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Performance Analysis of XBee ZB Module Based Wireless Sensor Networks

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Abstract— In this paper, performance analysis of ZigBee networks based on XBee ZB modules have been evaluated in terms of following performance metrics: received signal strength (RSSI), network throughput, packet delay, mesh routing recovery time and energy consumption in an indoor environment. Two main groups of network scenarios have been evaluated: (i) direct transmissions between the coordinator and the remote nodes, and (ii) transmissions with routers which relay the packet between the coordinator and the remote nodes. The wireless sensor node hardware designed for this experimentation consists of ZigBee (XBee S2 with 2mW wire antenna) wireless communication module from Digi International. X-CTU software is utilized for configuring and testing the ZigBee module of each sensor node. After configuration, the entire network is simulated in real time using Docklight V2.0 software. The results of this study are useful for building Wireless Home Area Network (WHAN) using the ZigBee where there are reflections due to indoor objects and also for scenarios where communication between nodes require multi-hop transmissions.

Index Terms— Energy consumption, mesh routing recovery time, multi-hop, network throughput, wireless sensor network, XBee, ZigBee

1 Introduction

A wireless sensor network is made up of self-configuring tiny sensor nodes that communicate wirelessly among themselves once deployed in an ad-hoc fashion. Presently, wireless sensor networks are being deployed at a swift pace. Some of the current applications are environment monitoring, smart metering, logistics, industrial control, smart agriculture and to name a few. In the near future, the smart cities and homes will also be incorporated by wireless sensor networks with accessibility to them via the internet. Such systems will transform the way we work and live.

The two main wireless standards mostly used for wireless sensor networks are ZigBee and IEEE 802.15.4 [1]. Due to low power consumption, simple network deployment, low installation costs and reliable data transmissions, these two standards are mainly preferred over Wi-Fi and Bluetooth. For this study, we will only analyze the performance analysis of a wireless sensor network using the ZigBee standard. ZigBee is built on top of the IEEE 802.15.4 standard which defines the Medium Access Control (MAC) and physical layers, operating in an unlicensed band of 2.4 GHz with a data transfer rate of 250 kbps. In terms of networking capability, ZigBee protocol supports three types of communication topologies such as point-to-point, point-to-multipoint and mesh topology. ZigBee enabled devices operate with low duty cycle, hence providing longer battery life which makes it the most widely used devices for a wireless sensor network. ZigBee protocol also features multi-hop communication capability, therefore providing a vast range of communication and a wide coverage area [2].

While ZigBee is ideal for smart applications as stated in [3-5], it also has few drawbacks. For instance, ZigBee supports low data rate, and this may make it inadequate for an industrial application which would have a higher requirement in terms of network bandwidth, reliability, scalability and latency than a domotic application [6]. A considerable number of researchers have addressed the issue of performance analysis of IEEE 802.15.4 and ZigBee networks [7-9] where most of the results have been acquired using theoretical analyses or simulators. Zheng and Lee [10] carried out a performance study of IEEE 802.15.4 by developing an NS2 simulator for conducting their experiments. Their study focused on features including beacon and non-beacon enabled mode. Similar work was also presented in [11] where performance of the IEEE 802.15.4 standard was obtained using the OPNET simulator.

Authors in [12] conducted experiments with XBee Series 1 modules where they have concentrated on indoor testing of the ZigBee radio properties such as range and timing. Through their study, the authors have presented their first ZigBee experience. A similar study was also done by researchers in [13] where XBee radio module was used for the evaluation of Body Sensor Networks (BSN). In [13], the authors presented a test bed experiments for evaluation of packet loss and packet delay using 2.4 GHz radio frequency band and stated that in scenarios with high traffic load, the interference causes a high degradation of the BSN performance.

Therefore, it is proposed that for this research all the results shall be obtained through experiments with real implementations of ZigBee networks. This would contribute to a better understanding about the capabilities and performance of ZigBee technology for real life wireless sensor deployments.

To address the above issues, this paper will focus on the performance of real time XBee ZB module based wireless sensor networks in indoor scenarios. Similarly, to the works presented in [14, 15], we have utilized common performance indicators such as received signal strength indication (RSSI), network throughput, packet delay, mesh routing recovery time and energy consumption. Contrary to [14-16], we have used the XBee ZB S2 modules which are ZigBee-complaint wireless sensor networking devices developed by Digi International, Inc. Each XBee ZB module has the capability to directly gather sensor data and transmit it without the use of an external microcontroller known as XBee direct. This offers many advantages. By excluding the external microcontroller, the overall size of the project can be reduced. This is essential when creating sensors that need to be inconspicuous. By using XBee alone, it can minimize weight which is an important factor for systems such as Body Sensor Networks or wearables. Omitting an external microcontroller also reduces power consumption which is a critical advantage for wireless systems that run on batteries and saves money. Furthermore, to reduce energy consumption and to increase the network lifetime, active and cyclic sleep modes for a battery-powered sensor node have been analyzed. In addition to, the impact of the number of Routers and the packet length on the system performance has also been investigated.

The rest of the paper is structured as follows. Section 2 describes the experimental setup and the different wireless network topologies being studied. Section 3 presents the experimental results obtained in terms of key performance metrics. Finally, Section 4 concludes the paper.

2 EXPERIMENTAL SETUP

For our experiments, we used XBee Series 2, 2mW modules from Digi International, model XB24-ZB. Each module is equipped with a wire antenna. We build single-hop and multi-hop wireless sensor networks where each node consists of XBee module. For programming each node, we used X-CTU, free software provided by Digi International. With this software, the user is able to update the parameters, upgrade the firmware and perform communication testing easily. Communication with XBee modules is done via XBee Interface board connected using a USB cable to a personal computer (PC) as shown in Fig. 1. All the nodes were configured to use the same Personal Area Network (PAN) ID with a baud rate of 115200bps. Under experimental results, we will also discuss why this particular baud rate was chosen for this experiment. XBee offers transmission range of 40 m in indoor scenarios and 140 m in outdoor. Docklight V2.0 software is used to perform time measurements and to send data packets by the Coordinator module to the other nodes.

Fig. 1. XBee connected to PC via Xbee interface board.

When conducting experiments, we used packet size from 10 bytes up to 80 bytes. Each experimental trial is repeated ten times and the average is taken to eliminate any measurement errors due to fading and multipath phenomena. All the experimental tests were conducted in an indoor environment; distance tests were carried out in a 40 m long hallway while other experiments were carried out in a 5m x 8m office space. The network topologies being studied are shown in Fig. 2. For each test, the number of nodes used to form the network and their roles are discussed. The experiments are conducted using industrial, scientific and medical (ISM) 2.4 GHz band, since XBee purchased for this experiment only supports this frequency band.

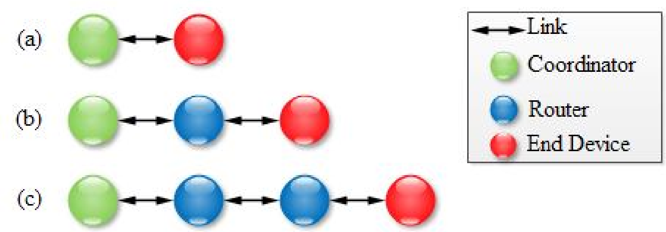

Fig. 2. Network Topologies being studied. Three possible scenarios are considered: (a) direct transmission between the Coordinator and the End Device, (b) transmission through one Router, and (c) using two Routers.

3 EXPERIMENTAL MEASUREMENTS AND RESULTS

3.1 RSSI Measurement

Received signal strength indicator (RSSI) is the signal strength level of a wireless device measured in –dBm of the last received packet [17]. The main idea behind the RSS system is that the detected signal strength value decays with the distance travelled. In free space, the RSS degrades with the square of the distance from the sender [18]. Using the Friis transmission equation, the ratio of the received power P_r to the transmission power P_t can be expressed as:

$$P_r = P_t \times G_t \times G_r \left(\frac{\lambda}{4\pi\, d} \right)^2 \quad (1)$$

where, G_t, G_r are gain of transmitter and gain of receiver respectively. λ is a wavelength, and d is the distance between the sender and receiver. It can be seen that the larger the wavelength of the propagating wave the less susceptible it is to path loss. The received signal strength is converted to RSSI which can be defined as the ratio of the received power P_r to the reference power P_{Ref}.

$$RSSI = 10 \log \frac{P_r}{P_{Ref}} \quad (2)$$

In order to collect experimental measurements, the network topology in Fig. 2 (a) is considered. Using X-CTU software one of the XBee modules is configured as Coordinator whiles the other as an End Device. The End Device after pairing with the Coordinator, starts transmitting. Once the Coordinator has received the data packets successfully, it sends back acknowledgment (ACK). The RSSI value is measured after sending 50 packets of 32 bytes each and then averaged to generate RSSI. The distance between the Coordinator and the End Device was varied to measure the relationship between RSSI values and the distances. Fig. 3 shows the measured RSSI as a function of the distance between two nodes. Three different values for transmit power P_t are studied: (i) 2 dBm, (ii) 0 dBm, and (iii) -2 dBm.

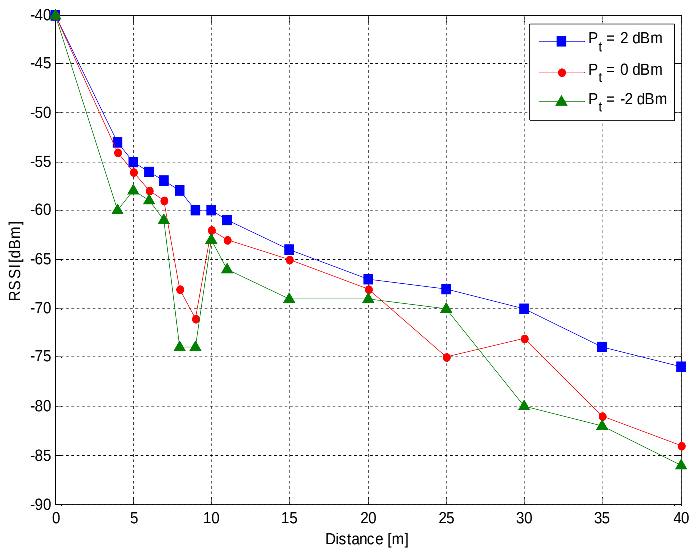

Fig. 3. Measured RSSI values versus distance at different values of transmit power.

As expected, measured RSSI values decreased linearly as the distance was increased. The fluctuations on the graph at distance between 5-10m with P_t of 0dB to -2dB can be correlated with the presence of reflection and multipath phenomena due to wall and interference from Wi-Fi Routers located between these points. Apparently, increasing transmit power lead to a better performance.

3.2 Throughput Measurement

Throughput is expressed as how much amount of data is sent or received during a defined period of time. Throughput of the system depends on the speed and packet size. It is calculated as the packet size divided by the total transmission time as indicated in the equation below:

$$TP = \frac{8 \times number\ of\ bytes}{total\ transmission\ time\ (\text{sec})} \qquad (3)$$

To measure total transmission time, we programmed Docklight V2.0 software to send packets consisting of 10 bytes, then increments of 10 up to 80 bytes. The packet is sent every 5 seconds to a remote XBee End Device. A hardware loop-back is created that connects the DOUT (TX) pin to DIN (RX) pin on the XBee module to echo back the entire packet sent by the host PC. This hardware loop-back also removed the additional latency which would have been contributed by the computer or microcontroller attached to the End Device. Total transmission time is described as the elapsed time starting immediately before sending the packet and ending when the entire packet has been received.

3.2.1 Throughput Measurement in Point-to-Point Link at different baud rates

The aim of this experiment is to measure the throughput of the XBee module as a function of the baud rate and the packet length to gain a sense as how does the baud rate affect the latency of the modules communicating over ZigBee protocol. For this experiment, the topology shown in Fig. 2 (a) is considered. XBee module configured as an End Device sends packets to Coordinator and calculates the total transmission time. Several measurements are carried out, in comparison to different values of packet length and baud rates. According to ZigBee fragmentation, each unicast may support up to 84 bytes of RF payload[17]. Therefore, to avoid reception overcharge with the ZigBee communication protocol, we used a lower value of packet length up to 80 bytes. The throughput in this case is shown as a function of packet size and the baud rate as illustrated in Fig. 4. The throughput is calculated over 50 received packets as the ratio between the number of bits received correctly and the total transmission time, in accordance with the equation 3. This experimental trial is repeated ten times. In addition to, this experiment was conducted to have a performance baseline for ZigBee networks using XBee S2 modules. It was observed that the network throughput increases as the baud rate increases. According to ZigBee standard, it guarantees a transmission data rate of 250 kbps, but the results obtained show that an experimental network performance is still far from this performance level. Only, a throughput of 5.4 kbps at a baud rate of 115200bps was achieved using maximum offered payload.

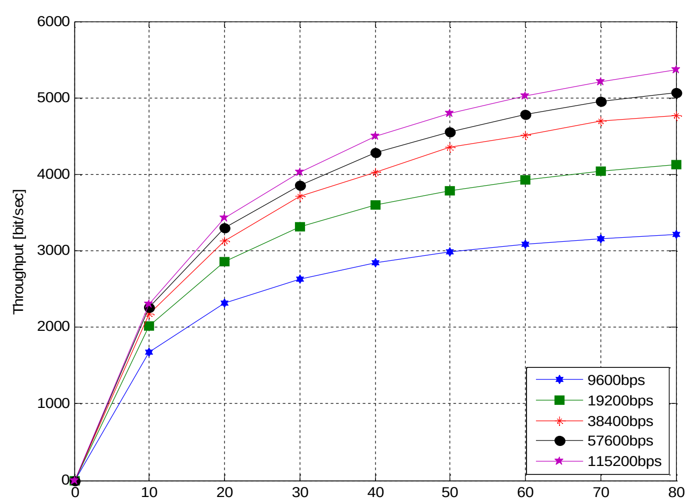

Fig.4. Throughput measurement results for ZigBee network at different baud rates and packet length.

3.2.2 Throughput Measurement in Multi-hop Network

The coverage area of wireless communication is restricted by the capability of the wireless device used [19]. Therefore, to cover a wider area, multi-hop configuration is utilized using Routers. We measured the multi-hop performance of the ZigBee network to compare the results with point-to-point measurements. Network topology in Fig. 2 (a) and (b) is considered where the packets transmitted from the End Device to the Coordinator are relayed by one Router and then using two Routers respectively. We repeated the previous experiments as stated in section 3.2.1 with two hops and three hops network. Data throughput measurements were made setting the serial interface rate to 115200bps and measuring time to send and receive the entire packet. During the tests, no route discoveries or failures occurred. The results in Fig. 5 show that the presence of the Routers has a significant effect on the data rate and the throughput of the entire network. In case of direct transmission (as shown in Fig. 2 (a)), the End Device sends data packets directly to the Coordinator, therefore the transmission channel is always free. In the network configuration as illustrated in Fig. 2 (b), when the Router retransmits its packets to Coordinator, the medium is occupied; therefore, the End Device must wait before transmitting the new data packet. In the scenario of two hops, the throughput is decreased by half. Generally, it was observed that the throughput decreases as ($1 / n_{hops}$), where n_{hops} is the number of hops travelled by a packet to reach its destination.

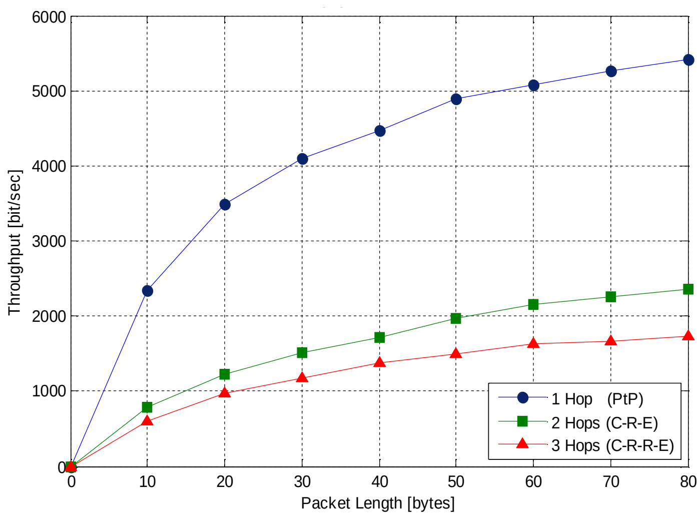

Fig.5. Throughput measurement results for ZigBee network for multi-hop configuration.

3.3 Packet Delay

Another significant indicator of ZigBee network performance is the packet delay between two consecutive packets accurately received by the Coordinator. The packet delays for this experiment is defined as the duration between sending a packet and until the entire packet has been received by the source also known as round-trip time (RTT). The distance between Nodes is 3m. Fig. 6 shows the results of direct transmission from an End Device to the Coordinator (Blue line) and indirect transmission through Routers. For single hop transmission, the average delay is around 0.11 sec for the maximum payload offered, while 0.27 sec for two hops and 0.37 sec for 3 hops respectively. Hence, the packet delay increases significantly with the number of hops due to an extra processing delay at the Routers and retransmission delay due to additional hop.

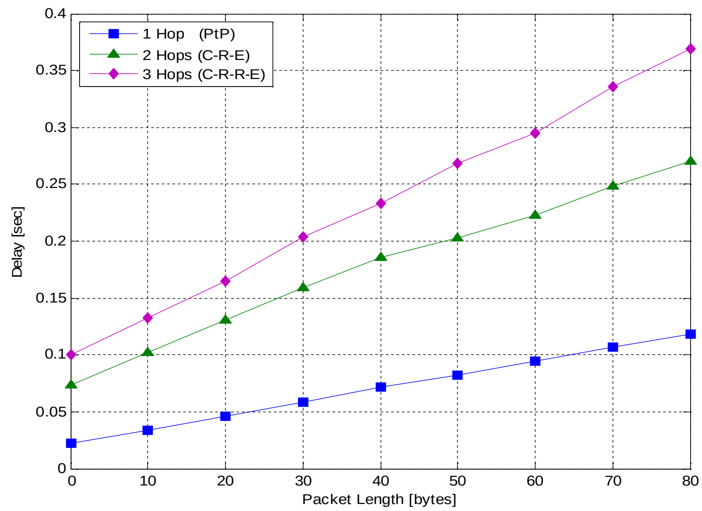

Fig.6. Number of Hops versus Packet Delay

3.4 Mesh Routing Recovery Time

Building a ZigBee mesh network is done automatically and seamlessly by the ZigBee devices. The Coordinator starts a ZigBee network, and other devices then join the network by sending association requests. Since, no additional supervision is required to create a network; ZigBee networks are considered self-forming networks. After forming the mesh network, to relay the message from one device to another, the most optimized path is selected. However, if one of the Routers becomes damaged or otherwise unable to communicate due to exhaustion of its battery, the network can select an alternative route. Hence, one of the most important characteristics of ZigBee mesh networking has been its self-healing capacity through mesh routing. In order to test the time cost of mesh routing, we measured the elapsed time between the elimination of one path and the search and formation of another. This experiment uses the network topology as illustrated in Fig. 7. To perform the test, we first start sending messages from Coordinator A to End Device D. Then we gradually moved the End Node further away from Coordinator until the link was disconnected. Next, we add the Routers to relay messages to an End Device through Router B. After some time, we turn off Router B so that the End Device needs to find another alternative route to deliver messages to the Coordinator. The route must be found through Router C, and we measure the elapsed time between the last message sent through Router B and the first message sent through Router C. This we have defined as

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mesh routing recovery time.

After measuring the time, we noticed a maximum delay of 130 ms and a minimum delay of 90ms, to deliver the message through the new route for the maximum payload of 80 bytes. Similar results were obtained when Router C is turned off and the End Device needs to deliver the messages through Router B.

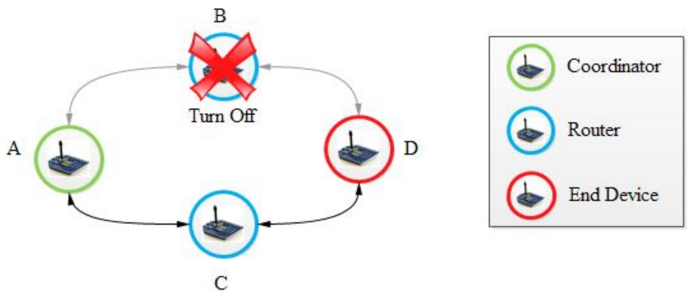
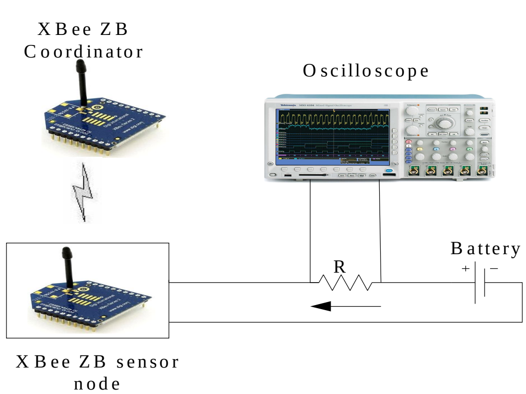


Fig.7. Mesh routing test layout

3.5 Energy Consumption and Battery Life Time Prediction

For wireless sensor networks, energy efficiency is one of the important functional indexes since it directly affects the life cycle of the system. Replacing batteries regularly for failed sensor nodes in huge wireless networks is not convenient due to terrain and space limitations and also due to hazardous environments in which they are placed in [20]. Therefore, the best method to save energy is setting sleep mechanism. The power consumption measurement is only carried out for the End Device as the Coordinator is mains powered at the base station.

For this experiment, an End Device is configured to be in a cyclic sleep mode (SM = 4). After transmission has completed, the End Device will return to sleep mode for another sleep cycle. In order to monitor the current consumption and the timing for each operating mode by the End Device, we place a shunt resistor with a value of R = 12.3Ω between the voltage source and the supply pin of the End Device. The test bed for this measurement is shown in Fig. 8 where the Coordinator was placed at a distance of 1 meter from the End Device while the voltage and the timing diagram for the operation of transmitting the sensed data to the Coordinator is illustrated in Fig. 9.



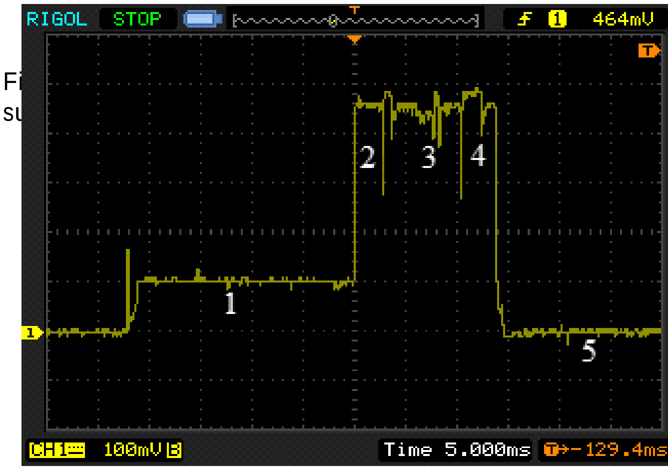


Fig.9. Measured supply voltage during the transmission of data frames in different stages.

The following Table 1 shows the measured current consumption and the time intervals during different modes of an End Device.

TABLE 1
CURRENT MEASUREMENT OF AN END DEVICE

Parameters	Stages	End Device
Activate and Deactivate time(t_{onoff})	1	20ms
Activate and Deactivate current (I_{onoff})		8.1mA
Listen time (t_{listen})	2 & 4	6ms
Listen current (I_{listen})		40mA
Transmitter current (I_{trans})	3	38mA
Sleep current (I_{sleep})	5	0.6mA
Battery Capacity		2000mAh
Battery Voltage		3.3V

Based on the actual current measurements, battery lifetime can be estimated as follows:

The mean current consumed by the XBee ZB mote to transmit a data packet of n bytes from the MAC layer is expressed as:

$$I_{active(n)} = \frac{t_{onoff} I_{onoff} + t_{listen} I_{listen} + t_{trans(n)} I_{trans}}{t_{active(n)}} \quad (4)$$

where, t_{onoff} is the total time for activation and deactivation of the transceiver module, I_{onoff} is the current during this period, t_{listen} and I_{listen} are the time and current while the transceiver is listening or receiving ACK packets from the Coordinator in an active state. Similarly, I_{trans} is the current absorbed by the module during transmission of *n* bytes where:

$$t_{trans(n)} = \frac{8\times(31+n)}{r} \quad (5)$$

As per IEEE 802.15.4/ ZigBee Mac layer, every transmission has a packet overhead of 31 bytes along with data packet (*n*) and *r* as the binary rate of 250 kbps, operating at ISM 2.4 GHz with *QPSK* modulation [21]. Finally, $t_{active(n)}$ is the time for complete activity:

$$t_{active\,(n)} = t_{onoff} + t_{listen} + t_{trans\,(n)} \quad (6)$$

The current at which the battery is drained considering *T* as the time between two consecutive transmissions and I_{sleep} as the sleep mode current, we can compute drain current as

$$I_{drain(n)} = \frac{t_{active(n)}}{T} I_{act(n)} + \left(1-\frac{t_{active(n)}}{T}\right) I_{sleep} \quad (7)$$

The lifetime (*L*) in years of battery with capacity *C* (mAh) can be estimated from $I_{drain(n)}$ as expressed

$$L = \frac{C/(I_{drain(n)}\times 1000)}{365\times 24} \quad (8)$$

Based on the analysis above, MATLAB® simulations were conducted to estimate the lifetime of XBee ZB wireless sensor node with variable data packet size and different values of consecutive transmission time (update period) as shown in Fig. 10.

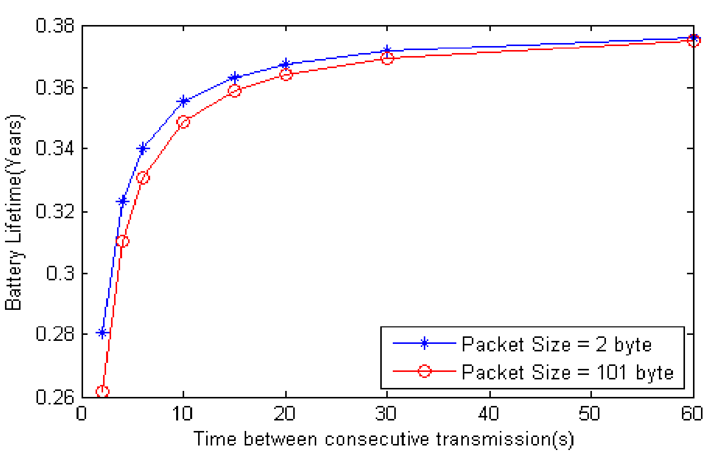


Fig.10. Wireless Sensor Network Node lifetime with different packet size and update period

From the results obtained, the XBee ZB End Device can operate for several years without the need for replacing a new battery. It was also observed that the lifetime of the node decreases as the packet size increases. It is also possible to achieve longer lifetime for battery powered sensor nodes using high current capacity lithium batteries. Apparently, the power consumption of ZigBee End Devices using the cyclic sleep mode can be reduced effectively, which will improve the lifetime of the entire network.

4 Conclusion

In this paper, we have analyzed the performance of different network topologies of XBee ZB module based wireless sensor network. We considered scenarios with direct transmission from the End Device to the Coordinator and with the presence of Routers for relaying messages. For multi-hop transmission with Routers, our results show that the performance of the network is highly degrading in terms of network throughput and packet delay. Therefore, to improve the system performance, the number of transmitting nodes should be minimized. It was also observed that the throughput varies with the packet size. A maximum throughput of 5.4 kbps was achieved which is much lower than the theoretical value of 250 kbps. Mesh routing recovery time was found to be between 90ms and 130ms for a simple route of two hops and it is expected that this recovery time will increase with the number of hops in the route. Furthermore, power consumption of ZigBee End Devices using the cyclic sleep mode can be reduced effectively, which will improve the lifetime of the entire network.

Overall, the performance analysis shows that the XBee ZB module is more suitable for low data rate applications not having very high reliability and real-time deadlines.

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