

A New Method for Battery Lifetime Estimation Using Experimental Testbed for Zigbee Wireless Technology

Dahlila Putri Dahnil^{#1}, Supiah Selamat^{#2}, Khairul Azmi Abu Bakar^{#3}, Rosilah Hassan^{#4}, Ahmad G. Ismail^{*}

[#]Center for Software Technology and Management, Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.

E-mail: ¹dahlilaputri@ukm.edu.my, ²supiah.slmt@gmail.com, ³khairul.azmi@ukm.edu.my, ⁴rosilah@ukm.edu.my

^{*}Institute of Microengineering & Nanotechnology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor
Email: ghad@ukm.edu.my

Abstract— Many Zigbee-based wireless sensor networks have been developed for outdoor applications such as agriculture monitoring. The main attractiveness of Zigbee wireless module is in its potential to set up self-organizing network that requires no network backbone and extremely low cost with low-power wireless networking. Many simulations have been performed for testing the capabilities of wireless communication device and the battery lifetime. However, the results from the simulation do not capture the actual environment effects and the simulators allow users to isolate certain factors by tuning to different parameters. This paper provides experimental results on actual voltage drop using Zigbee protocol devices when communicating temperature, humidity and soil moisture data using a 900mAh battery both in indoor and outdoor environments. It is observed that the wireless nodes are capable of relaying data up to 143 meters on unobstructed line of sights in an outdoor environment with some observation of packet drop. The results differ from previous researches that perform the experiments on shorter range which only covers 50 cm distance between transmitter node and receiver node for 2 bytes of data transfer. The paper proposes a new method for battery lifetime estimation which is derived from number of times data packet can be transmitted. This study also suggests to conduct experiment by including the environmental factors to capture the actual performance of wireless device and the impact to packet drop. The experiment concludes the suitability of Zigbee wireless communication for short-range applications of up to 143 meters which is significantly farther than other reported experiments.

Keywords— Zigbee wireless technology; Arduino; Xbee; lifetime.

I. INTRODUCTION

The foundation of monitoring system lies on wireless network capability to sense the physical environment and to forward information to a central processing unit [1-2]. There are two main components involved namely the sensor devices that interact with the physical environment and a wireless module for sensor devices to communicate wirelessly. These devices when connected form wireless sensor networks [3].

Wireless sensor networks become popular in many applications due to its ability to sense the physical environment's attributes and transmit the sensed data to a central processing unit for smart decision-making [4]. One of the most promising wireless technologies for wireless sensor networks is 802.15.4/ZigBee. ZigBee builds upon the IEEE 802.15.4 standard [5], which defines the physical and Media Access Control (MAC) layers of the communication protocol stack [6]. Zigbee has been proposed in many applications despite its immature state [7] and has emerged

as principle wireless technology for transmitting data between devices due to its simplicity of installation, extremely low cost, low-rate data transfer and low-power wireless networking [8]. It is suitable for applications that require connectivity up to 100 meters and most popular for short-range wireless personal area network [9].

Zigbee devices operate on batteries and require to be operational for several months to several years. Most of the battery consumption happens during transmission and reception time. Since IEEE 802.15.4 uses low duty cycle, the device turns to low power (sleep mode) most of the time so that the battery lifespan can last for many years. Many attempts for energy harvesting have been done for wireless sensor networks applications [10-12]. However, due to some reasons related to weather invariants such as rain or sun blockage, the required amount of energy cannot be harvested. Battery operated equipment is still favorable and more reliable. Therefore, there is a need to improve both equipment and communication protocols in such a way that

they consume less power and work reliably under outdoor agricultural conditions [13].

The lifetime of the wireless sensor networks depends significantly on the battery usage. The study of battery consumption mostly has been done on the simulated environment [14] because building a real testbed is costly, complicated and time-consuming [15]. However, the results from the simulation do not capture the actual environmental effects, and the simulators allow users to isolate specific factors by tuning to different parameters [16]. An experiment performed on more realistic testbed is required because the battery drainage needs to be measured when the actual environment is taken into consideration. Once deployed, the weather conditions will be one of the factors in determining the success rate of wireless data transfer.

This paper presents experimental results when actual testbed is set up for transmitting agriculture parameters such as soil moisture, temperature, and humidity between two Xbee S2 Pro (Xbee is hardware that uses Zigbee communication protocol) devices operated on Lithium Polymer (LiPo) batteries. The paper provides voltage measurements in indoor and outdoor environments with three different distances, i.e. 38 m, 143 m, and 230 m. A new method for battery lifetime estimation is proposed in term of sometimes data packet can be transmitted. The results differ from previous research that experimented on the 50cm distance between the source node and the coordinator node for 2 bytes of data transfer [58]. Our results show the extended range of up to 143m when transmitting 15 bytes of data on the unobstructed line of sight and 230m with some trees between the source node and the coordinator node.

II. MATERIAL AND METHOD

A. Agriculture Applications

Wireless networks have many advantages including easy installation, cost-efficiency, and reliability, which lead to a wide range of applications [17]. Unlike wired networks, wireless networks such as Zigbee, Long Range (LoRa), Wireless Fidelity (Wi-Fi networks), and satellite communication systems, are independent of fixed infrastructure [18-23]. Many agricultural applications have been proposed in wireless sensor networks [24-28]. Traditional agriculture activities require farmers to collect information manually at the scene [22, 29-30]. Today, wireless sensor networks modernize agriculture activities with remote monitoring. Information on the plants can be obtained wirelessly and in real-time [30-34]. Pictures of the farming plot can be obtained from sensor networks to farmers regardless of their locations. The sensor networks can manage automatic plant watering based on the soil water content [35]. Other information of the soil such as humidity, temperature, and potential of hydrogen (pH) level can be sent to farmer's monitoring application either on mobile or web in a real-time manner [36]. The technology can be used to increase production efficiency, improve crop quality and at the same time protect the environment [37].

B. Zigbee Battery Measurement Review

There are many agriculture applications developed for wireless sensor network using Zigbee technologies [38-45].

The biggest challenge reported by Tuijl et al. (2007) for agriculture and horticulture application for short communication distance of between 10 to 30 m is the maintenance cost for frequent replacement of batteries, which goes back to the cost of implementation [46].

Agricultural applications depend significantly on the battery to power up the sensor devices. Most of the battery consumption is based on the simulated environment, and the battery prediction model are derived from this setup [47].

The work in [48] studied the current consumption of commercializing chipset including Bluetooth, Ultrawideband, IEEE 802.11, and IEEE802.15.4/Zigbee technologies during transmission and reception. The paper reported that IEEE802.15.4 required very small current which was one-tenth of UWB, Wi-fi and half of the current needed by Bluetooth.

The work in [49-50] conducted a study on the impact of coexistence of 802.15.4 with other wireless technologies operating in the same 2.4GHz ISM band. The results showed the interference from other wireless technologies would have a serious effect on the throughput.

The study in [7] presented an empirical characterization of the current consumption of actual IEEE802.15.4/Zigbee under different operations and provided the analytical performance models. The presented results were based on the measurement of the current drained from the sensor mote during several phases namely start-up, when associating with the coordinator, during packet transmission, during the loss of connection and sleep mode. The experiment was performed on eZ430-RF2480 Kit by Texas instrument and repeated using Texas Instruments CC2520 [51] and the Freescale MC1322x platform.

The work in [7] was extended by [58] by providing the current consumption on one duty cycle that consists of current consumption during start-up, an association of sensor motes to a coordinator, packet transmission, and loss of connection and during sleep mode. The paper also presented the analytical model to predict the maximum, minimum and the expected battery life for a short distance that is less than 50cm between the coordinator node and the sensor mote.

In this paper, we further extend the work to cover a longer distance of communication between the coordinator and the sensor nodes and increase the packet size to capture a more realistic application in indoor and outdoor deployments. This is because most outdoor Zigbee applications [22-26] implement a coordinator node placed at a longer distance between the sensor nodes. The experiment is performed using 15 bytes of a data packet for ten times continuously in indoor and outdoor environments. The data transmission between the coordinator and sensor nodes is observed on the bright sunny day at 143 m on Application programming interface (API) mode and 230 m on (Transparent Mode) AT mode. The voltage of the battery is measured after each 150 data packets is sent.

C. Hardware for 802.15.4b/Zigbee

The experiment measures the voltage drop across the LiPo rechargeable battery. The measurement is taken after source node sent a cycle of 150 data packets to a coordinator node where one data packet consists of 15 bytes. These

voltage measurements are taken with a different type of communication modes as shown in Table I.

TABLE I
ENVIRONMENT SCENARIO

The distance between source and coordinator (m)	Environment				
	Indoor		Outdoor		Obstacles
38	AT	API	-	API	
42	-	API	-	-	No
143	-	-	-	API	No
230	-	-	AT	-	Yes (some trees)

1) *Sensors*: There are two sensors used for measurements which are temperature and soil moisture sensors. The temperature sensor also provides two types of measurements, which are temperature (Celsius) and humidity (percentage). The soil moisture sensor is placed into the soil to measure water content in the soils.

2) *Microcontrollers*: The microcontroller contains memory, programmable peripherals and a processor. In this project, Arduino UNO [52] is used and based on ATmega 328P. There are six analog inputs in the Arduino UNO where pin A0 is set for temperature sensor while pin A1 is set for soil moisture sensor.

3) *Wireless Communication Module*: *Wireless* communication device used in this project is XBee series 2 (S2). This device uses radio frequency of 2.4GHz for data transmission [53]. The baud rate of 115200 is set for the XBee using XCTU software from Digi [54].

4) *Anemometer*: Anemometer is a standalone digital device to measure air velocity and temperature during the test [55] for every 150 packets sent. The unit is used to measure the air velocity in meter per second (m/s) with $\pm 5\%$ accurate while the temperature unit is in Celsius ($^{\circ}\text{C}$) with ± 2 accurate.

5) *Battery*: Another important part of this battery measurement setup is the battery itself. LiPo rechargeable battery GE Power 900mAh 20C [56] is used where its voltage is measured to transmit a set of data.

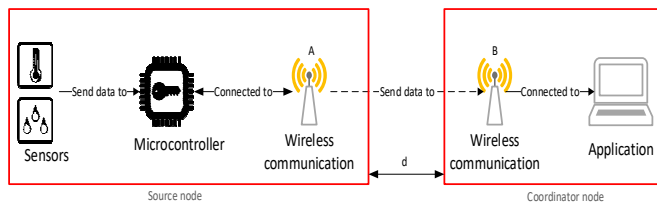


Fig. 1 Battery measurement setup

Fig. 1 shows the setup of the battery measurement experiments. The system consists of a set of sensors, microcontroller, multimeter and Zigbee wireless communication device. The data transmission happens between a source node and a coordinator node separated by a distance d . First, the temperature sensor reads the air temperature value and the soil moisture sensor reads the moisture level of the soil. These values are then sent to Arduino UNO. The microcontroller attached to the Arduino UNO executes the uploaded programmed code and sends the

data to the XBee, noted as A in Fig. 1. Wireless device XBee (A) transmits the data wirelessly to XBee (B), the coordinator node. Upon receiving the data, XBee (B) sends the data to the application in the coordinator node. The voltage across the battery is then measured at the source node.

6) *Programming Language*: In this setup, C programming language is used as it is compatible with Arduino UNO board. Arduino Sketch is one of the applications that is used to write the codes. The baud rate is set to 115200 with as the transmit interval per serial byte sent.

D. Data Transmission

XBee can transfer data in multiple ways, i.e., point-to-point, point-to-multipoint, and multipoint-to-multipoint transfers. In this paper, the experiment is set to point-to-point data transfer. XBee operates in two kinds of modes which are AT and API modes with this point-to-point transfer.

XBee configured in AT mode transmits data immediately to the other remote XBee identified by the destination address. AT mode is an effortless operation where the XBee module receives wireless data exactly as it is sent. However, in AT mode, the receiver cannot recognize the ID of the source node where it receives the data from.

Unlike AT mode, API mode communicates in a structured interface known as a frame. XBee receiver configured in API mode knows from where the data is coming from because the received packets contain the source address of the sender.

E. Process Before Data Transmission

Before transmitting the data, the node discovery process is needed to discover the source node in the network. For this project, XCTU application installed on the computer connected with the coordinator node executes the node discovery process. The coordinator node scans the node available in the network. Once the other node is found, the connection between the source node and coordinator node is established. The node discovery process shows the connection quality from very strong, strong, moderate or weak. The node discovery process is only applicable for API mode. This is because, in AT mode, nodes are configured to know each other's destination address

F. Data Packet

In AT mode, the receiver gets everything precisely the same as what the sender transmits. Unlike AT mode, API mode needs a data packet with the structured frame to send and receive data. The received frame structured regarding hexadecimal number is shown as in fig. 2.

1) *Start Delimiter*: The start delimiter is the first byte of a frame. This start delimiter indicates the beginning of a data packet which is 0x7E. The value of 0x7E in the frame enable the application to check for a new arriving frame. Fig. 2(a) to fig. 2(c) show the starting value of the frame is 0x7E for temperature, humidity, and soil moisture data packets.

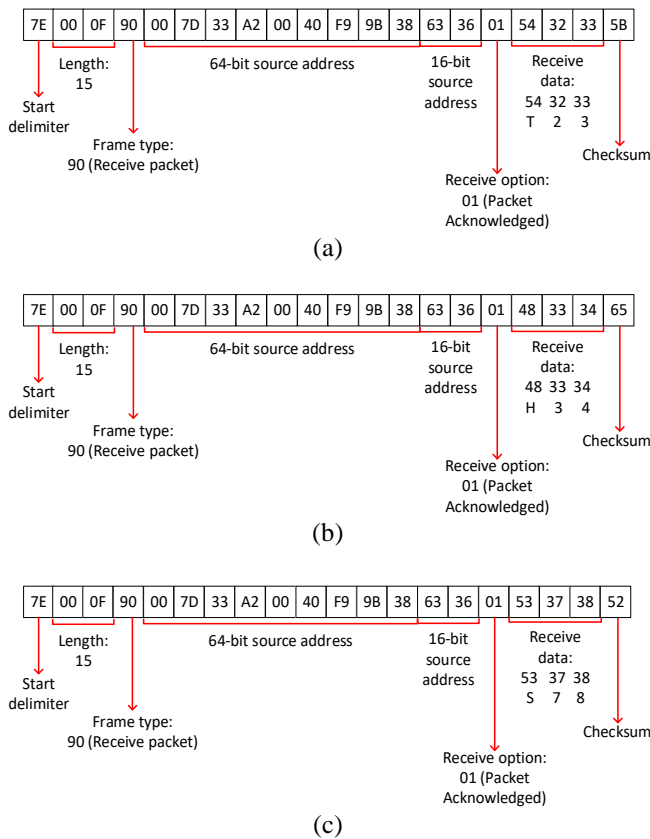


Fig. 2(a) Temperature data packet; (b). Humidity data packet; (c). Soil moisture data packet

2) *Frame Length*: Next to the start delimiter bit is the length of the frame. The length field is the total number of bytes in the data frame. This length field has a two-byte value that ignores the start delimiter, the length, and the checksum. Fig. 2(a) to fig. 2(c) show different values because of the different size of the data payload. The length of temperature data packet in fig. 2(a) to fig. 2(c) show that the length of the packet is 15.

3) *Frame Data*: Next to the length field is the frame data field. The frame data field holds the information whether the device transmits or receives. The frame data field is divided into two which are:

- **Frame type**: frame type field is the API frame type identifier which determines the type of data for the data packet. Fig. 2(a) to fig. 2(c) indicate the frame type is 0x90 which is for temperature, humidity, and soil moisture data packets.
- **Data**: data fields consist of 64-bit source address, 16-bit source address, receive option and the data itself. Fig. 2(a) to fig. 2(c) show the same 64-bit source address (0x00 0x7D 0x33 0xA2 0x00 0x40 0xF9 0x98 0x38), 16-bit address (0x63 0x36) and receive option (0x01). Receive option data frame of 0x01 means that the packet is acknowledged. The received data value in fig. 2(a) for temperature data packet is 0x54 0x32 0x33 which represents 23 degrees Celsius. Fig. 2(b) shows the received data for humidity data packet is 0x48 0x33 0x34 which means the percentage of humidity is 34%. Lastly, fig. 2(c) shows the percentage of soil moisture is 78%.

4) *Checksum*: The last byte in the data packet is the checksum. The checksum is calculated by summing up the API frame before it, excluding the start delimiter and frame length. The frame with the incorrect checksum leads to data being ignored. From fig. 2(a), the checksum for temperature data packet is 0x58. The checksum for humidity data packet in fig. 2(b) is 0x65. Lastly, the checksum for the soil moisture data packet in fig. 2(c) is 0x52.

The testbed includes two important considerations, first the Arduino setup and second, the location and distance selections.

G. Arduino Setup

The source node contains Arduino UNO, XBee, and the two sensors. For the coordinator node (receiver), the XBee module is attached to the laptop with XCTU application. In this test, two persons are required at both the source and coordinator sides. One person manually measures the battery's voltage using a multimeter.

At the coordinator node, another person informs that the XBee has stopped receiving data via a walkie-talkie. The steps to measure the voltage are as follows:

- The battery voltage is measured at the source node using the multimeter.
- The source node sends 150 data packet to the coordinator node.
- Coordinator receives data through XBee for all 150 data packets
- The voltage drop is calculated by taking the voltage reading before and after transmission at the source node.
- Proses i-iv is repeated for 20 times to get 20 readings.

H. Location and Distance

Location and distance are the important factors to consider in this experiment. It is essential to choose the right location because XBee communication works with line of sight. This means there should not be any trees, buildings or moving vehicles between the transmitter and the receiver. Therefore, a stadium and a car park are the two places selected to run the outdoor test. An empty university hall and faculty laboratory hallway are the venues for the indoor test.

For the stadium set up, the source node is located in an open stadium field whereas the coordinator node is stationed in the stadium. The coordinator node view is facing the source node on a slightly higher position. The distance between two points is measured to be 143 m. The additional experiment is performed at two other different locations further from the stadium which is 230 m distance apart with some trees in between.

III. RESULTS AND DISCUSSION

A. AT to AT Mode

AT to AT mode in this experiment means that the XBee's are configured with AT mode for both the source and coordinator nodes. The AT-mode source node with temperature and soil moisture sensor sends the data to the coordinator node configured with AT mode. In this experiment, the data is received and captured using XCTU software at the coordinator node

B. API to API Mode

API to API Mode means that the XBee's are configured with API mode for both source and coordinator nodes. The API-mode source node with temperature and soil moisture sensor sends the data to the coordinator node configured with API mode. Fig. 3 shows the data received from the source node. Different from AT mode, the received data in API mode is a structured packet that starts with 7E as the starter of the frame shown in XCTU

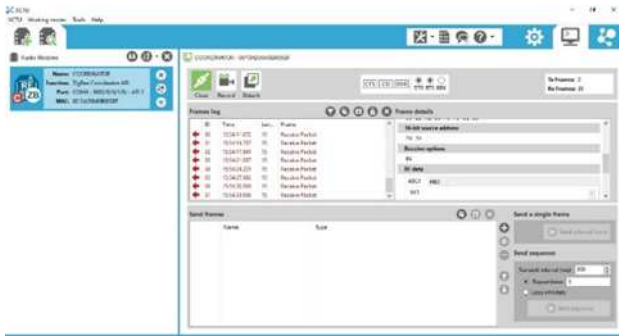


Fig. 3 Coordinator Node configured with API mode received data shown in XCTU

C. Battery Voltage Measurement

The experiment is conducted to obtain how many transmission of data packets can be performed before the battery drops to a level where it is not able to send any more data packet. Fig. 4 below shows the transmission of 15 bytes of data continuously for ten times.

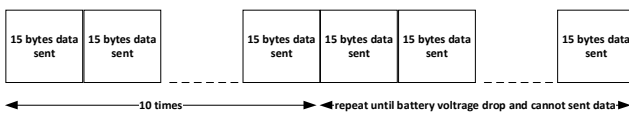


Fig. 4 15 bytes data sent continuously

Fig. 5 shows the voltage measurements for API mode for the indoor environment at 42 m apart from source to the coordinator node.

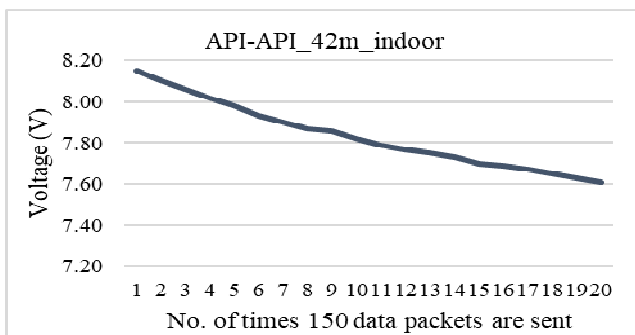


Fig.5 API-API mode 42 m, indoor.

Fig. 6 shows that there is a more considerable voltage drop for both AT and API mode in both indoor and outdoor environments for the first six times of sending data packets. This might be due to the time required to stabilize the wireless devices. The readings become stable afterward. This result shows that the mode of communication does not give a big impact to voltage since in both modes the average voltage drop is between 0.027 V and 0.016 V.

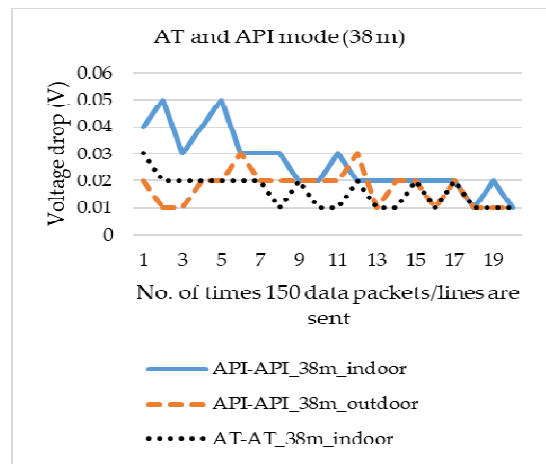


Fig. 6 AT and API mode 38 m, indoor and outdoor

Fig. 7 shows voltage measurement versus the number of times 150 data lines and 150 data packets are sent for AT and API modes at a distance 38 m away between the source node and coordinator node. It is observed that the voltage drops for AT to AT mode and API to API mode has the same linearly decreasing pattern. We can deduce that the voltage drop is not affected by the communication mode but due to data transmission. This conclusion is true for short-range communication coverage.

Fig. 8 is plotted for the experiment performed at a distance of 143 m between source and coordinator nodes. The wind velocity also is measured to investigate their effects on packet and voltage. The graph shows AT mode has a small voltage drop as compared to API mode. This is due to AT mode that sends the raw data without the packet frame. The experimental results are used for battery life estimation in term of a number of times transmissions can be done before the minimum operating voltage required for Xbee to transmit data is reached.

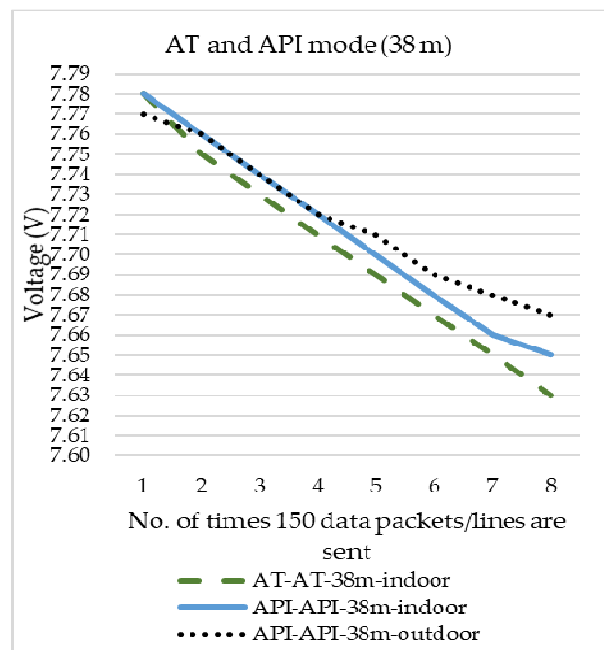


Fig. 7 AT and API modes 38 m, performed indoor and outdoor

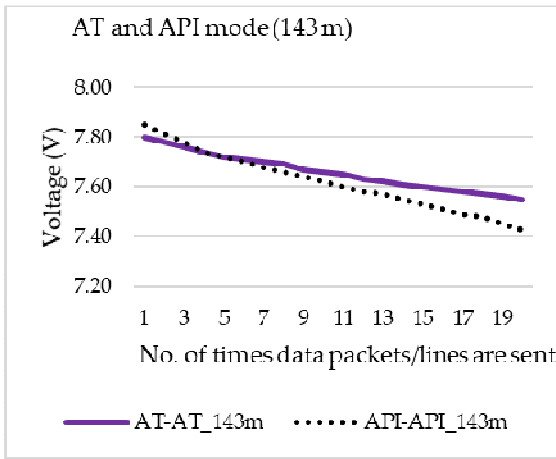


Fig. 8 AT-AT mode and API-API mode 143 m performed outdoor

Fig. 9 shows the experimental results for AT mode performed at 230 m with some trees in between. This plot also shows that the packet can be received with a few obstacles.

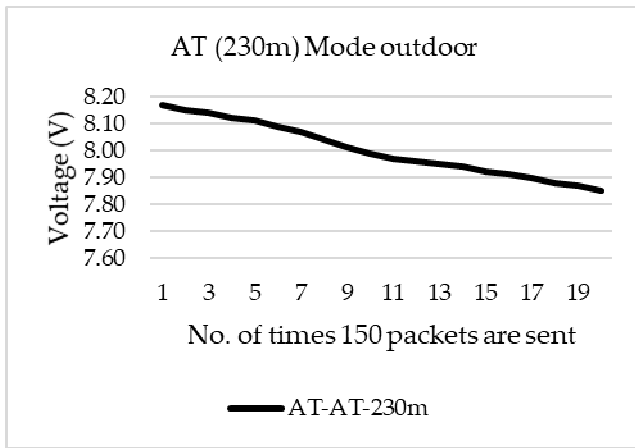


Fig. 9 AT-AT mode 230 m performed outdoor

D. Packet Drop

The experiment for the outdoor scenario is performed on a sunny day between 9 am to 2 p.m. for 38 m and 143 m distances. We observe the packet drops significantly in an outdoor environment. For a distance of 38m, the worst-case scenario is when the number of packets received is 141 as shown in Table II. For a distance of 143m, the worse case scenario is when the number of packets received is 109 as shown in Table III. We observe that vehicle movement and the wind speed might cause the packet drops. However, the results are not conclusive, and further experiment on wind must be carried out to determine whether it might influence the number of packet drops. Equation (1) is used to get the percentage of packet delivery ratio for both 141, and 109 packets received.

$$\text{Packet delivery ratio} = \frac{(\text{Data sent} - \text{Data received})}{\text{Data sent}} * 100 \quad (1)$$

$$\text{Packet delivery ratio} = \frac{150-141}{150} \times 100 = 6\% \quad (2)$$

Packet drop by 38 m is 6% while the packet drop worsens at a longer distance (143 m) where packet drop becomes 27.3%.

E. Battery Lifetime Estimation

In this paper, the battery lifetime estimation is based on the number of data transmission performed. We consider this during the data transmission as it is the major contribution in voltage drop while assuming other factors, such as microcontroller processing or sleep mode as negligible [57]. The voltage drop (V_{drop}) for transmitting 1 data packet is given in equation (3):

$$V_{drop} = \frac{V_{avedrop}}{150} \quad (3)$$

Eavesdrop is the average voltage drop for sending 150 data packets. Thus, the number of transmissions can be calculated as in equation (4):

$$\text{Transmission}_{num} = \frac{V_{init} - V_{min\ operate}}{V_{avedrop}} \times 150 \quad (4)$$

Where $\text{Transmission}_{num}$ is the number of transmissions can be performed, V_{init} is the initial battery voltage, $V_{min\ operate}$ is the minimum operational battery for Xbee module to transmit data, which is specified to be between 2.1 - 3.6 V [53].

From the experiment, taking the average voltage drop = 0.0175 ~0.02 V, $V_{min\ operate} = 2.1$ V and $V_{init} = 7.85$ V as tabulated in Table III for API mode, we can calculate the number of transmission of the data packet until the minimum operational battery is reached as shown in equation (5).

$$\text{Transmission}_{num} = \frac{7.85 - 2.1}{0.02} \times 150 = 43125 \quad (5)$$

Each API data packet consists of 15 bytes. This value gives an estimation of the battery life for any wireless device on the Xbee module. From (5), the value indicates for 15 bytes data packet; the battery can last for 43125 number of transmissions.

IV. CONCLUSION

For more practical results, an actual environment is needed for a testbed for Zigbee wireless module applications. In this study, the experimental results are used to derive the battery lifetime in term of sometimes data packet can be transmitted. Further investigation of the environmental factor such as wind velocity need to be investigated, and the correlation needs to be established to study the effects on packet drop as future work. The results present the voltage measurements when transmitting in indoor and outdoor for AT and API modes. This study also suggests experimenting by including the environmental factors to capture the actual performance of the wireless device. The experiments are concluded by suggesting the suitability of Zigbee wireless module for short-range outdoor applications up to 230 m in AT mode and 143 m for API mode.

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TABLE II
AVERAGE VOLTAGE DROP PER 150 DATA PACKETS SENT

No of times 150 data packets/ lines ares sent	API_API_38 m_indoor		API_API_38 m_outdoor		AT_AT_38 m_indoor	
	Voltage drop	Data Packet	Voltage drop	Data Packet	Voltage drop	Data Packet
1	0.04	150	0.02	150	0.03	150
2	0.05	150	0.01	150	0.02	150
3	0.03	148	0.01	150	0.02	150
4	0.04	150	0.02	150	0.02	150
5	0.05	150	0.02	150	0.02	150
6	0.03	150	0.03	144	0.02	150
7	0.03	150	0.02	148	0.02	150
8	0.03	150	0.02	143	0.01	150
9	0.02	150	0.02	150	0.02	150
10	0.02	150	0.02	147	0.01	150
11	0.03	150	0.02	141	0.01	150
12	0.02	150	0.03	150	0.02	150
13	0.02	150	0.01	148	0.01	150
14	0.02	150	0.02	145	0.01	150
15	0.02	150	0.02	150	0.02	150
16	0.02	150	0.01	149	0.01	150
17	0.02	150	0.02	150	0.01	150
18	0.01	150	0.01	150	0.01	150
19	0.02	150	0.01	150	0.01	150
20	0.01	150	0.01	150	0.01	150
Average	0.0265		0.075		0.016	

TABLE III
VOLTAGE MEASUREMENT FOR API MODE (143 M)

No of times 150 data packets/ lines ares sent	Voltage Drop	Received Data Packet	Temperature (°C)	Humidity (%)	Soil Moisture (%)	Observed Wind Velocity (m/s)	Anemometer-Temperature (min, max)
1	7.85	150	36	68	69	0	32.7, 36.0
2	7.81	150	37	54	69	0	36.0, 38.3
3	7.78	150	36	68	70	0	40.4, 40.6
4	7.74	148	36	57	69	1.5	37.4, 39.5
5	7.72	150	42	49	69	1.6, 1.8	34.7, 37.4
6	7.7	150	43	41	69	1.1	34.6, 39.8
7	7.68	150	43	38	68	1.2	35.1, 39.8
8	7.66	150	34	56	68	0	34.0, 34.2
9	7.64	150	37	58	68	0	34.2, 34.5
10	7.62	149	37	57	69	1.4, 1.6	32.0, 32.2
11	7.6	109	35	56	68	1.7, 0.8	32.2, 32.8
12	7.58	150	35	55	68	0	32.8, 32.9
13	7.57	150	35	56	67	0	33.7, 33.6
14	7.55	150	35	55	67	0	33.4, 34.9
15	7.53	150	35	58	68	2.0, 1.1	33.3, 34.3
16	7.51	150	41	50	76	1.6, 1.3	32.6, 32.7
17	7.49	150	36	55	73	2	33.0, 34.1
18	7.48	150	37	57	72	1.5, 1.1	32.9, 34.0
19	7.45	134	35	56	72	2.2, 2.0	35.7, 41.6
20	7.43	131	41	47	70	1.5, 1.7	34.5, 35.9

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