Performance Investigations of Frequency Agile Enabled TelosB Testbed in Home Area Network

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***Abstract*— Home area network (HAN) consists of several wireless technologies and appliances that normally operate in the ISM 2.4-GHz band. This spectrum sharing environment can introduce interference problems and prevent peaceful coexistence especially for low power radio devices. Therefore, it is significant that these radio devices are spectrum agile as to avoid harmful interference and utilize the spectrum reliably. In this paper, the performance of a ZigBee Frequency Agile (FA) technique implemented on *TelosB* testbed is studied experimentally. The measurement results show that this technique can effectively overcome the interference caused by the Wi-Fi-based devices by changing the operating frequency of the ZigBee's FA-enabled testbed to the channel with the least interference level. In addition, the testbed with FA achieves throughput improvement by about 86%, reduces delay by 73% and enhances transmission energy efficiency by 64% as compared to the testbed without FA. Consequently, this proves that the FA mechanism can guarantee a seamless communication as well as incurring low transmission cost.**

***Index Terms*— ZigBee, Frequency Agile, Interference Detection, Channel Evaluation, Interferences Mitigation, Loss Detection.**

I. INTRODUCTION

Home Area Networks (HAN) is a local area network that is developed from the need to facilitate communication and interoperability among digital devices present inside or within home area [1]. It is usually composed of homogeneous and heterogeneous wireless technologies such as Wi-Fi [2], ZigBee [3] and Bluetooth [4]. The Wi-Fi technology is typically used for internet applications including video streaming, Voice over Internet Protocol (VoIP) and video conferencing [2]. The ZigBee technology is normally used for low power consumption and low data-rate applications such as home automation, and smart-grid metering and demand response [3]. Whereas, the Bluetooth technology is employed for short range devices which include headphone, hands-free gadget, mouse and keyboard [4]. The use of these technologies is useful in eliminating cabling needs between electronic devices and accessories.

Generally, Wi-Fi, ZigBee and Bluetooth appliances operates in the 2.4-GHz Industrial, Scientific and Medical (ISM) band in a HAN network. Such coexistence of heterogeneous wireless technologies and appliances introduces interference issues and can be harmful to ZigBee-based devices due to their low transmit power as compared with Wi-Fi-based devices. The interference issue is further aggravated if the HAN also receives potential interfering signals from neighboring HANs.

There are significant interests on the coexistence issues among the research community, comprising of academia, industries and standardization bodies, particularly the coexistence between 802.15.4 and Wi-Fi. An experimental measurement reported in [5] showed that a *TelosB* mote experienced degraded packet delivery ratio (PDR) caused by a nearby Wi-Fi access point (AP). Similar effect of Wi-Fi on Body Area Network (BAN) which uses IEEE802.15.4 compliant *Tmote Sky* as the testbed was reported in [6]. Likewise, significant impact of the 802.15.4 coexistence with 802.11 b/g in term of the received signal strength indicator (RSSI) was demonstrated in [7]. Besides, the coexistence issues from other wireless devices such as the coexistence between 802.15.4 with microwave oven and Bluetooth are also addressed [8] [9].

Spectrum agile radio is a novel approach proposed by DARPA [10-12] with one of its main objectives is the interference preservation. Agile radio devices operate in an opportunistic way and will adapt to their interference management policies by modifying their transmission parameters, i.e., selecting other frequencies and transmission powers. ZigBee Alliance specifies an interference mitigation technique that allows a ZigBee network the capability to detect interference on the current operating frequency channel, sense other channels in the entire ISM band, and switch the network to a new channel that has the least interference level [13].

In this paper, ZigBee's frequency agile (FA) technique is adopted to be implemented on the *TelosB* wireless sensor network (WSN) testbed and improvised with loss detection mechanism to mitigate channel synchronization problem. A series of measurements of the FA technique is performed to gain information on its effectiveness of promoting peaceful coexistence and allowing each user of the band to fulfil its communication goals in a spectrum sharing environment. The focus of the experiments is the coexistence between the IEEE802.15.4 WSN and IEEE802.11 Wi-Fi radio systems in the 2.4 GHz license-free ISM frequency band.

The rest of the paper is organized as follows. Section II describes the ZigBee FA technique. Section III presents the layout area for measurements as well as the channel and frequency assignments for ZigBee-based motes and Wi-Fi system. Experimental results are presented in section IV. This is followed by discussion and analysis in section V. Section VI concludes the paper.

II. ZIGBEE FREQUENCY AGILITY TECHNIQUE

In this paper, the improvised FA operation implemented on the *TelosB* WSN testbed can be divided into four stages; channel detection, channel evaluation, interference mitigation and loss detection. Brief description of each is given in the following.

A. Interferences Detection

The ZigBee Coordinator will monitor the number of unsuccessful packets transferred by using Packet Error Rate (PER) analysis technique. If the ratio of the unsuccessful packets, *nFail* to the total number of sent packets, *nSent* is greater than twenty-five percent, then the interference is deduced. For this interference detection mechanism to work, the minimum number of packet sent must be at least twenty packets.

B. Channel Evaluation

Once the ZigBee Coordinator has deduced interference is present in current frequency channel, it will scan the energy level present or receive signal strength indicator (RSSI) and link quality indicator (LQI) at all ZigBee operating channels in the frequency range from 2405 to 2480 MHz.

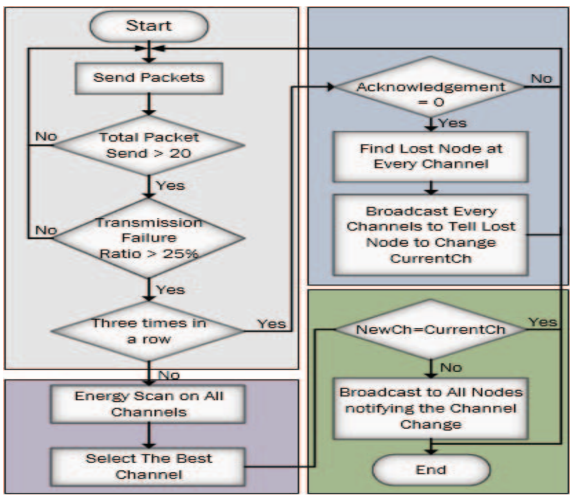
C. Interferences Mitigation

After the RSSI reading by the coordinator at all ZigBee operating channels, the coordinator then will decide on the best channel based on which has the lowest energy level. Then the Coordinator will broadcast to all ZigBee enabled devices (ZEDs) to request them to switch from the current channel to the new channel which has no or the least interference.

D. Loss Detection

The purpose of this phase is to identify lost ZEDs due to brief loss of power to operate, reset or traffic congestion. If the coordinator detects the same ZED is giving *nFail* greater than 25% three times in a row, it will then check for any acknowledgement from that ZED for all packets that have been transferred. If the acknowledgement is more than or equal to 1, it means that the ZED occupies the same channel as the coordinator and the coordinator only needs to find new channels with less interference. Consequently, a zero acknowledgement means that the particular ZED is totally lost from current channel. The Coordinator will then execute a search by broadcasting at every channel to instruct the lost ZED to switch to the current channel and this will continue until it is found.

The flow chart of ZigBee FA operation and the related processes in each stage is illustrated in Figure 1.



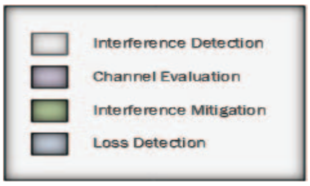


Figure 1: ZigBee Frequency Agility Operation.

III. EXPERIMENTAL LAYOUT AREA

Several experiments were carried out in an office environment to emulate HAN scenario. Figure 2 presents the layout area for measurements. As seen, the area is very crowded with computers, laptops, smartphones and *XBee* devices. An *XBee* device shares similar features with *TelosB* as it communicates on low power and at the same frequency band of 2.4 GHz [14]. Additionally, every personal computer (PC) and laptop as well as some smartphones are connected to the Wi-Fi access point (AP). The experiments are carried out using four *TelosB*, one act as Coordinator and the rest acts as ZEDs. The Coordinator is used to monitor the communication among motes to keep reliable communication with the least interference.

The channel distributions for IEEE 802.11b/g/n and IEEE 802.15.4 cover frequency range of 2412-2472 MHz and 2405-2480 MHz, respectively.

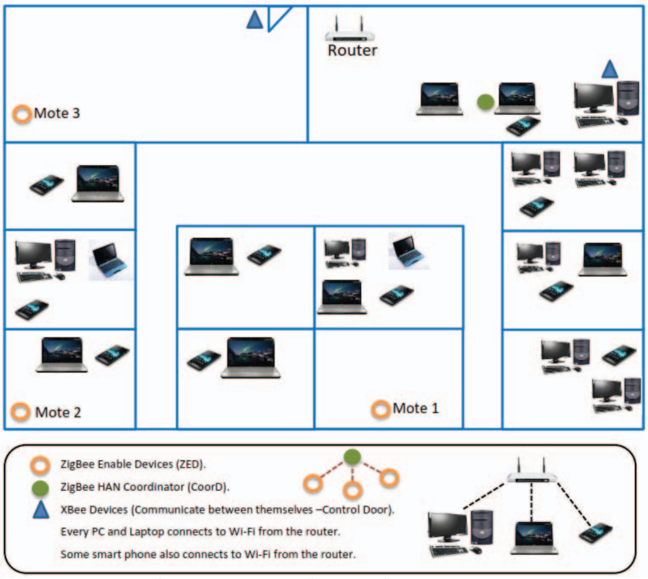


Figure 2: Experimental Layout Area.

IV. EXPERIMENTAL RESULTS

A series of measurements is taken from several experimental setups. For performance study of ZigBee FA technique, these metrics are considered:

Packet Error Rate (PER): The PER is the ratio of the unsuccessful packets to the total number of sent packets. This is calculated at the network layer.

Received Signal Strength Indicator (RSSI): The RSSI is the energy measured at the radio frequency (RF) pin of the mote. It is used to indicate the energy level of the channel or the received packet including acknowledgment. Lower value of RSSI indicates lesser interference [15].

Link Quality Indicator (LQI): The LQI is a characterisation of the strength or quality of received packet. A correlation value of ~110 indicates a maximum quality frame while a value of ~50 is typically the lowest quality frames detected by *CC2420* [16].

Measurements results are further explained in the following.

A. *Experiment 1*

In this experiment, features of FA were not yet implemented because the objectives of this experiment are to assess channel availability from channel 11 – 26 and to determine suitable power to be used. It is the prerequisite stage before implementing the FA technique in the testbed.

The measurements in terms of RSSI and LQI for Mote 1 are shown in Figures 3 and 4, respectively. The RSSI value is in dBm and there is an RSSI offset for *TelosB* mote provided by the manufacturer that is -45 dBm [16]. LQI parameter is unit-less. It can be deduced from the fluctuations for both RSSI and LQI readings that most channels are not stable. Only a few, such as channels 14, 15, 16, 17, 18 and 20, show some stability. The power is represented by respective levels from 1-31, with increasing levels translated into increasing power consumption as shown in Table 1 [16]. It can be concluded from Figures 3 and 4 that level 7 is the minimum required power for data transmission. However, power at level 18 displays some disturbances. This may be due to the busy traffic caused by Wi-Fi network.

Table 1: Output Power level as specified by TelosB manufacturer

PA_LEVEL	Output Power [dBm]	Current Consumption [mA]
31	0	17.4
27	-1	16.5
23	-3	15.2
19	-5	13.9
15	-7	12.5
11	-10	11.2
7	-15	9.9
3	-25	8.5

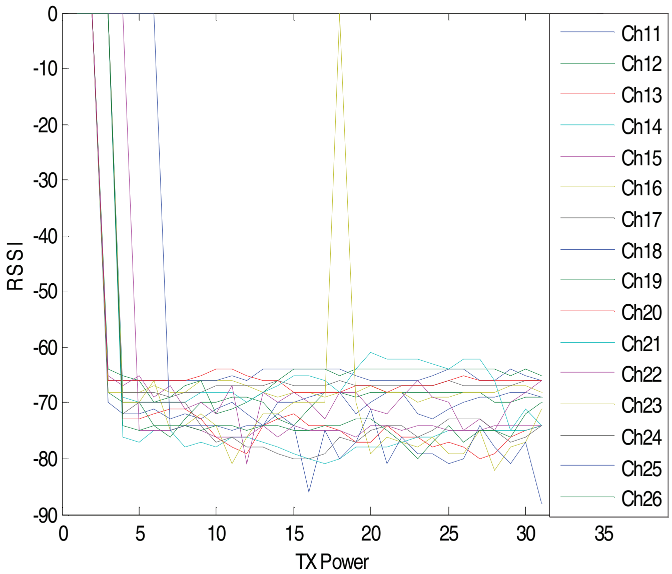


Figure 3: RSSI measurements for Mote 1.

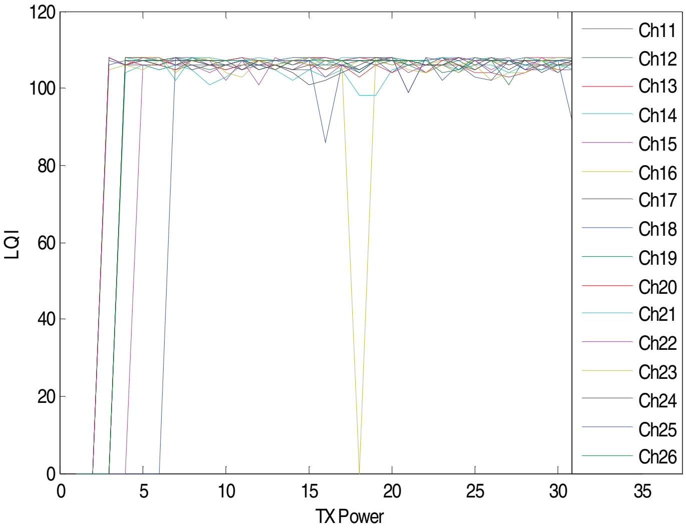


Figure 4: LQI measurements for Mote 1.

For Mote 2, the RSSI and LQI measurements are shown in Figures 5 and 6, respectively. All channels are seen to be stable for the RSSI measurement. However, for LQI measurement, there are fluctuations for channel 11, 12, 14 and 24 which indicate poor quality of frames at certain power levels. Moreover, the fluctuation from the affected channels seems to occur at different power level. Power at level 10 is observed to be the minimum requirement for data transmission. It can be concluded that Mote 2 possesses stability for all channels as the nearby PC and laptop do not perform internet access during the measurement period.

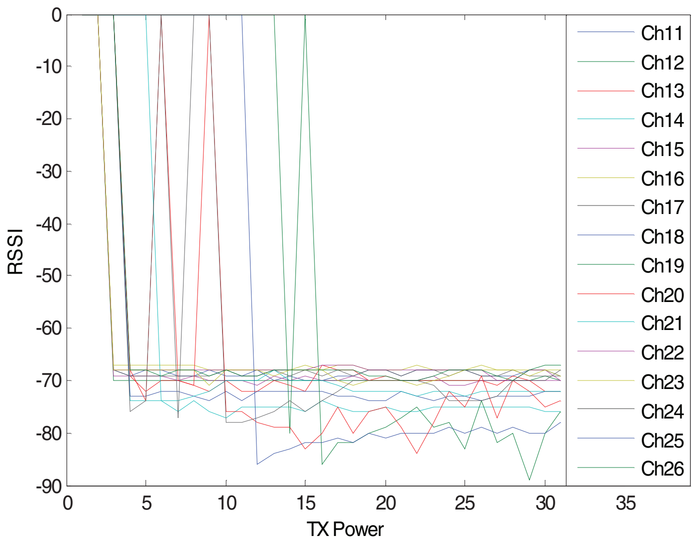


Figure 5: RSSI measurements for Mote 2.

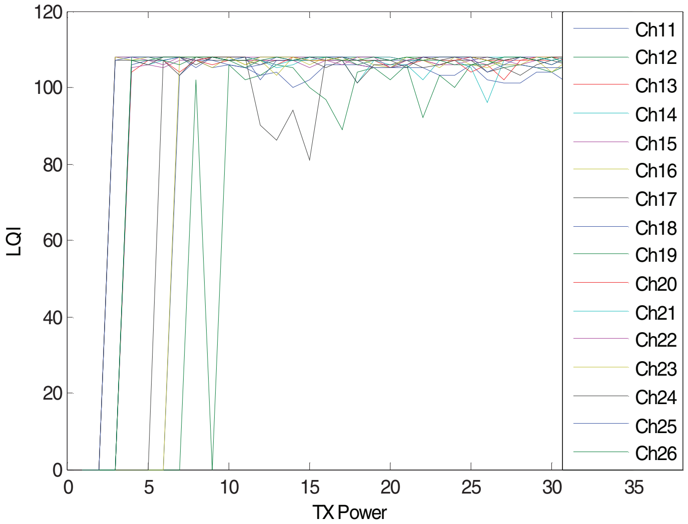


Figure 6: LQI measurements for Mote 2.

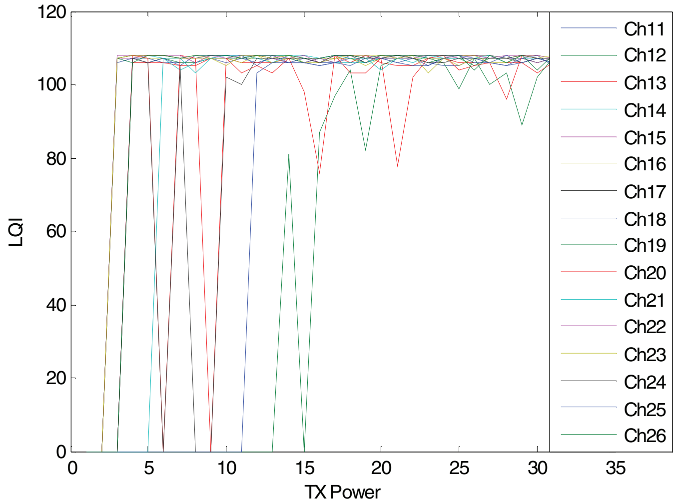


Figure 8: LQI measurements for Mote 3.

As noted from Figures 7 and 8, most of the channels for Mote 3 exhibit stability except channels 19, 20 and 24. The minimum required power is perceived to be at level 16. The unstable channel is due to the router or AP located in between Mote 3 and the Coordinator which affects their communications.

Although the experimental area and the distance between motes are not large, each node displays different results. Furthermore, it is determined from observations that the suitable power level for data transmission is at level 20 as there are no disturbances seen after that level and therefore considered reliable. Due to different RSSI and LQI performances captured at each mote as well as power level fluctuations and interruptions across the channels, it can be established that FA is very much needed in order to maintain a reliable and seamless communication in HAN.

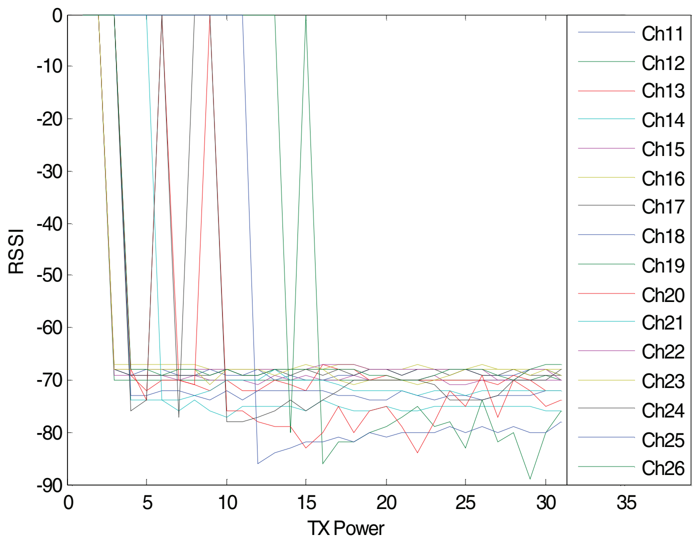


Figure 7: RSSI measurements for Mote 3.

B. *Experiment 2*

In this experiment, two features of FA that are interference detection and channel evaluation were implemented in the testbed and their performances are investigated. The power was fixed at level 20 and the packet size was also fixed at 50 packets per channel for each mote.

Table 2 presents the results for PER readings for a trial run. Reading of less than *1* indicates an error, while a perfect *1* reading indicates perfect communication with no error. With FA interference detection in place, only minor errors are detected in some channels at *0.75* which implies that most communication can be maintained satisfactorily.

Table 2: PER and best channel for Sample 1.

CurrentCh	PER			BestCh
	Mote 1	Mote 2	Mote 3	
11	1	1	1	11
12	0.75	1	1	16
13	0.65	1	1	11
14	1	1	1	11
15	1	0.952	1	11
16	1	1	1	12
17	1	1	0.72	11
18	1	1	1	11
19	0.75	1	0.75	11
20	1	1	1	14
21	1	1	1	11
22	1	1	1	11
23	1	1	1	11
24	0.75	1	1	11
25	1	1	1	11
26	1	1	1	11

Channel evaluation is needed only for two occasions; sample 1 from Mote 1 at channel 13 and Mote 3 at channel 17 which received PER reading below than *0.75*. These errors of more than 25 percent have the potential to produce unreliable communication. The channel evaluation stage is thus enabled for this occasion to search for other channel with less interference. For the trial run, channels 11, 12, 14 and 16 are randomly selected as the best channel for the motes. Consequently, channel 11 claims to be the best during the measurement period for being selected 13 out of 16 times.

It can be confirmed from the results that FA technique in the motes is highly required in order to send the data reliably over time, frequency and space. In addition, it is shown that the FA features of interference detection and channel evaluation have performed well in ensuring that. In the next experiment, the remaining FA features, interference mitigation and loss detection will be added and investigated.

C. Experiment 3

For this experiment, full FA features were implemented. This experiment is more complex and difficult compared to the previous two as it requires an experimental area with high interference from the surrounding APs. In order to identify the APs' activities in the experimental area, XIRRUS software is used. The findings show six APs detected within the experimental area at varying signal strength levels and each AP detected is using different channel and frequency assignments. To introduce high interference to this area, an interferer system made of two PCs, one as a server and another one as a client, as well as JPERF software for data transfer are utilized. Both PCs will communicate peer-to-peer wirelessly through a nearby AP. The server will transmit packet to the client using UDP protocol via the AP with an amount of 20Mbps to induce interference in the network.

The results of this experiment are illustrated in Figure 9. The blue line represents *TelosB* mote which can automatically switch channel and green line is the Wi-Fi AP, which is flooded with data transfer to induce interference. The flooded channel is manually changed from one to another via AP website. As observed, the implemented FA technique in the mote has served well by reacting effectively by switching channel immediately once the interference is detected. Every time the AP switches channel at almost the same frequency with the *TelosB* mote, the mote will automatically switch to another channel to avoid interference from the Wi-Fi AP. Channel 11 remains as the best as it is chosen to be accessed at most times after channel evaluation. The interference mitigation feature also is functioning well for decision making on channel switching.

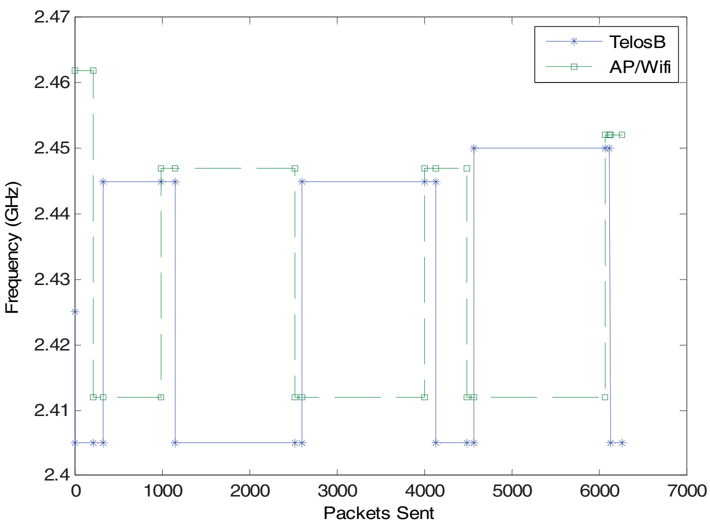


Figure 9: Channel occupied by *TelosB* and AP.

For loss detection mechanism, there are many trial runs being done where every node was reset manually to check whether the Coordinator can find the lost mote or not. The result is very convincing as the lost mote is found every time it was reset.

V. ANALYSIS OF THE RESULTS

The performance from the series of measurements are analysed in term of achieved throughput and delay. The throughput is the amount of correctly received data in bits per second [17 - 19] and is given by the formula:

$$Throughput, P = \frac{size\ of\ data\ (bits)}{time\ file\ transferred\ (s)} - - - (1)$$

Table 6 shows the performance comparison between the testbed with and without FA. For example, if each packet sent contains 40 bytes of data, from Table 3:
Throughput for testbed without FA, P1:

$$P1 = \frac{40\ x\ 8\ x\ 258}{501.53} = 165\ bits/s\ - - - (2)$$

Throughput for testbed with FA, P2:

$$P2 = \frac{40\ x\ 8\ x\ 488}{132.93} = 1175\ bits/s\ - - - (3)$$

P2 is improved by 85.96% compared to P1 which proves that the testbed with FA can guarantee higher data transmission rate than the testbed without FA.

Table 3: Comparison of testbed with and without FA

Parameters	Without FA	With FA
Packet sent	500	500
Error	242	12
Received Packets	258	488
Time (s)	501.53	132.93

It is also observed that, for ZigBee without FA, the communication for the testbed requires many retries in order to send the packets. While, for ZigBee with FA, retries are only needed during interference and only at the beginning because there will be a channel switch immediately afterwards to mitigate the interference. In addition, it is shown in Table 3 that FA improves the system by reducing the delay by 73.5%.

The error rate is reduced as well as less retries is required with the implementation of FA as illustrated in Figure 10. It is extracted from the figure that the total number of transmission to send 500 packets is 547 and 1538 for testbed with and without FA, respectively. Furthermore, the experiments used power at level 20 to send the packets and from Table 1, this indicates power level of almost -4.5dBm or 0.35mW is used in every transmission. Therefore, the transmission power used by testbed without FA will be:

$$P(t) = 1538 \times 0.35m = 538.3mW\quad - - - (4)$$

While power used by testbed with FA is given by:

$$P(t) = 547 \times 0.35m = 191.45mW\quad - - - (5)$$

The calculation gives a reduced power consumed for transmission of about 64% for testbed with FA compared to the one without FA. In summary, the system cost is minimized and is more efficient due to increased throughput, lower delay, reduced transmission-energy consumed from having less retries as a result of less error.

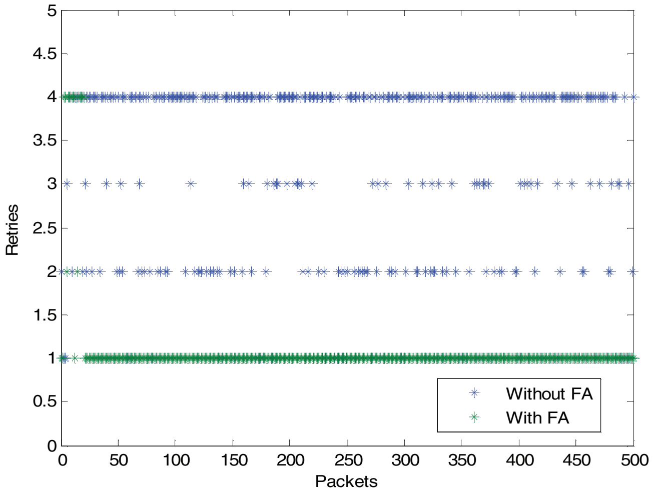


Figure 10: Comparison of number of retries between testbed with and without FA.

VI. Conclusion

The performance studies of ZigBee FA complemented with loss detection mechanism on *TelosB* testbed in HAN demonstrate that it can provide reliable and seamless communication among ZigBee-based devices. It can detect interference, evaluate the channel status and mitigate the interference by switching channel to the selected best channel. The findings also show that the scheme promotes cost effective system as it incurs low power consumption and significantly improves the throughput and delay. For future works, this FA technique can be implemented in Wi-Fi AP for improved spectrum utilization and reliable wireless communication during busy traffic.

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