Implementation and performance evaluation of WSN for energy monitoring application

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Abstract

The aim of this paper is to develop a wireless sensor network to measure and analyze energy consumption in buildings and to investigate the bounds of coverage in different building construction materials. The performance of the designed system is evaluated in different indoor channel conditions using both computer simulations and hardware measurements. The basic design elements include current sensors, microcontrollers, and wireless transceivers implemented using GSM/GPRS platform and ZigBee technology. The use of GSM/GPRS platform makes it possible to control or gather information about the system from anywhere just by sending a request using SMS. Many measurements have been done to find the exact limitation of the designed system in terms of coverage and signal strength in the presence of objects of different materials including: cardboard, metal, concrete bricks, wood and corkboard. The results show that the metal represents the worst material in terms of signal strength reduction. At 4m distance between the base station and the sensing node, the loss in signal strength are 15, 20, 21 and 32 dBm when using metal as compared with cardboard, corkboard, wood and concrete bricks respectively.

Keyword: Wireless Sensor Network, Energy Monitoring, ZigBee, GSM/GPRS

تنفيذ وتقييم أداء شبكة استشعار لاسلكية لتطبيقات مراقبة الطاقة

الخلاصة

الهدف من هذا البحث هو تطوير شبكة استشعار لاسلكية لقياس وتحليل استهلاك الطاقة في المباني، والتحقيق في حدود تغطية الشبكة تحت تأثير مختلف مواد البناء. يتم تقييم أداء النظام المصمم في مختلف أوساط نقل الإشارة باستخدام المحاكاة وأجهزة القياس. وتشمل العناصر الأساسية لتصميم الشبكة: أجهزة استشعار التيار الكهربائي، متحكم دقيق، وأجهزة الارسال والاستقبال اللاسلكية والتي نفذت باستخدام "GSM/GPRS platform" وتقنية "ZigBee". استخدام تقنية GSM/GPRS، يجعل من الممكن السيطرة أو جمع المعلومات من الشبكة من أي مكان بمجرد ارسال طلب باستخدام الرسائل القصيرة من أي هاتف محمول. وقد تم اجراء العديد من القياسات لإيجاد محددات النظام المصمم من حيث التغطية وقوة الإشارة في داخل الأبنية تحت تأثير الجدران وعوازل السقوف المختلفة بما في ذلك: الورق المقوى، المعادن، الطوب الاسمنتي، الخشب والفلين.

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وتبين النتائج ان المعادن كال (stainless steel) كان أكثر المواد تأثيرا على قوة الإشارة. وعند مسافة 4 متر، بين المحطة الأساسية وعقد الاستشعار، تكون الخسارة في قوة الإشارة هي (15، 20، 21 و32 ديسيبل ملي واط) عند استخدام المعادن مقارنة بالورق المقوى، صفائح الفلين، الخشب والطوب الاسمنتي على التوالي.

INTRODUCTION

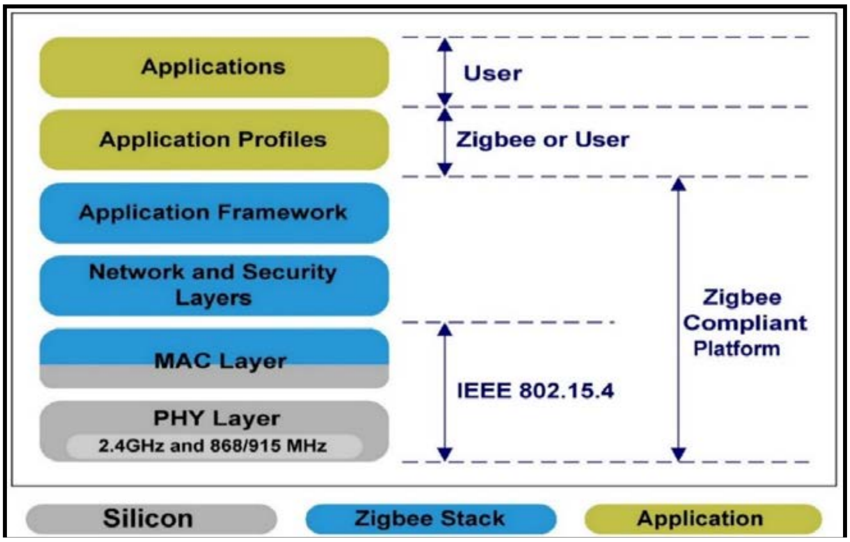
Wireless personal area networks (WPAN) and wireless sensor networks (WSN) have received significant attention in recent years. These networks are designed with power consumption and device cost as the primary considerations, and sacrifices are made in performance and reliability in order to meet these objectives [1, 2]. There are many applications in which a WSN can be used such as military, healthcare and environmental monitoring [2, 3].

In early 2003 the IEEE STD 802.15.4 was ratified after many years of effort. This standard represented a significant break from the “bigger and faster” standards that the IEEE 802 organization continues to develop: instead of higher data rates and more functionality, this standard was to address the simple, low-data volume universe of control and sensor networks, which existed without global standardization through a miasma of proprietary methods and protocols [4]. The IEEE standard identifies and controls only the RF, PHY and Medium Access Control (MAC) layers, and there are a variety of custom and industry-standards based networking protocols that can sit atop this IEEE stack. The standard states that wireless links can operate in the 2.4 GHz, the 915 MHz or the 868 MHz Industrial Scientific and Medical (ISM) bands. The standard allocates 16 channels in the 2.4 GHz band, 10 channels in the 915 MHz band, and only one channel in the 868 MHz band and that makes a total of 27 channels are allocated by this standard. Despite the fact that any of these bands can be used by the standard devices, the 2.4 GHz band is more common as it is certified in most of the countries worldwide [5]. However, several different networking techniques have been developed outside of the standard to take advantage of this radio such as ZigBee Alliance and its ZigBee mesh network [4].

Many researches were carried in the field of energy monitoring, some of them focus on the network topologies and power management [6, 7, 8], others focus on improving the performance of ZigBee based WSNs using computer simulations [9, 10]. However, we found that there are a very little information about the description of ZigBee based WSN system setup in terms of hardware interfacing and software control. Also, we don’t find in the literature a study of the effect of different constructional materials on the ZigBee sensing signal strength with distance as a parameter. This paper presents the hardware implementation of ZigBee based WSN system for power monitoring with detailed circuits interfacing and illustrative case studies. It also investigates the impact of changing the construction material on coverage boundaries of the sensing nodes. The rest of the paper is organized as follows: first a technical background about ZigBee and its relation to IEEE STD 802.15.4 is given. Then, the components used in the system design are briefly described. Next, the proposed system model, hardware implementation and experimental results are discussed. Finally some conclusions drawn throughout the work are given.

Zigbee and Its Relation To IEEE STD 802.15.4

ZigBee is a protocol that uses the IEEE STD 802.15.4 as a baseline and adds additional routing and networking functionality. It was developed by the ZigBee Alliance [11]. It defines a set of communication protocols for low-data-rate short-range wireless networking. ZigBee-based wireless devices operate at 868 MHz, 915 MHz, and 2.4 GHz frequency bands with a maximum data rate of 250Kbps [12]. The Alliance has worked hard to provide a technology that takes best advantage of the robust IEEE STD 802.15.4 short-range wireless protocol. This is done by adding flexible mesh networking, strong security tools, well-defined application profiles, and a complete interoperability, compliance and certification program to ensure that the end products destined for residential, commercial and industrial spaces work well and network information smoothly. Figure1 shows the relative organization of the IEEE radio with respect to the ZigBee functionality [4].



Figure(1): ZigBee Architecture

The main function that was added to the core of 802.15.4 radio in the development of ZigBee protocol is mesh networking. Mesh networking is used in applications where data is to be sent between two points beyond the scope of coverage of the radio devices located in those points. This is solved in mesh networking by adding some radios in-between that are capable of forwarding any message to and from the intended radios [11]. The ZigBee protocol is also designed so that if a number of different radios were arranged as in Figure 2, then a network is automatically formed by the radios without user interference. The ZigBee protocol within the radios takes care of retries, acknowledgements and data message routing. ZigBee also has the capability of self-healing the network. If any of the radios is removed for some reason, a new path would be used to route messages from source to destination [5]. In ZigBee specification; the devices can either be used as end devices, routers (which can also work as end devices) or coordinators. As a result of using 802.15.4 standard to define the PHY and MAC layers; the frequency, signal bandwidth and modulation techniques are identical [11].

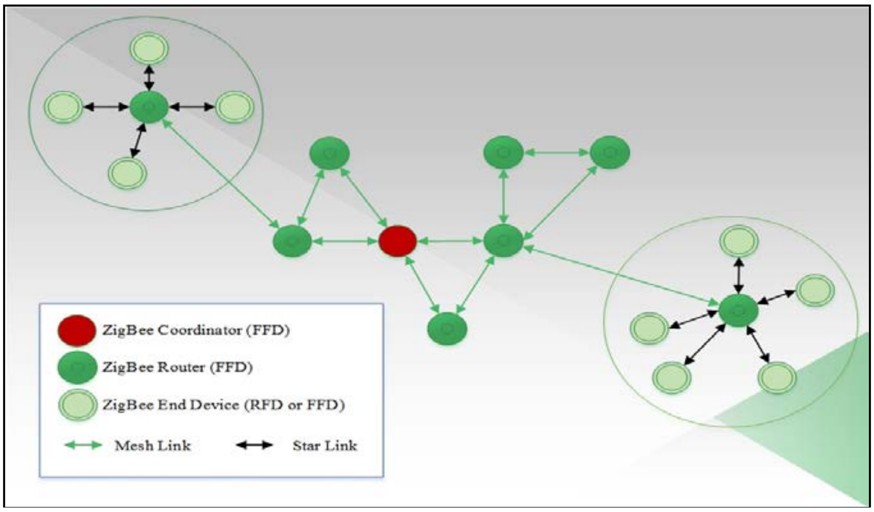


Figure (2): ZigBee Mesh Network and Device Types

Because ZigBee was designed for low power applications, it fits well into embedded systems and those markets where reliability and versatility are important but a high bandwidth is not. Table 1 provides a comparison of features with several other popular wireless technologies and their different applications [5, 11]. The low data rate of the ZigBee devices provides better sensitivity and range, but of course offers fewer throughputs. The primary advantage of ZigBee lies in its ability to offer low power and extended battery life [11, 12].

Table (1): Comparison of several wireless standards

	ZigBee and 802.15.4	GSM/GPRS CDMA	802.11	Bluetooth
Focus Application	Monitoring and Control	Wide Area Voice and Data	High-Speed Internet	Device Connectivity
Battery Life	Years	1 Week	1 Week	1 Week
Bandwidth	250 Kbps	Up to 2 Mbps	Up to 54 Mbps	720 Kbps
Typical Range	100+ Meters	Several Kilometers	50-100 Meters	10-100 Meters
Advantages	Low Power, Cost	Existing Infrastructure	Speed, Ubiquity	Convenience

Description of Proposed Wireless Sensing System Elements

There are four main components used to implement the system, these are:

XBee Series 2 (XBee ZB & XBee-PRO ZB) Transceivers: XBee and XBee-PRO ZB ZigBee modules provide cost-effective wireless connectivity to devices in ZigBee mesh networks. Utilizing the ZigBee PRO Feature Set, these modules are interoperable with other ZigBee devices, including devices from other vendors [13]. The main difference between these two modules lies in that XBee-PRO ZB provides wider range: 300 ft. (90 m) indoor & 2 miles (3200 m)/Int'l 5000 ft. (1500 m) outdoor compared to 133 ft. (40 m) indoor & 400 ft. (120 m) outdoor provided by the XBee ZB module. The configuration of these modules is done using a software called X-CTU [13, 14].

- **Microcontroller:** Arduino (UNO R3 and MEGA 2650) is used as the micro-controlling unit in the designed system. Arduino is a tool for making computers that can sense and control more of the physical world than normal computer. It is an open-source physical computing platform based on a simple microcontroller board, and a development environment for writing software for the board. Arduino can be used to develop interactive objects, taking inputs from a variety of switches or sensors, and controlling a variety of lights, motors, and other physical outputs [15, 16]. The main advantages that make Arduino preferred over other known techniques like FPGA are: its low cost, cross-platform (supports different operating systems), simple & clear programming environment, open source and extensible software and hardware [17]. Note that Arduino is based on Atmel's ATMEGA8 and ATMEGA168 micro-controllers. The main difference between Arduino UNO and Mega is that Arduino Mega provides more I/O lines than UNO.

- **Cellular Shield:** This shield allows us to control and monitor the designed system using SMS, GSM/GPRS and TCP/IP. SparkFun Cellular Shield-SM5100B is used which includes all the parts needed for interfacing an SM5100B cellular module with Arduino.

- **Current Sensor:** The main element used to measure current and power. There are two types of current sensors widely used: Hall Effect Current Sensor (HES) and Non-Invasive Current Sensor (NICS). NICS (also known as a split core Current transformer CTs). This sensor is clamped around the source line of an electrical load to tell us how much current is passing through it. It does this by acting as an inductor and responding to the magnetic field around a current-carrying conductor. By reading the amount of current being produced by the coil, we can calculate how much current is passing through the conductor [18].

The Proposed System Model

The proposed wireless sensing system is shown in Figure 3. It consists of several nodes that can be classified according to their function into three types, these are:

Base Station or “Monitoring Node”: there is only one of such node in the system which monitors and controls the system. It consist of the following components:

1. Micro-controlling Unit (MCU).
2. ZigBee Module working as a coordinator in AT mode.
3. Liquid Crystal Display (LCD).
4. GSM/GPRS Module.
5. DC Power Supply.
6. System Controlling Unit.
7. See Figure 4A.

End Points (EP) or Current Sensing Nodes: these nodes senses the current and sends its readings to the monitoring node. Each one of these nodes consists of the following components:

1. MCU.
2. ZigBee Module.

3.Current Transformer (CT).
4.DC Power Supply.
See Figure 4B

Routing Nodes:

These nodes can be used to extend the system range i.e. work as a router and can work as a sensing node too. These nodes consist of ZigBee working in Routing AT Mode (See Figure 3).

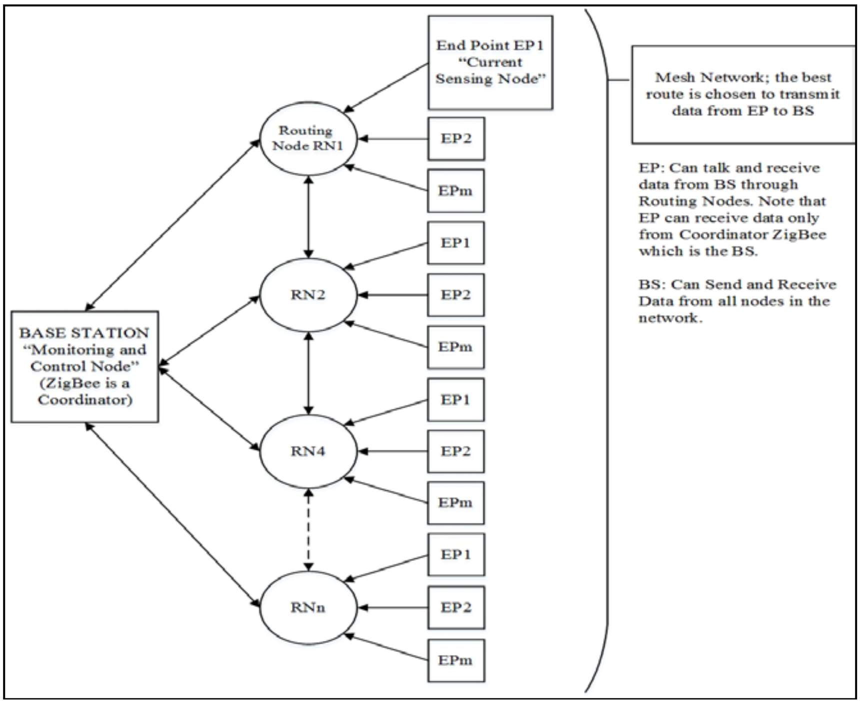


Figure (3): The proposed system model

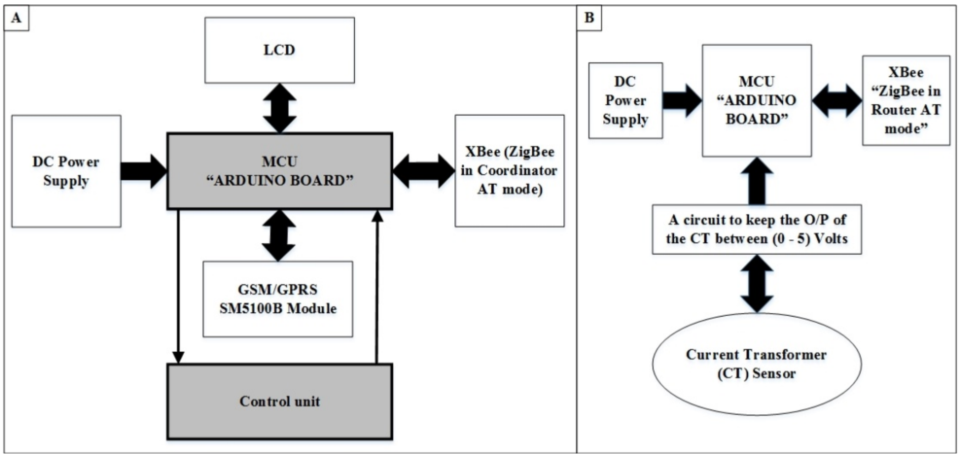


Figure (4): (A) Base Station Block diagram
(B) End Points Block Diagram

The Base Station functions as shown in Figure 5. When power is applied to BS it enters waiting state, i.e. the GSM module and MCU is waiting for a user request to give a response. So the action of BS is divided into two types: the first when SMS is received and the second when a user request is made directly from the control unit of the BS. Now if an SMS is received the MCU starts processing the SMS received by the GSM module to take an action. If the SMS received contains an existing command, then the MCU proceeds to the next step otherwise it goes back to the waiting state. As for next step the MCU sends a request signal via coordinator ZigBee in the BS to the intended node and waits for feedback from that node. As soon as the message arrives to BS it creates an SMS using GSM module that contains the requested data and sends it then goes back to waiting state.

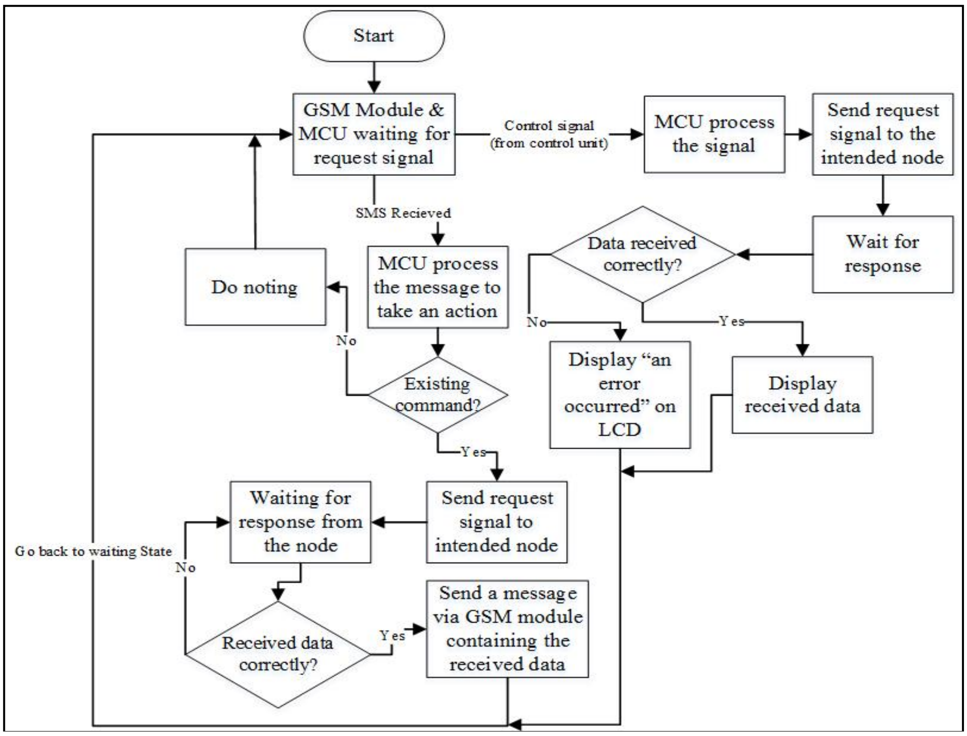


Figure (5): Flow chart of Base Station control operation.

Concerning the second type, if a control signal is made by user then it is also processed, then a request signal is sent to the intended node through coordinator node then the MCU waits for feedback. If any error occurs then a message is displayed on the BS LCD saying "an error occurred" otherwise the received message will be displayed on the LCD and then the BS goes back to waiting state. The function of end nodes is shown in Figure 6. As the node is powered up it enters waiting state.

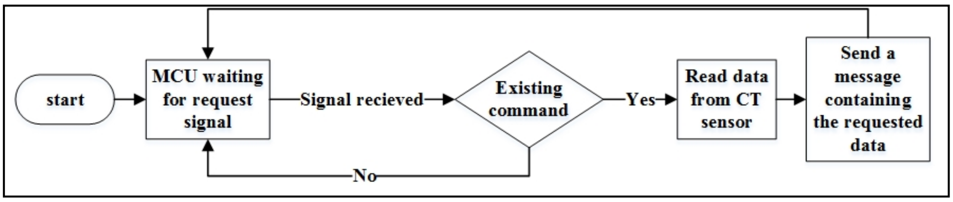


Figure (6): End Nodes "current sensing nodes" function

When a request signal is received via ZigBee module then the MCU process this signal and check if the command exist, i.e. since the signal received is arrived on all ENs of the system, then each node has a unique code that differs from other nodes and if the code is correct then the EN take an action. By reading data from CT and converting it to its corresponding current and power values these data are sent via ZigBee module also to the BS to be displayed or sent as SMS via GSM module. Then the EN goes back to the waiting state. It is worth noted that routing nodes can function as an end node and mostly used to give more paths for signals i.e. to extend the coverage of the system.

Hardware Implementation of The Proposed System

The system implementation procedure can be summarized into five steps as follows:

1. Establishing connection between XBee Modules.
2. Interfacing XBee Modules with Arduino Board.
3. Interfacing Current Transformer CT sensor with Arduino Board.
4. Interfacing LCD with Arduino.
5. Interfacing GSM/GPRS SM5100B Module with Arduino.

Figure 7 shows photos that illustrate configuration of the hardware implementation of WSN where a base station and only one current sensing node is connected for the sake of simplicity. The network can be extended by adding more nodes depending on the size of monitoring system.

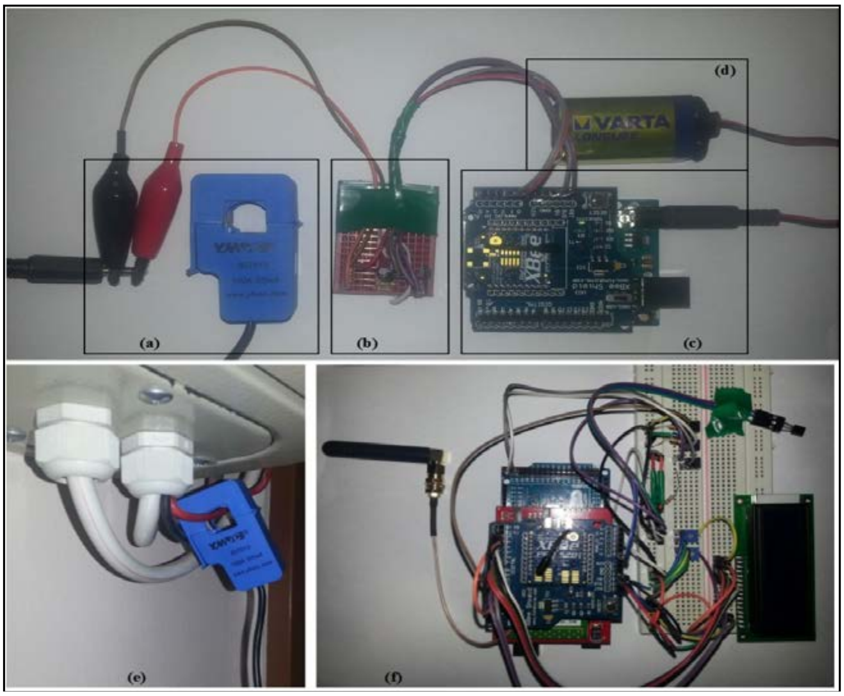


Figure (7): Coordinator (Base Station) node and one Current Sensing Node (a) Current transformer (CT) sensor. (b) Burden resistor plus voltage divider circuit. (c) MCU plus ZigBee. (d) 9V Battery. (e) CT clipped on load line. (f) Base station (BS)

Figure 7(a) shows the current transformer (CT) sensor which is clipped on the load line as shown in Figure 7(e). This sensor produces an output of small current applied to a circuit shown in Figure 7(b). This circuit consists of a burden resistor and voltage divider circuit to keep the input voltage to the Arduino between 0 and 5 volts. This circuit is necessary, since the Arduino board can sense voltages between 0 to 5 volts and any higher voltage will damage the board. The MCU of the EP, which is the Arduino board is shown in figure 7(c) which is powered by 9V DC battery shown in Figure 7(d). Finally, the implemented base station (BS) is shown in figure 7(f).

Figure 8(a) shows an example monitoring interaction using SMS requests. As shown in figure 8(a) a request message “#a1” is an asking request for sending the current readings of node1 which is followed by the response from node1. The request message “#a2” is an asking request for sending temperature reading of node1 which is followed by the response of node1 and so on for other nodes. Note that temperature sensing is done just to investigate the possibility to use other types of sensors in the WSN system. The successful test indicates that the proposed system can be easily developed to achieve multiple tasks of building management. Figure 8(b) shows the system monitoring activity using the serial monitoring software X-CTU terminal.

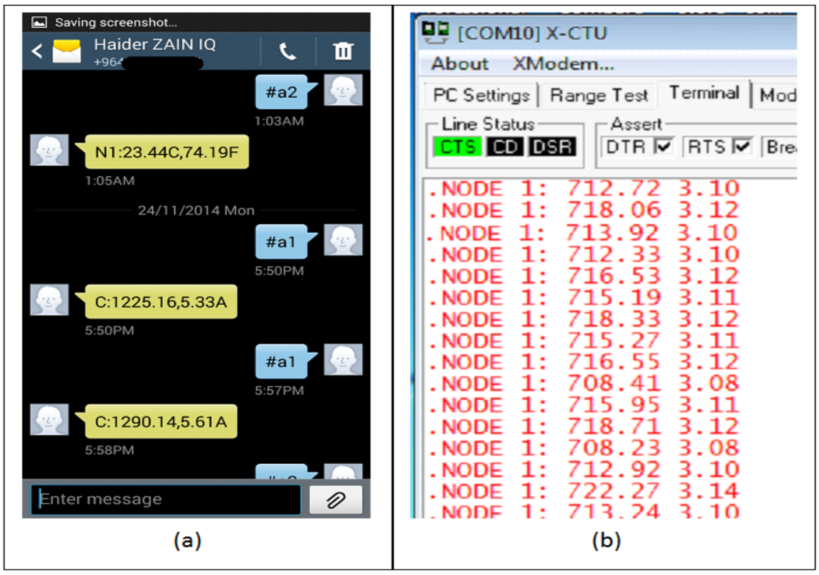


Figure (8): a) System monitoring using SMS. b) System monitoring using X-CTU terminal window

Experimental Measurements

The overall system performance is analyzed in terms of the bounds of coverage in different construction materials. One fixed node that works as a coordinator connected to PC is used to monitor the sent and received data of mobile node that works as a router or end point. The software tool X-CTU has been used to read the distance measurements using the Received Signal Strength Indicator (RSSI) available in this tool. Figure 9 shows the (GUI) of this software with some brief description of its function. Many measurements are made and in each of them the sent packet size was 32 bytes.

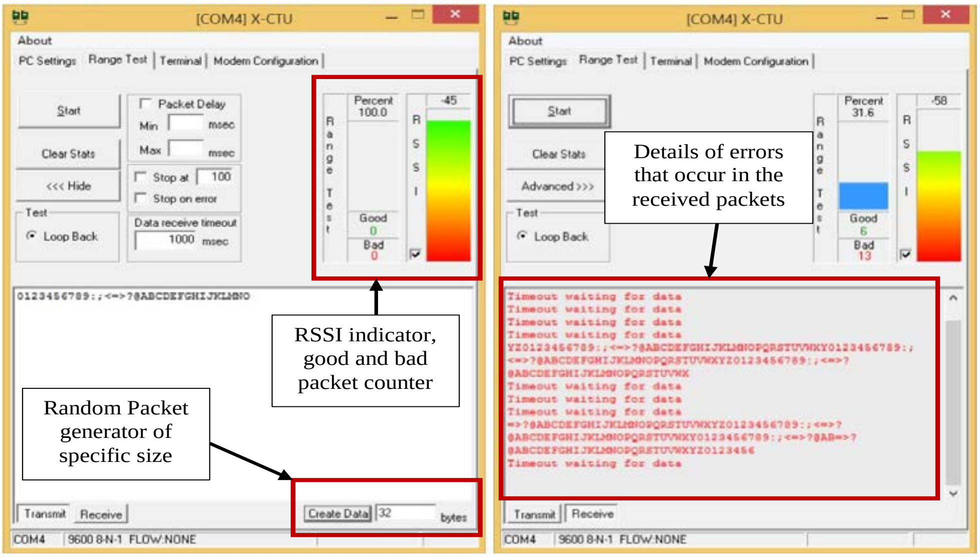


Figure (9): X-CTU graphical user interface GUI

Every 27 sent and received packets, the RSSI value is monitored carefully and the average of these readings is recorded. This kind of test is called *loop back method* since the coordinator sends the data and the routing node resends every received packet back to the coordinator node. If the packet was received as it was sent this would be indicated as good packet. But if any error occurs during sending/receiving of the packet, then it would be indicated as bad or lost packet. The Measurements are carried out in a room of 5m wide, 6m in length and 3m in height. The walls of the room were made of concrete. The distance between the coordinator and end point is carefully measured. It is important to mention that no obstacles are placed in the room i.e. the effect of fading was neglected. Note that the measurements are made in a real or normal environment; not in a noise-free laboratory to simulate the real life operation.

The measurements are made at distances starting from 0.5m to 4m and the measurements were carried at different environments. First the condition of Line Of Sight (LOS) between the coordinator and router (end point) is considered. Then the router is inserted in boxes made of different materials such as stainless steel, wood, cardboard, corkboard, concrete and bricks. RigExpert IT-24 wireless spectrum analyzer whose photo is shown in Figure 10 is used to monitor the signal of ZigBee modules. It is important to note that the coordinator was powered by the PC but the routing node was powered by a 9V DC battery which was replaced in each test to ensure that a correct result is achieved.

Figure (10):
RigExpert IT-24

Experimental Results

Figure 11 shows the RSSI value in -dBm at different distances for some construction materials that are used in buildings and LOS case which is considered as the ideal case. We note that at distance of 0.5m, all cases have the same RSSI value of -40dBm except for the case of corkboard -45dBm and metal box -55dBm which is the worst case. At 1m distance, we note that LOS case and bricks case still give the best performance at signal strength of -40dBm. As for wood box, concrete bricks, and bricks the RSSI value is almost the same but the corkboard and metal cases still have the worst RSSI values. Going further at 4m, we note that the RSSI value is decreasing for all cases. However, it is noticeable that metals and corkboard have very high (or worst) effect in decreasing the performance of ZigBee modules and thus decreasing the performance of overall system. The lowest RSSI value that the system can still operate-in without any packet loss is -95dBm and the highest value is -40dBm.

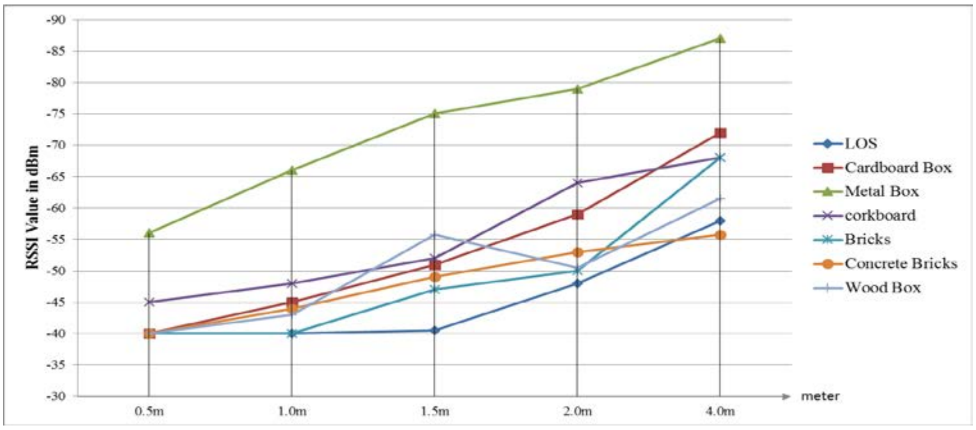


Figure (11): RSSI value VS. Distance in meter for some cases

Using RigExpert IT-24, we noticed that the operating channel is automatically chosen by the ZigBee modules i.e. the module usually scans all possible channels (16 channel for 2.4GHz ZigBee module) that it can operate in and places the connection in the best channel but this choice is somewhat not that really good. In Figure 12a, we see that ZigBee is operating in 2425MHz channel which is occupied by Wi-Fi signals. To ensure that there would be no interference with Wi-Fi signals (even though the possibility of this scenario is low since ZigBee uses DSSS) and to improve performance we switched (manually) the operating channel of ZigBee modules to 2480MHz which is free to use and usually forbidden for the use by Wi-Fi signals, see Figure 12b.

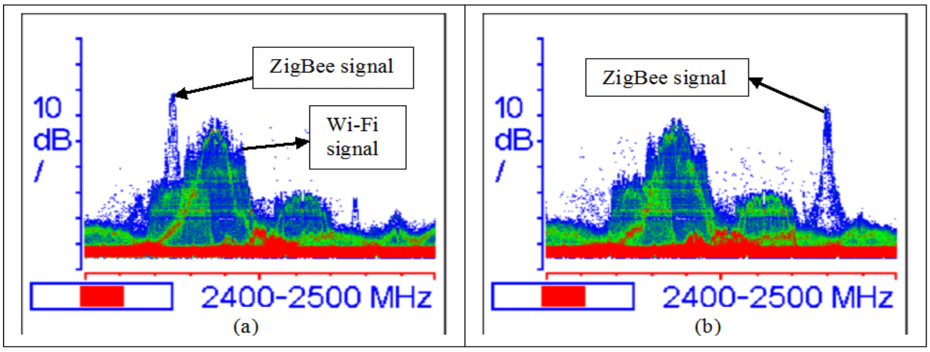


Figure (12): (a) ZigBee operating at a busy channel.
(b) ZigBee signal after shifting to a free channel.

Figure 13 shows the difference in signal strength at 2425MHz and 2480MHz for LOS case and Metal case. We notice that there is a slight improvement in the signal strength and as a result the performance will be improved as well. Also, we note that the RSSI value is the same at 0.5m and 1m but the difference is noticeable at distances greater than 1m.

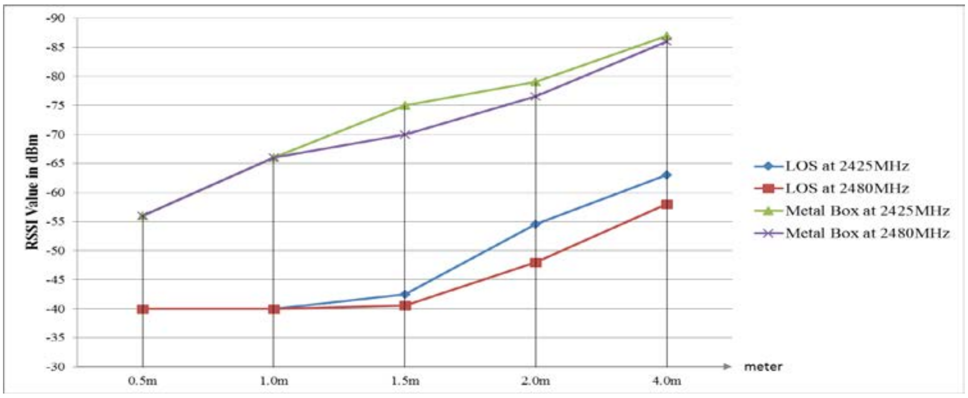


Figure (13): Comparison of signal strength at 2425 and 2480MHz for LOS and Metal cases

Conclusions:

The use of ZigBee in electric power monitoring provides the WSN more flexibility and reduced power consumption. With the aid of the software tool X-CTU, the RSSI of ZigBee transceiver can be virtualized which provide a numerical measure can be used to evaluate the impact of propagation media. The practical test measurements of signal strength can be done efficiently using RigExpert IT-24 wireless spectrum analyzer. Through experiments on a group of materials may be used in the construction of buildings, it is recognized that the effect of these materials is varying the performance of ZigBee data transfer. Using these results we can locate appropriate installation locations for increased range and performance of the system. In general as it is seen that metals and cork used in roofing and walls have a dramatic effect on reducing the performance of these devices. Finally, the manual selection of the operating frequency using the signal strength measuring device (RigExpert IT-24) according to the spectrum density may provide better results than the automatic selection. This is because ZigBee modules is programmed to switch operating frequency automatically when other ZigBee signal is detected only.

References

[1] S. Lanzisera and K. Pister, "Theoretical and Practical Limits to Sensitivity in IEEE 802.15.4 Receivers," in 14th IEEE International Conference on Electronics, Circuits and Systems, Marrakech, 2007.

[2] B. M. Khammas, "Design Neural Wireless Sensor Network Using FPGA," Eng. & Tech. Journal, vol. 30, no. 9, pp. 1641-1661, 2012.

[3] F. L. Lewis, "Wireless Sensor Networks," in Smart Environments: Technologies, Protocols, and Applications, New York, John Wiley & Sons, Inc., Hoboken, New Jersey, 2004, pp. 11-46.

[4] J. Zheng and M. Lee, "A Comprehensive Performance Study of IEEE 802.15.4," Sensor Network Operations, IEEE Press, Wiley Interscience, pp. 218-237, 2006.

[5] A. R. Raut and D. L. G. Malik, "ZigBee: The Emerging Technology in Building," International Journal on Computer Science and Engineering (IJCSE), vol. 3, no. 4, pp. 1479-1484, 2011.

[6] S. Gill, N. Suryadevara and S. Mukhoopadhyay, "Smart Power Monitoring System Using Wireless Sensor Networks," in Sixth International Confrence on Sensing Technology (ICST), Kolkata, 2012.

[7] N. K. Suryadevara, S. C. Mukhopadhyay, S. D. T. Kelly and S. P. S. Gill, "WSN-Based Smart Sensors and Actuator for Power Management in Intelligent Buildings," IEEE/ASME Transactions on mechatronics, vol. 20, no. 2, pp. 1-8, 2014.

[8] L.-C. Huang, H.-C. Chang, C.-C. Chen and C.-C. Kuo, "A ZigBee-based monitoring and protection system for building electrical safety," Energy and Buildings, vol. 43, no. 6, pp. 1418-1426, 2011.

[9] H. K. Choudhari, A. A. Waoo, P. S. Patheja and S. Sharma, "Performance Evaluation of ZigBee Using Multiple Input Single Output (MISO) Architecture in the Secured Environment," International Jornal of Innovative Technology and Exploring Engineering (IJITEE), vol. 2, no. 6, pp. 36-44, 2013.

[10] Y. V. Varshney and A. K. Sharma, "Comparitive Analysis of OQPSK and MSK Based Zigbee Tranceiver Using MATLAB," International Journal of Advanced Research in Computer Science and Software Engineering, vol. 3, no. 6, pp. 948-956, 2013.

[11] White Paper, "Demystifying 802.15.4 and ZigBee," [Online]. Available: http://www.digi.com.

[12] S. Farahani, ZigBee Wireless Networks and Tranceivers, Elsevier, 2008.

[13] Digi International Inc., "XBee® & XBee-PRO® ZB, ZigBee® Embedded RF

Module Family for OEMs".
[14] Digi International Inc., "XBee®/XBee-PRO® ZB RF Modules," 2014.
[15] Arduino SA, "Arduino Introduction," Arduino, [Online]. Available: http://arduino.cc/en/guide/introduction.
[16] E. K. A, F. Faiz, D. Varghese, D. Ravindran and E. Jose, "Development of Automatic Light Control System for Energy Efficient Buildings," International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, vol. 3, no. 2, pp. 29-36, 2014.
[17] H. N. Abdullah and H. A. Hadi, "Design and Implementation of a FPGA Based Software Defined Radio Using Simulink HDL Coder," Eng. & Tech. Journal, vol. 28, no. 23, pp. 6750-6767, 2010.
[18] "Non-Invasive Current Sensor - 30A," [Online]. Available: http://www.active-robots.com/non-invasive-current-sensor-30a.

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