RMS	0.0422	3.3	0.1392	42
12	Sending one character "M" between two XBee	Avg.	0.0027	3.3	0.009	43
13	XBee module receiving a letter at irregular interval (Oscilloscope)	Avg.	0.0411	3.3	0.1356	43
14	XBee module receiving a letter at irregular interval (Multimeter)	Avg.	0.0322	3.3	0.1063	43
15	USB-Shield (adapter) without XBee (Connected to computer USB port)	Avg.	0.0099	5	0.0495	37
16	USB-Shield (adapter) without XBee (Powered by Arduino) - using Oscilloscope	RMS	0.004	5	0.02	37
17	USB-Shield (adapter) without XBee (Powered by Arduino)	Avg.	0.0026	5	0.013	37

7.2 Range test

As we described in section 6, Range Tests affects by many parameters, from the simplest configuration to the complex conditions. This section will make a comparison between each result to find out the best environment and configuration for XBee communications. It aims to find out a reliable communication between the different XBee modules.

7.2.1. Max Power (PL) and Max range reception:

I have two different distances depending on the environment and XBee modules positions. These diagrams represent results when no barrier is isolating the two XBee modules.

7.2.1.1 Inside my apartment:

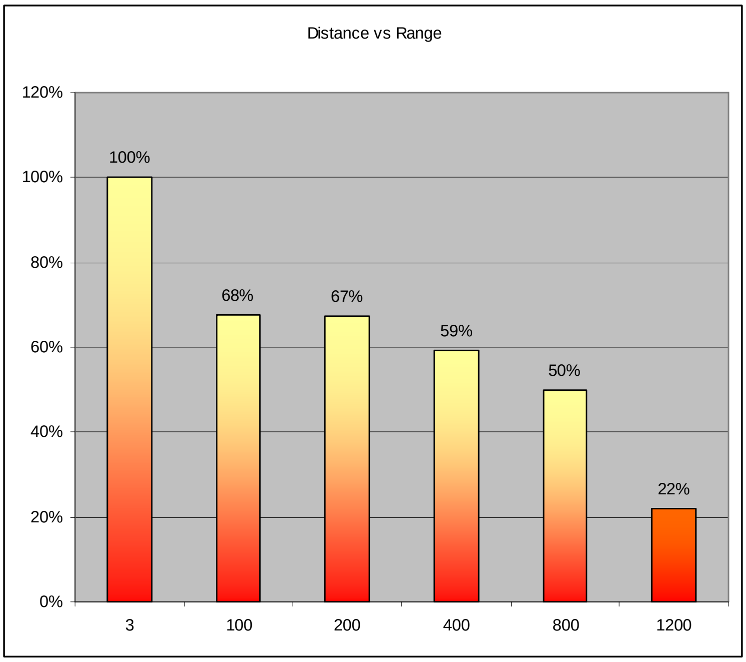

Figure 7-1A: Distance effect (in cm) on the reception - Apartment

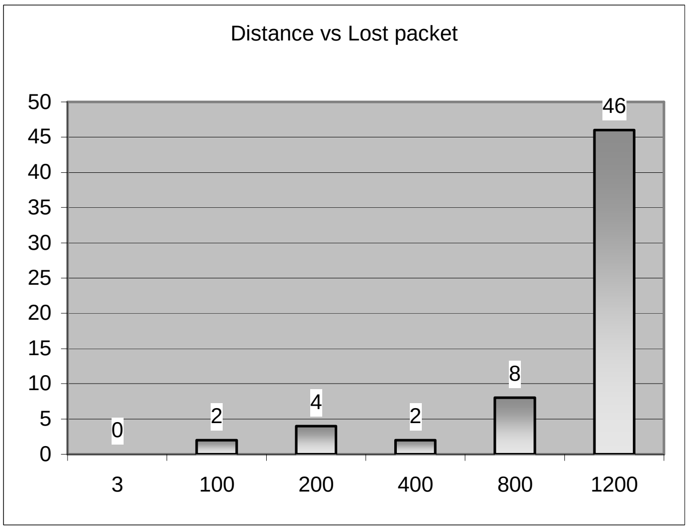

Figure 7-1B: Distance effect (in cm) on the lost packet - Apartment

7.2.1.2 AT UNIVERSITY (GROUND FLOOR- H10):

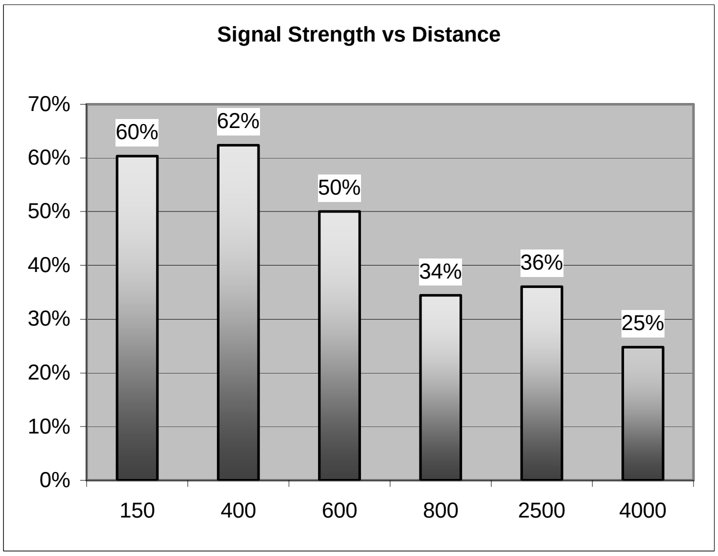

Figure 7-2: Distance effect (in cm) on the reception H10 ground floor

7.2.2 MAX POWER /LOWEST POWER EMISSION CONFIGURATION (PL):

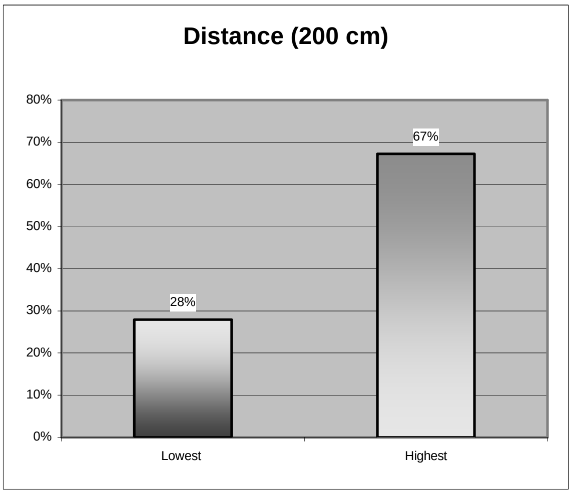

Figure 7-3: Difference in power emission – the same distance

The diagram shows how lowest power emission by XBee becomes unreliable. 200 cm is the critical point and what the max distance for reception is. After this point, most of the packet will be lost. Critical means that it is not a recommended range to use with the lowest power sending configuration.

7.2.3. Different Angels but the same distance:

In this section we will proof the effect of the angle between the XBee

A. The Distance is only 2 cm:

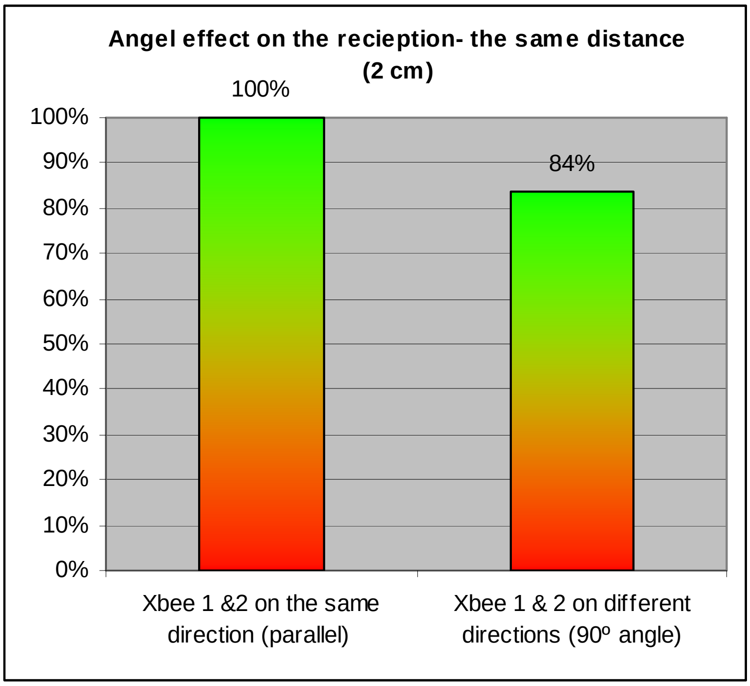

Figure 7-4-A: Angle effect on the reception 2cm

B. The distance is 8M:

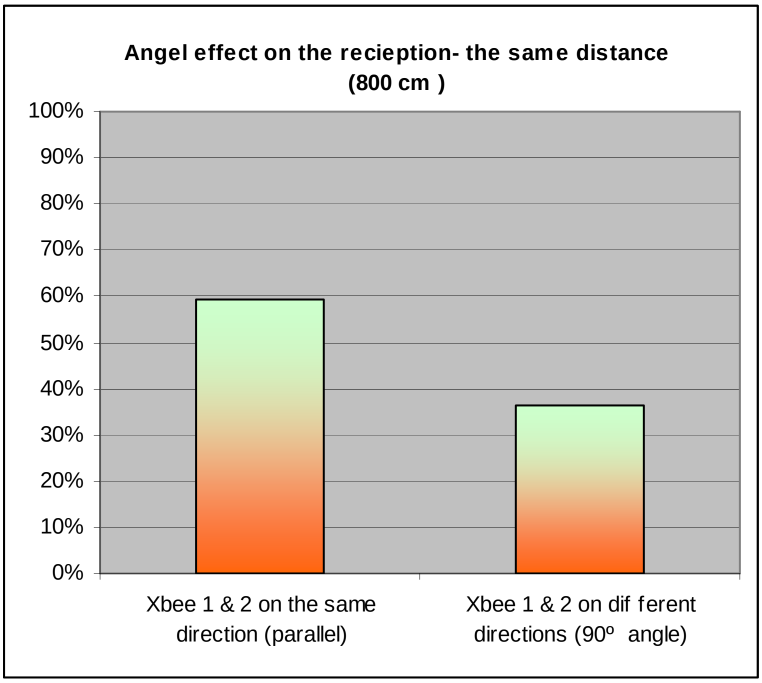

Figure 7-4-B: Angle effect on the reception 800cm

7.2.4 DIFFERENT HEIGHT FOR ONE OF THE MODULE (900 CM):

In this test, the distance is the same, I had no reception when the XBee modules where in the same level in SAL 83

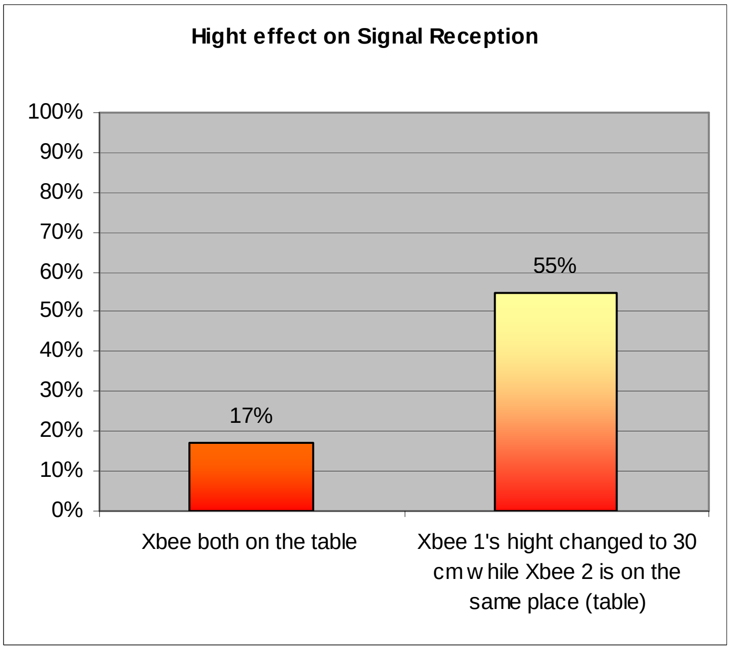

Figure 7-5: Height effect on the reception

8 SUGGESTIONS AND FUTURE WORK

In this chapter, some suggestions and some future works will be explained in details. Suggestion that could help other students and researcher to avoid some of the mistakes I discovered. Future works will explain the need for further research in different subject related to this research.

8.1 SUGGESTIONS:

Here are some suggestions the research comes out with:

8.1.1 AT MODE:

1- X-CTU is usable but not perfect for testing the XBee modules, as many parameters are not possible to change using the terminal from the X-CTU. For example, the communication channel is not changeable manually using the X-CTU. However, the program is good for range testing and other test done by this research.

2- XBee transmitting channels could cause too much problem when they do not get correct values or they mismatch. Coordinator should force the router or end device to take the channel the coordinator decides, however this is not working always. Programmer should take in consideration this problem. Acknowledgement system should assure a healthy communications channel.

3- To get the network working, user needs to reconfigure the XBee using the embedded system and sending AT commands to remote XBee modules. It is definitely clear that XBee Coordinator, Router is not doing the job as the documentations describe. One of the attribute that Coordinator should force the XBee modules in the PAN networks is the Channel. This behavior tested using AT mode and it is not working at all. The problem is the communication channel cannot manually assign. This is a bad property of the XBee. A WI-FI router gives the opportunity to change the channel works fine for that environment. This should be possible for the XBee also.

4- Using Coordinator and Router in AT mode did not make any noticeable effect in improving the quality of the signal.

5- It could be possible to make a library that use AT Mode for making a network. A library that takes care of addressing issue and other issues that made in hardware in the API mode. If a system doesn't need to use API mode as it is complicated, it should be possible to do that in the embedded software.

Note:
I tried this setting by using two XBee END DEVICE:s having different channels, but the same PAN address, and a coordinator with the same PAN, first by starting the coordinator and later the two XBee module and start doing some communications. The coordinator could not force the END DEVICE:s to get the same communications channel. With multiple power try and powering ON and OFF END DEVICE:s, at last they did get the same communication channel. However, this behavior is not trustable in real application as these XBee END DEVICE modules might be used with an embedded system, and debugging such a system will be hard, bugs are not easy to find either.

8.1.2 API MODE:

1- To test API mode, special program (code) needs for both Arduino and Computer.
2- It is possible to calculate the amount of the power consumes by API-MODE compared with the results we got from the ATI-MODE simply by calculating the increase of sending one character, look at figure (6-9). The following equation is the total character which each packet will encapsulates in a packet of :
   If data = n bytes
   18 bytes needed
   Total bytes will be= 18 +n

   An Example:
   7E000F100100**13A2004071CEFF**FFFE0000**4D**71
   The Red letters is the address and the blue letter is the character "M" that is the real message content.
3- Coordinator will work continuously without been able to go to sleep mode. The power consumption of the Coordinator is difficult to calculate exactly as the roll of the coordinator is much more complex than any end device XBee. However, there is max and min power consumption. This calculation and measurements of max and min power consumption gives an idea and help any developer to make proper assumption of total power consumption and.
4- Given that the API mode is more complex, finding proper position of the modules are necessary. Best positions for different distances (as height, angel ...etc) must be decided before leaving the embedded system. Not doing proper test could lead to malfunctioning overall system and a behavior that is unknown.
5- Coordinator is supposed to select communication channels and supervise the network. Any problem in the Coordinator will result in malfunctioning XBee network. This is true especially when no router is in the network.
6- It was not possible in this research to find out the reason behind the problems occur in the API mode with the XBee modules. More tools and more hardware need to do such tests. It needs much more time and much more feedback from the producer.

8.1.3 ARDUINO:

For developers that use Arduino as a platform in developing XBee networks, there are many critical issues that need to find out plats in their calculations. The following are the issues I wish to rise up:

1. Developer needs to select the communication Baud Rate carefully, since Arduino does not use crystal oscillator as clock generator for the microcontroller (Figure 5-4).
2. Any XBee device connects to TX and RX pins of the microcontroller should have the same voltage level. If it uses another voltage levels for the logical states (0 and 1) there should be a convertor between these two devices. This is true for all XBee modules. It is not safe to connect directly XBee to Arduino or any other microcontroller uses 5 Volt VCC. Look at the section (2-5)
3. Arduino has limited power supply ability to external devices. For proper operation of external devices, I recommend using separate external power supply.
4. The microcontroller will not get enough voltage (5 Volts) when only a USB cable is the feeder of the power to the Arduino Uno module. Using 6 volt or USB cable will gives only 3.4 Volts to the Atmega IC. Look at section (4-1)
5. Given that synchronization between different XBee modules could be lost, resynchronization via restarting the system (all members of the network or one in the system) should take place in calculations. Embedded software need to have a kind of checking on the communications status. And making proper reset of the device to restart both XBee module and the Arduino (ATmega IC) program.
6. Arduino works just fine in the AT mode. However, I faced too much problem using the API mode. I tried everything possible to find out the reason. It was not possible to find out the reason. The RSSI LED is not becoming ON. This means that the Module cannot or not communicating to other XBee modules. The signal coming to the XBee from the Arduino was correct, and it was correctly connected to the XBee but the module did not send any message. There are hidden errors that make this to happen. More research should be done in this field.
7. API mode worked fine using XBee USB-shield and computer. This confirms that the software is not the problem. I used the same code in both cases.

8.2 FUTURE WORK

1. The results clarified many issues concerning the XBee usage and power consumptions. Calculating power consumption is almost impossible for a continuous communication using API mode, since the sending – receiving has a quite complex current waveform. Using special computer program which should be developed could do this calculation. These results in this document give researcher an idea about the amount of the current required by sending or receiving. Putting those numbers in equation that take care of the captured waveform should make it possible to calculate packets power consumption.

2. XBee Sleep mode consume less power, but it is unclear if a load with a variable sate in form of pulses, cause problems for batteries and cause less lifetime if the XBee is powered by batteries. To get a clear picture about the effect of such load, further research will be required.

3. In a variable-load high power device such as a digital camera, the battery level indicator gives a prediction of remaining battery life, based on current rate of consumption. Since different operations consume different amounts of power, the battery gauge may appear inaccurate if changing the operations being performed by the camera, which changes the rate of power consumption.

4. In this research, it was not possible to compare XBee with other Zigbee hardware implementation. I suggest that the university bring other Zigbee compatible modules and make similar research to figure out if the problems I faced are a general problem with the Zigbee protocol or it is only XBee problems.

5. Using Multimeter to measure current flow to XBee is not the correct way as it fails. The matter is too complicated and needs very accurate devices to measure and have an acceptable accuracy. In my calculation I depended mostly on the Oscilloscope to measure the current required by the XBee.

6. API mode communication needs a special research to figure out the problems. I couldn’t find any difference in range test using a coordinator. It didn’t make the covering better. More than one student should participate in a project uses API as it require more computers and more observations. This was impossible for me.

7. Range test using XBee module that have other kind of Antenna. It should give a better range. It will be good to make a comparison with this research.

8. These entire problems made it impossible for me, as one student in this project, to manage use the API mode in range test. There are many problems regarding the API mode that make it difficult for one student to manage the tests.

9 CONCLUSIONS

9.1 ELECTRICAL CHARACTERISTICS AND POWER CONSUMPTION

1. Using sleep mode configuration to get standby mode is not working as it should when there is only one XBee in the area and powered ON. It will try to find another XBee module regularly which increases the power consumption. The same result could be found when an XBee module looses contact with the rest of the network, and it will consume much more power.
2. In the sleep mode, the minimum time needed for the XBee is 10 ms. Sleep mode configuration should be carefully selected, and a good calculation should be made between the End devices, router and coordinator. As router/coordinator save and hold packet while an end device is in standby, but the sleeping time shouldn't be more than the time the router/coordinator can keep the packet. The Minimum time that XBee will be ON during the sleep mode – cycle configuration is 10ms. XBee Datasheet describes these configurations in details.

3. One of the factors that affect the power consumption is the baud rate. As a higher baud rate generates more packets lost, it means also more power consumption since the network or the system needs to deliver the packet and send it again.

4. I prefer not to use the XBee USB- shield in measuring power consumption. And I prefer to use XBee with a separate power supply. But it should be a proper power supply source with minimum ripple. Filters (capacitors) between the regulator and the VCC pin of XBee should be used or the XBee will not work well since noise will affect the communication.

5. The measurements obtained in the current section could be used in measurements for complicated systems. By using each part of the configurations and power consumption obtained in this research, researcher will be able to calculate the consumed power for any other system that XBee is the communication module.

6. Care must be taken when two different logical levels connects together. XBee modules need a level converter if the microcontroller has 5Volts logical level.

7. Arduino has hardware bugs. The clock generator is not accurate which results in an accurate baud rate. An accurate baud rate will increase the packet lost and power consumption.

8. Regardless which mode uses, power consumption of XBee will be the same. The only factor affect the power consumption by the sender is the configuration byte called PL (Power Level under the RF configuration).

9.2 RANGE TEST

1. XBee used in this research is not giving the distance mentioned in the documentation. It says that XBee should works for a range of 40 m. But in practice, the XBee didn't work at this range or even shorter range and failed to deliver packets securely. Secured range is only 8m without loosing packets. Up to 8 m distance there will be no problem if full power transmission is used. Signal receiving which is fewer than 40% is not good and cannot be trusted.

2. XBee modules are sensitive for the physical direction and the 3D angle they have with each other. This angle-sensitivity questions the XBee hardware deeply. If any embedded device uses XBee modules with in different angels to each other, this could result in uncertain conditions. It cannot be guaranteed that they work together. Because of that I suggest to make filed test for any produced embedded devices before installing the system, especially if the range is more than 8m.

3. Communication failure and resynchronization between XBee should be managed in the code. There should be a regular checking of status of the network. Channel communications should be also manually controlled by software as it will fail some times. My research proved that Coordinator is not always forcing the XBee end devices to come to the same channel. Only by several power cycling (Power OFF/ON) I could bring the end device to the same channel. X-CTU will not provide full configuration of the XBee.

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[10] http://www.jsjf.demon.co.uk/XBee/XBee.pdf
[11] ftp://ftp1.digi.com/support/documentation/90001067_a.pdf
[12] http://diydrones.com/forum/topics/XBee-range-problem-solved
[13] http://www.hkr.se/templates/Page____854.aspx
[14]https://apps.fcc.gov/oetcf/eas/reports/ViewExhibitReport.cfm?mode=Exhibits&RequestTimeout=500&calledFromFrame=N&application_id=243570&fcc_id=%27OUR-XBEE2%27
[15] http://sensor-networks.org/index.php?page=0831631643
[16} http://transition.fcc.gov/aboutus.html
[17] http://www.wikid.eu/index.php/Infrared_networking
[18] http://fanazra.blogspot.se/2009_08_01_archive.html
[19] http://www.ember.com/pdf/ember-EM250.pdf
[20] http://web.archive.org/web/20080508221624/http://www.digi.com/support/kbase/kbaseresultdetl.jsp?kb=160
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APPENDICES

APPENDIX A

Code used in the research for both AT and API mode:

1. ATMEGA:
2. Computer: