Energy Consumption Optimization of Zigbee Communication: An Experimental Approach with XBee S2C Module

Preprint · July 2022

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Abstract. Zigbee is a short-range wireless communication standard that is based on IEEE 802.15.4 and is vastly used in both indoor and outdoor Internet of Things (IoT) applications. One of the basic constraints of Zigbee and similar Wireless Sensor Networks (WSN) standards is limited power source as in most of the cases they are battery powered. Thus it is very important to optimize the energy consumption to have a good network lifetime. Even though tuning the power transmission level to a lower value might make the network more energy efficient, it also hampers the network performances very badly. This work aims to optimize the energy consumption by finding the right balance and trade-off between the transmission power level and network performance through extensive experimental analysis. Packet Delivery Ratio (PDR) is taken into account for evaluating the network performance. This work also presents a performance analysis of both the encrypted & unencrypted Zigbee with the stated metrics in a real-world testbed, deployed in both indoor and outdoor scenarios. The major contribution of this work includes (i) to optimize the energy consumption by evaluating the most optimized transmission power level of Zigbee where the network performance is also good in terms of PDR (ii) identifying and quantizing the trade-offs of PDR, transmission power levels, current, and energy consumption. (iii) creating an indoor and outdoor Zigbee testbed based on commercially available Zigbee module XBee S2C to perform any sort of extensive performance analysis.

Keywords: Zigbee, Energy Consumption Optimization, Zigbee Testbed, Current, and Energy Consumption Measurement, Wireless Sensor Network, PDR.

1 Introduction

The evolution of wireless communication has evolved IoT in recent years. It now allows multifarious applications which definitely improves the quality of every sphere of life [1]. The Wireless Sensor Network (WSN) consists of sensor nodes being deployed in remote locations and perform wireless communication among themselves. While considering wireless sensor network, the critical metrics might be constrained power source and hence lower transmission power level might be preferred. As a result, the strength of the signal is reduced and consequently the PDR is compromised. Our objective is to find a balance between the two concerns as in determining an optimized power level to obtain decent rate of packet delivery, i.e. good PDR with considerably lower energy consumption, as this has not been addressed by the research community yet.

Zigbee is one of the most popular low powered wireless sensor network which is based on IEEE 802.15.4 standards. The Physical (PHY) and Medium Access Control (MAC) layer are associated with transmission, channel selection and operating frequency, while on the contrary, the Network (NWK) and Application (APL) layers involves the network infrastructure, encryption and decryption of network and others [2]. Fig. 1 presents the Zigbee protocol stack. The lower two layers of Zigbee– PHY layer, and MAC layer of Zigbee is exactly same as the IEEE 802.15.4. However, Zigbee Alliance improvise the upper three layers to introduce multi-hop, & mesh network and to improve the application & usability of WSN.

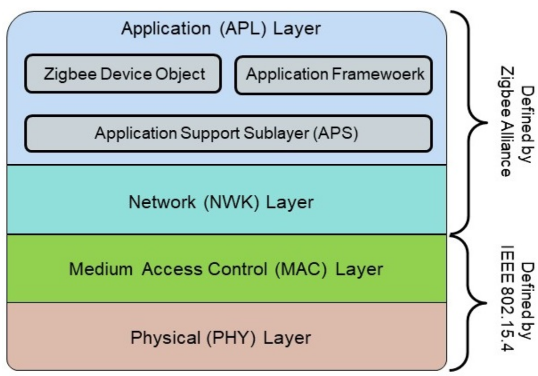


Fig. 1. Zigbee Protocol Stack

Though Zigbee is one of the most energy efficient WSN, further optimization of the energy consumption is necessary due to the constraint power supply to the Zigbee end nodes. It would also help to better understand its trade-offs with performance metrics like PDR and energy efficiency. Setting up the transceiver to highest possible transmission power level might improve the PDR, but it also hampers the energy efficiency drastically which might cause early death of nodes creating holes in the mesh network. On the other hand, tuning the transmission power level to the minimum might result in drastic drop of PDR and link quality. Moreover, different applications have various priorities in terms of performance metrics. Thus to optimize the energy consumption and network performance at the same time, a comparative study of the transmission power levels, energy consumption and corresponding PDR is necessary. For this, an experimental study with actual transceivers deployed in practical environment is much needed. Even though, Zigbee has been the center of attraction of a large research community for a decade, such experimental study has not been addressed yet. Thus, this work intends to optimize the energy consumption of Zigbee communication with analytical experiment on Xbee S2C module. The contribution of the work includes: (i) setting up the indoor and experimental test beds for measuring the PDR and energy consumption (indoor only) at different transmission power levels: 1 dBm, 3 dBm, 5dBm. (ii) to study the variation of the PDR with the change of transmission distance and power levels at both indoor and outdoor scenario. (iii) optimize the energy consumption by analysing the per packet transmission energy at different transmission power levels and determine most optimized transmission power level which would also perform with decent PDR (iv) to study the trade-offs of the transmission power level, energy consumption and PDR.

The rest part of the paper is organized as following: section 2 presents the necessary background and relevant literature on the research field, section 3 describes the experimental test beds. Study on PDR, current & energy consumption, and optimization of the energy consumption is conducted in section 4 and the work is concluded in section 5.

2 Background and Relevant Literature

Even though there is not enough literature on this aspect based on experimental study, Pathak et al. proposed an optimization technique of Zigbee in patient monitoring by fine tuning the transmission duty cycle [3]. Wang et al proposes an energy efficient routing algorithm by switching the cluster head in a simulation based study [4]. Li et al proposes an load balancing based routing protocol which optimize the energy consumption by directing the propagation of RREQ [5]. Zhang et al. proposes an adaptive MAC layer based energy saving algorithm based on both simulation and experimental study [6]. Essa et al. propose an power sensitive ad-hoc on demand routig protocol by managing the operations and routes [7]. Gocal et al. proposees an algorithm based on timing channels for different data priorities to optimize the energy efficiency of Zigbee [8].

Most of the previous analysis are based on software simulations and optimizing the routing protocol where the variation between indoor and outdoor configuration and optimization of transmission power has been merely discussed. Thus this work presents a unique analysis based on performance metrics like current consumption and packet delivery ratio in both indoor and outdoor environment to optimize the energy efficiency of the Zigbee network. Zigbee node can be set up with three different modes namely (i) Coordinator, (ii) router and (iii) end node. Coordinator being the central node of the network, performs the data transfer from central node to any other nodes by allowing them to join the network. The router allows two way communication between coordinator and end nodes while the end nodes interacts with environment by means of sensors.

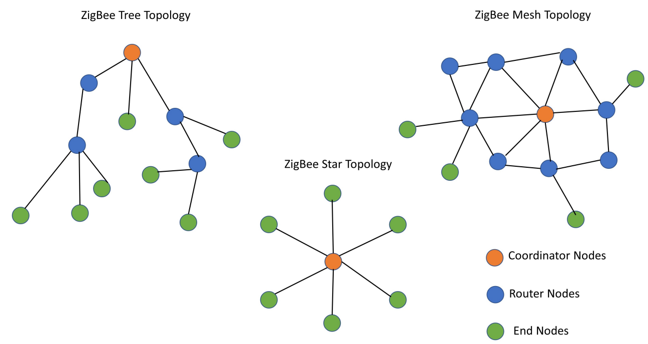


Fig. 2. Different topology of Zigbee protocol

Zigbee mainly operates on three types of topology namely (i) Tree, (ii) Star and (iii) Mesh topology as depicted by fig 2 [9] [10]. In tree topology coordinators is connected to router or end node in a one to one fashion While the star topology only consists of coordinator and end nodes in direct contacts without involving any router as inter medium. The mesh topology is the most efficient one and known to be self healing as it finds the best route for two way data communication between coordinator and end nodes by means of mesh arrangement of routers. However, our study focuses only on the end nodes as the router and coordinator nodes always remain awake and are assumed to un-constrained power supply. Zigbee indoor application involves home automation, smart surveillance, energy management and others [11]. All of them face hindrance because of indoor obstacles due to its Non Line of Sight (NLoS) arrangement. Radio frequency interference affect the performance severely as the operating frequency of zigbee overlaps the identical operating frequencies of WiFi, Bluetooth, Z-wave and create cross technology interference to drastically deteriorate the performance of Zigbee network [12] [13]. It is evident from the literature that a real life experiment with testbed deployment would provide much better estimation of the performance parameters like PDR and energy consumption. Thus, this work is based on both indoor and outdoor testbed deployment with real data measurements which takes into account of the practical world interference and environment.

3 Experimental Setup

The hardware setup has been carried out for both indoor and outdoor experiment. The Xbee S2C module has been used at 3 different Tx power levels– 1 dBm, 3 dBm and 5 dBm with an operating frequency of 2.4 GHz. The outdoor set up is conducted in an open space by placing the coordinator node at one end and the end nodes at a distance ranging 0-40 m from the coordinator. A big parking lot is taken into consideration for outdoor testbed allowing minimum noise & interference. For indoor testing, the lab space is taken into consideration as indicated in Fig 3. The placements of the end nodes are annotated by E_0, E_{10},

E_{20}, E_{30}, E_{40}, E_{50} which are respectively at a distance of 0 m, 10 m, 20 m, 30 m, 40 m and 50 m distance from the coordinator which is placed at C_0. The end nodes are placed at level one and at random location with NLoS. It is also to mention that the whole building is under Wi-Fi coverage with moderate amount of Bluetooth devices in use which would surely affect the Zigbee performances in comparison to the outdoor scenario [1].

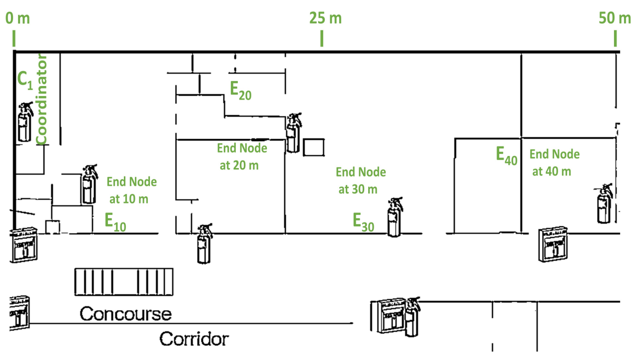


Fig. 3. Experimental testbed in the indoor lab environment

Different PDR measurements are taken by placing the end nodes at various locations indicated by Fig 3. This would facilitate to understand the trend of PDR in terms of transmission distance and transmission power levels. On the other hand, to analyze the energy consumption better, it is important to understand how the communication is performed, thus a data packet is transferred from a coordinator to an end node or vice versa. Zigbee protocol is based on IEEE 802.15.4 and Zigbee follows this standard completely for medium access control (MAC) and physical (PHY) layer. However, it is modified and different than that of IEEE 802.15.4 in the network (NWK) and application (APS) layer where it allows the Zigbee protocol to form a mesh network and enable multi-hop communication from the end node to the coordinator [2]. However, the energy consumption of a sensor network heavily depends on PHY and MAC layer which are the same as the IEEE 802.15.4. Zigbee follows the CSMA/CA to send data from one node to another. In this experiment, data packets of 30 bytes are sent from the coordinator to an end node. For measuring the current consumption, the end node is powered up from a 3.5 DC supply and connected to an oscilloscope across a shunt resistor of 9 Ω. This setup for real-time current consumption measurement during data transmission is presented by fig 4.

The current consumption measurement is done for various P_{Trans} level from which the power and energy consumption for a successful transmission of a packet can also be derived.

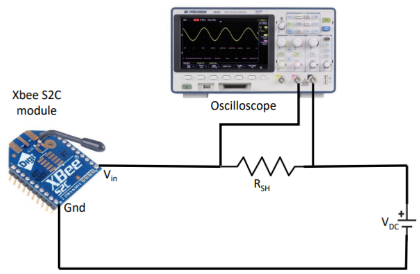


Fig. 4. Real-time current consumption measurement setup

4 Energy Consumption Optimization by Analysing (P_{Trans}) levels with corresponding PDR

Different Tx power levels are considered in this experimental study with a view to comparing and determining the optimized energy consumption with a fair enough PDR. We will now look in details on this analysis procedure.

4.1 Variation of Current and Energy Consumption with Various P_{Trans} Levels

The coordinator and the end nodes exactly follow the principle of IEEE 802.15.4 protocol in PHY and MAC layer. A current consumption capture is presented in fig 5 which would help in better realizing the different steps of a packet transmission and corresponding current & energy consumption. According to the CSMA/CA, The sender node (end node / coordinator) initiates the communication which is coordinator in this case study.

the coordinator broadcasts a beacon message of length 30 bytes in its network [14]. The end nodes are configured in cyclic sleep mode. They wake up after the predefined sleep time and listen for the beacon message from the sender which is the coordinator in this case. To wake up from sleep and receive the broadcasted beacon from the coordinator, the receiver takes some time. During this wake-up time, the receiver stays in radio idle mode as presented by annotation 1 whereas annotation 2 denotes the reception of this beacon message. After that, the receiver sends a data request to the coordinator. After receiving a broadcast beacon, the receiver stays in radio standby mode as annotation 3 until it sends the data request to the coordinator as presented by annotation 4. Then the receiver radio goes to idle mode and stays in idle mode until it receives the acknowledgment of the data request. After receiving the data request from the receiver, the sender (coordinator) waits for a backoff time according to the predefined contention window and then performs the clear channel assessment (CCA) before sending the data. The receiver goes to the receiving mode after the reception of this acknowledgment from the coordinator and remains in that mode until the data transfer is over as denoted by annotation 5. It processes the

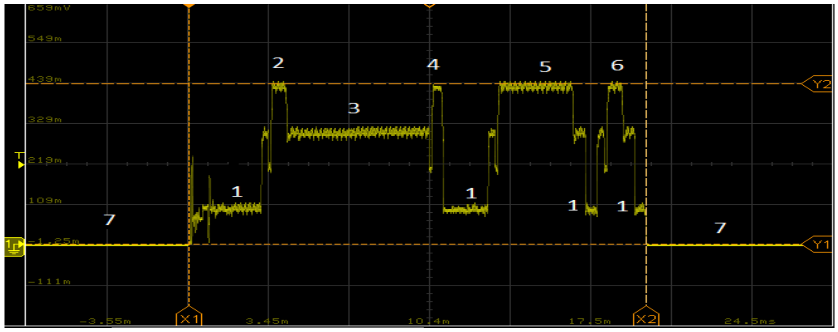
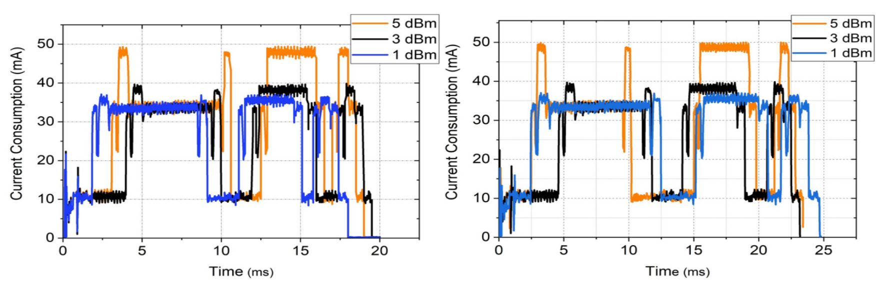


Fig. 5. Real-time current consumption capture of a successful packet reception

received data and upon successful reception of the data it sends an acknowledgment back to the coordinator which is denoted by annotation 6 and then goes to sleep mode again. These steps keep repeating for every packet transmission and all these stages of packet transmission are summarized in table 1.

The current consumption captures of the packet reception at different P_{trans} levels with both 128-bit AES encryption and without encryption are presented in fig 6.



(a) (b)

Fig. 6. Current consumption of a single packet (a)without and (b) with AES encryption

It is to be mentioned that the end node can receive the broadcast beacon from the coordinator at any time during its wake up duration. Thus, the duration of the first idle time (before receiving the beacon broadcast) as depicted by annotation 1 (first one before annotation 2) of fig 5 may vary randomly. To normalize this effect for each of the instances, a mean of 20 readings is taken into consideration. The figure shows that the current consumption during transmitting, and reception of a packet is highest for P_{trans} level of 5 dBm which is followed by 3 dBm and the current consumption with a transmission power of 1 dBm is

Table 1. Different stages of data reception corresponding to fig 5

Annotation of fig 5	Stages of data Transmission	Brief Explanation
1	Idle Time (Tidle)	Node is active, but radio is not active. Node tends to stay in idle mode to save energy
2	Data Reception Time Trx	Reception of the beacon message broadcasted from a coordinator
3	Radio Standby Time Tsb	Radio stays in standby mode before sending a data request to a coordinator or any sender as it waits for backoff time and performs CCA.
4	Data Transmit Time Ttx	End node sends the data request to the coordinator/sender
5	Data Reception Time Trx	End node receives the ACK of the data request and goes to receiving mode and waits until data transmission is over
6	Data Transmit Time Ttx	ACK is sent upon successful reception of the packet.
7	Sleep Time Tsleep	End node remains in the sleep mode before and after the reception of the data packet as defined by the experiment configuration

the lowest. Moreover, it is evident from fig 6 that, the difference of the current consumption with different transmission power levels mostly differs in transmit and reception mode. The current consumption during radio standby time, idle time, and sleep time is almost the same for all the P_{trans} levels. Moreover, with AES encryption the current consumption during transmit and reception is slightly higher than that of unencrypted data due to the higher time and resource requirement of the encryption procedure. The exact current and energy consumption during each stage of the data reception for all the P_{trans} levels with both unencrypted and encrypted communication are depicted in table 2 and table 3 respectively. The mean of the 20 readings is taken into consideration for the data collection. The energy consumption for each stage of the transmission is calculated with equation (1) where I is the average current consumption, R_{sh} is the shunt resistor of 9 Ω across which the XBee module is connected, and T is the duration of that stage.

$$EnergyConsumption = I^2 R_{\mathrm{sh}} T \tag{1}$$

From tables 2 and 3, we can see that for both the encrypted and unencrypted communication the energy consumption is highest with the transmission power level of 5 dBm and lowest with 1 dBm. As encrypted communication performs

Table 2. Current and energy consumption during each stage with unencrypted communication

Annotation of Fig. 6	Stages of Data Transmission /Recetion	Ptrans								
		1 dBm			3 dBm			5 dBm		
		Dura -tion (ms)	Average Current Consum- ption (mA)	Energy Consum -ption (mJ)	Dura -tion (ms)	Average Current Consum -ption (mA)	Energy Consum -ption (mJ)	Dura -tion (ms)	Average Current Consum -ption (mA)	Energy Consum -ption (mJ)
1	Idle Time Tidle	6.1	10.5	6.05	8.4	10.5	8.33	6.8	10.5	6.74
2	Data reception time trx1	0.9	36.0	10.49	0.9	38.2	11.81	0.9	47.9	18.58
3	Radio standby time Tsb	6.0	33.8	61.69	5.5	33.7	56.21	5.5	33.9	56.88
4	Data transmit time Ttx1	0.7	35.1	7.76	0.7	36.0	8.16	0.7	47.5	14.21
5	Data reception time trx2	4.0	35.0	44.10	4.0	36.0	46.65	4.8	46.0	91.41
6	Data transmit time Ttx2	2.1	33.9	22.23	2.1	36.0	25.07	2.1	40.0	30.24
Total energy consumption (mJ)				152.32			156.23			218.06

Table 3. Current and energy consumption during each stage with encrypted communication

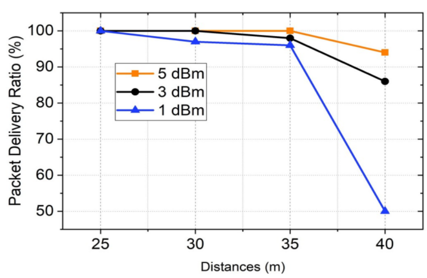
Annotation of Fig. 6	Stages of Data Transmission /Recetion	Ptrans								
		1 dBm			3 dBm			5 dBm		
		Dura -tion (ms)	Average Current Consum- ption (mA)	Energy Consum -ption (mJ)	Dura -tion (ms)	Average Current Consum -ption (mA)	Energy Consum -ption (mJ)	Dura -tion (ms)	Average Current Consum -ption (mA)	Energy Consum -ption (mJ)
1	Idle Time Tidle	7.3	10.5	7.29	10.0	10.75	10.4	10.75	10.75	11.18
2	Data reception time trx1	1	36.0	11.66	1.05	38.8	14.22	1.0	49.0	21.60
3	Radio standby time Tsb	5.4	34.0	56.18	5.2	34.0	54.1	6.25	34.0	65.02
4	Data transmit time Ttx1	0.8	35.3	8.97	0.8	38.4	10.61	0.8	49.8	17.85
5	Data reception time trx2	6.0	35.0	66.15	5.0	37.5	63.28	4.8	47.5	97.47
6	Data transmit time Ttx2	2.5	34.5	26.78	2.3	36.0	26.82	2.3	41.0	34.79
Total energy consumption (mJ)				177.03			179.43			247.91

functions like encrypting the data before transmission and decrypting the data after reception it consumes more energy for all the transmission levels in comparison with unencrypted communication. However, provided the security the AES encryption provides to the communication, this increased energy consumption for the encryption is considerable and is recommended for most indoor and outdoor IoT applications.

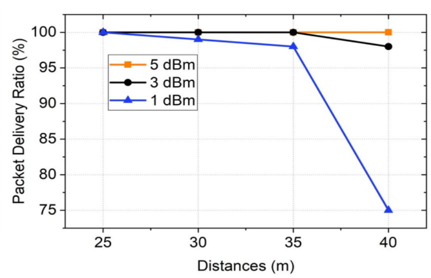
4.2 PDR performances at different $\mathbf{P_{Trans}}$

The packet delivery ratio can be represented by equation (2) which signifies what percentage of the sent data packet is received at the other end, a vital metric in WSN. If the PDR is bad, the network is prone to losing important data and it also increases the number of re-transmissions which eventually increases the power consumption, network traffic, and data overhead. For the indoor scenario, the PDR is measured by placing the coordinator at C1 and end nodes at E25, E30, E35, and E40, at a distance of 25 m, 30 m, 35 m, and 40 m from coordinator respectively, as presented in fig 4. 1000 data packets are sent from the coordinator to the end node at each location and from the number of received packets, PDR has been calculated. To equalize the effect of interference of other 2.4 GHz wireless technologies three different tests at a different time of the day have been carried out with the same setup and the mean of these three tests is taken into consideration. The transmission power is kept unchanged throughout the experiment and the whole process is repeated for each of the transmission power 1 dBm, 3 dBm, and 5 dBm. For the test in the outdoor scenario, the coordinator node is placed in an open parking lot and end nodes around it with direct LoS where the interference is also minimum. Fig 7 presents the variation of PDR at different distances with three different transmission power.

$$PDR = \frac{TotalPacketsReceived}{TotalPacketsSent} \tag{2}$$



(a)



(b)

Fig. 7. PDR vs distances with three different transmission power levels for (a) indoor and (b)outdoor scenario

With 1 dBm, at 30 m of transmission distance, the PDR decreased to 96% and 97% respectively for indoor and outdoor scenarios, which are still quite reliable. The PDR with 3 dBm starts decreasing after 30 m and reaches to 98% at 35 m with indoor scenario whereas it still performs with 100% PDR in outdoor. So, up to a transmission distance of 35 m, transmission with all the P_{Trans} performs reliably. However, the PDR performances degrade drastically at 40 m in the indoor scenario for the transmissions of all the power levels which are 94%, 86%, and 50% for 5 dBm, 3 dBm, and 1 dBm respectively. For the outdoor scenario, the PDR performances did not degrade so drastically: 96% and 75% with P_{Trans} of 3 dBm and 1dBm respectively, whereas the transmission with 5 dBm still performs with 100% PDR at a transmission distance of 40 m even. It is evident from the analysis that, the decrease of the PDR at 3 dBm is not as drastic as at 1 dBm. The transmission link with 1 dBm becomes quite unreliable at 40 m for both indoor and outdoor scenarios whereas for 5 dBm and 3 dBm it remains reasonably reliable with decent PDR in indoor and performs with even better PDR in outdoor. To optimize the energy consumption finding the optimized

P_{Trans} level with decent PDR and energy consumption is necessary through comparative analysis. This would also help to realize the trade-offs between P_{Trans}, PDR, and energy consumption and to find an optimized P_{Trans} level where it can perform both reliably and energy efficiently.

4.3 Evaluation of P_{Trans} levels for Energy Optimization

One of the interesting facts of both encrypted and unencrypted communication is that the difference of the total energy consumption between 1 dBm and 3 dBm P_{Trans} level is very little in comparison with the energy consumption difference between 3 dBm and 5 dBm. In fact, with encrypted communication, this difference of energy consumption between P_{Trans} levels of 1 dBm and 3 dBm is almost inconsiderable. On the contrary, if PDR for different P_{Trans} levels are analyzed, it is noticeable that PDR improved significantly from 1 dBm to 3 dBm. As with 1 dBm, at 40 m, the PDR drops down drastically to 75% and 50% respectively for outdoor and indoor environments, it is no longer reliable and beyond consideration. With 3 dBm, the PDR is 100% up to a transmission distance of 35 m and 30 m respectively for outdoor and indoor environments. And this drops down to 96% and 86% for outdoor and indoor environments respectively at a transmission distance of 40 m which is decent for most IoT applications. As with very little increase of energy consumption from 1 dBm to 3 dBm, the PDR improves radically, at 3 dBm transmission power level optimized energy consumption and performance are achieved . To improve the PDR further with a 5 dBm P_{Trans} level, the energy consumption increase significantly which will decrease the overall network life dramatically. Thus, considering the trade-off between PDR and energy efficiency, P_{Trans} level of 3 dBm achieve optimized energy consumption with decent transmission performance. The further detail works are presented in [15].

5 Conclusion

In this work, a case study is performed based on the real-world indoor and outdoor testbeds and measurements where the XBee S2C module is used as the transceiver. Aim of this work is to optimize the energy consumption of Zigbee communication with a comparative analysis of current, energy and power consumption with PDR at two different scenario: indoor and outdoor. The performance evaluation of PDR, current and energy consumption is also performed based on the practical data collected from the deployed indoor and outdoor scenario. This work draws out the trade-offs and performance limitations of these metrics which would benefit both academia and industry for designing and deploying Zigbee in both indoor and outdoor applications. The study shows the transmission power level of 3 dBm is the most optimized one in terms of PDR and energy consumption i.e the node lifetime. It is to be noted that the experiment that is conducted in this study is based on the XBee S2C module. However, the results can be generalized as most of the commercially available modules share the similar performance trend.

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