Adaptive Transmit Power Adjustment Technique for ZigBee Network Under Wi-Fi Interference

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Abstract. Energy consumption is one of the most fundamental constraints in wireless sensor network (WSN) design. While data transmission is usually the most energy consuming event, minimizing the transmit power under the condition of satisfying the required packet transmission quality would be an important and effective strategy for reducing energy consumption. In this paper, a novel Adaptive Transmit Power Adjustment technique (ATPA) for ZigBee network under Wi-Fi interference is proposed and implemented in the Crossbow MICAz motes of our testbed. The proposed ATPA technique dynamically and rapidly adapts to the varying interference from the collocated wireless local area network (WLAN) and selects optimal transmit power level that not only decreases the energy consumption of packet transmissions, but also maintains the required packet loss rate (PLR). The effectiveness of ATPA has been validated through the comprehensive performance evaluation experiments conducted on our testbed.

Keywords: Wireless sensor network · Energy consumption · Coexistence · Transmit power control

1 Introduction

Most sensor nodes in wireless sensor networks (WSNs) are powered by batteries, which could be difficult or impossible to replace (e.g. military applications in battlefield environment). Hence, it is very important to use energy in an efficient way so as to extend the lifetime of sensor nodes and WSN as a whole. Since data transmission is one of the most significant factors of energy consumption in sensor nodes, it is advisable to seek effective strategies to minimize the transmit power of sensor nodes on condition that satisfactory quality of communication between sensor nodes can be maintained. Studies (e.g. [1]-[3]) have shown that the low-power ZigBee based WSN are particularly vulnerable to the interference of collocated Wi-Fi wireless local area networks (WLAN) due to the considerably higher transmit power of Wi-Fi devices and their pervasive deployment. With such time varying coexistence interference, it is crucial for sensor nodes to adaptively select appropriate transmit power level, which affects the signal to interference and noise ratio (SINR) of the received packets, thus

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the communication link's quality. Furthermore, the choice of transmit power for each node in a mesh based WSN determines its set of neighbors. Based on these two facts, the transmit power adjustment schemes in WSN can be mainly classified into two categories: transmission range based topology control and link quality control.

The target for transmission range based topology control is to choose the optimal transmit power for each node, so that the global network connectivity can be maintained and energy metrics (e.g. network lifetime) can be optimized. Several topology control algorithms [4-8] have been developed that select the optimal power for each node in WSN to maintain the network connectivity, i.e. each node is able to communicate to any other node in the WSN via single hop or multi-hop. These solutions derive the static optimal transmit powers at the stage of initial deployment based on the network graph or node density. However, due to the background noise (e.g. thermal noise or environmental noise) and the interference from other wireless networks, the quality of WSN communication links varies with time and environment. The optimal transmit power calculated for fixed or initial channel conditions and a fixed network topology cannot guarantee the communication links' quality.

In recent years, some transmit power control schemes were designed for adapting to the external interference/noise level and adjusting the transmit power to the minimal level that can satisfy the required link quality. Some dynamic transmit power control mechanisms [9-13] adjust the power based on the RSSI readings of the received ZigBee packets. However, these RSSI readings may be the superposition of ZigBee signal and interference. In the case of strong interference, the RSSI reading does not reflect reliably the link's quality. In [14], two power control schemes, named as MIAD PC and PER PC, are proposed. In MIAD PC, the transmit power is increased after a packet loss and decreased after a successful packet reception. When frequent packet loss occurs, this method may lead to unstable operation. PER PC determines the background noise level with periodical measurements of RSSI and then derives the SINR based on the applied channel models (AWGN model or Rayleigh model). With the derived SINR, optimal transmit power is obtained. This approach requires complicated operations and calculation, and is not easy to implement at the resource limited ZigBee motes.

In this paper, a novel and efficient Adaptive Transmit Power Adjustment (ATPA) technique, capable of responding promptly to the changing external interference conditions, is proposed. The ATPA technique estimates the link quality based on the periodically calculated packet loss rate (PLR), and adjusts the transmit power accordingly to meet the PLR requirement. The proposed ATPA was implemented in the Crossbow MICAz motes of our testbed, and evaluated experimentally using the results collected through extensive experimentation. The results show that the ATPA technique improves the energy efficiency of the ZigBee packet transmission while maintaining the predefined maximum tolerable PLR of the application.

The remaining part of this paper is structured as follows. In Section 2, the testbed and system parameters are introduced. Section 3 provides a detailed description of the proposed ATPA technique. In Section 4, a series of comprehensive experiments are performed to evaluate the performance of ATAP technique under Wi-Fi interference and the acquired results are presented. Finally, conclusions are drawn in Section 5.

2 Testbed and Experiment Setup

In this study, we established a testbed using off-the-shelf computing and communication devices and carried out extensive experiments to assess the effectiveness of the proposed technique. By implementing our proposed technique as firmware running on commercially available devices, we ensure the proposed technique is easily implementable and fast deployable. And by performing experimental studies, we get more realistic performance evaluation results without leaving the impact of certain hidden factors on the performance unaccounted or adopting any simplified mathematical models or assumptions, which are often inevitable in theoretical analysis and computer simulations.

The experimental network is formed by ZigBee motes and Wi-Fi nodes. The collocated interfering WLAN consists of an IEEE 802.11 b/g/n wireless router (WR) (ASUS RT-N16), a Dell Inspiron 1545 laptop with Dell Wireless 1515 (IEEE 802.11 a/g/n) WLAN half mini-Card installed, and a Toshiba Satellite 2450 laptop connected to one of the Ethernet ports of the WR. WR is used as Wi-Fi traffic source in our testbed because it provides stable transmit power. The Toshiba laptop runs the Distributed Internet Traffic Generator (D-ITG) [15] and generates traffic with different packet payload, packet rate and inter-departure time (IDT) distribution, which are then fed into the WR for generating various interfering 802.11g Wi-Fi traffic that is having the Dell laptop as destination node. One Crossbow MICAz mote equipped with IEEE 802.15.4-compliant CC2420 transceiver is used as ZigBee client, transmitting IEEE 802.15.4 traffic to the ZigBee coordinator. Another MICAz mote installed on a Crossbow MIB600 programming board is functioning as coordinator, receiving data from the client. A PC is connected to the MIB600 board, collecting the received data from the ZigBee coordinator.

Custom ZigBee client and coordinator software programs were developed and run on the MICAz motes. The client software generates ZigBee traffic with different packet size, generation rate and IDT distribution, and responds to feedbacks from the coordinator (e.g. packet retransmission or transmit power adjustment). The coordinator software collects the received data packets, calculates the PLR, and sends acknowledgements (ACKs) or other feedback messages (e.g. transmit power adjustment commands). The client and coordinator software also perform statistic tasks such as calculating the number of transmitted or retransmitted packets, received packets, cancellation packets, and so on.

Fig. 1 illustrates the testbed setup used for studying the performance of ATPA under Wi-Fi interference. The distance between the WR and the ZigBee source mote is 1m and the distance between the Dell laptop and the ZigBee coordinator is 2m. There is a strong line-of-sight path between the ZigBee source mote and coordinator, with a distance of 1.5m. The Wi-Fi router uses 50 mW transmitting and generates IEEE 802.11g traffic; the transmitting mote can flexibly adjust its transmit power.

By scanning all the Wi-Fi channels, we determine that ZigBee channel 20 (2.449-2.451GHz) is not “contaminated” by interference from any other Wi-Fi access points in the building. To minimize the interference from other coexisting WLANs, ZigBee channel 20 is used as our ZigBee operating channel. In addition, since ZigBee channel 20 is located within the range of Wi-Fi’s channel 9 (2.441-2.463GHz) where the power spectral density is the strongest, Wi-Fi channel 9 is used with the WR of our testbed to investigate the ZigBee packet transmission performance in the worst case scenario.

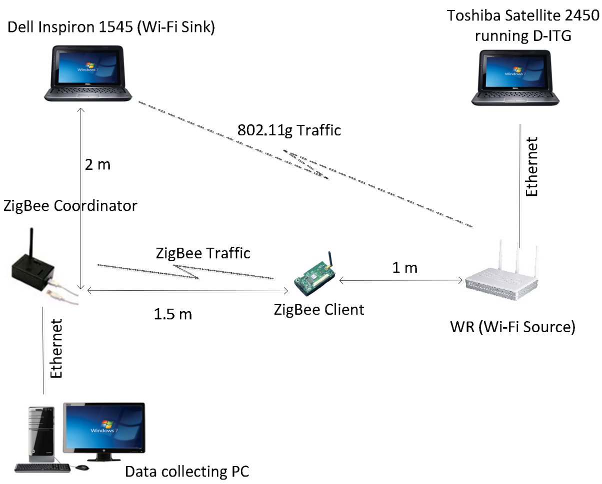

Fig. 1. Testbed setup for studying Zigbee packet transmission under collocated Wi-Fi interference

3 Adaptive Power Adjustment Technique

The MICAz motes can be programmed to operate at different levels of RF power, which enables the implementation of adaptive transmit power adjustment technique, i.e., dynamically adjusting the transmit power according to the strength of the time varying external interference. Table 1 shows the different programmable power levels supported by the CC2420 transceiver in MICAz motes and their corresponding current consumptions [16].

Table 1. Output power settings and current consumptions [16]

Power Level Index	Output Power [dBm]	Current Consumption [mA]
8	0	17.4
7	-1	16.5
6	-3	15.2
5	-5	13.9
4	-7	12.5
3	-10	11.2
2	-15	9.9
1	-25	8.5

As shown in Table 1, MICAz offers a considerable wide range for adjusting the transmit power. It is evident that the SINR decreases when the ZigBee mote transmits with lower power, which consequently leads to more packet losses. Our experimental performance evaluation results, which will be presented in the next section, also show that there is a significant difference between PLRs when the mote operates at the minimum and the maximum power under Wi-Fi interference. From the energy efficiency perspective, the MICAz mote should work at the lowest possible power level as long as the PLR requirement of the sensing application can be met. As external interference is unpredictable and varying with time, for a sensing application with a PLR requirement, an adaptive power control mechanism should be developed to adjust the transmit power according to the external interference. Ideally, when the ZigBee communication link suffers from varying external interference, the motes should be able to adjust their transmit power adaptively according to the interference level and the PLR requirement set by the sensing application, i.e., increase the transmit power when the PLR exceeds the required threshold value due to strong interference, or reduce the transmit power when the interference decreases as long as the PLR requirement can be satisfied. The proposed ATPA is designed to provide such timely power adjustment based on the changing PLR values. The flowchart of the proposed ATPA is illustrated in Fig. 2.

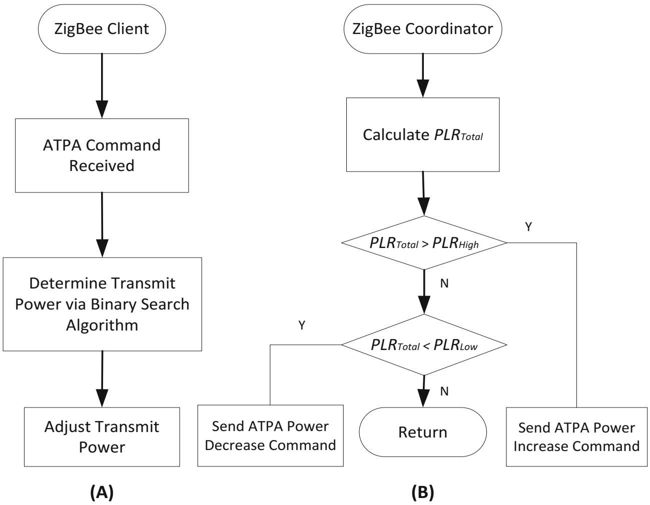

Fig. 2. Flowchart of ATPA: (A) ZigBee Client (B) ZigBee Coordinator

In the proposed ATPA scheme, the required PLR of a specific sensing application is set at the ZigBee coordinator's firmware. To avoid frequent change of transmit power, two PLR threshold values are introduced, denoted as PLR_{High} and PLR_{Low}, respectively. PLR_{High} has the value of the required PLR, while PLR_{Low} is set to a lower value for indicating that the external interference or noise has decreased to a point that the transmit power can be reduced to improve energy efficiency. The motes maintain the transmit power when the measured PLR falls between PLR_{High} and PLR_{Low}. T_{update} is the time interval for calculating and updating the PLR value. The value of T_{update} depends on the needs of dealing with the changing Wi-Fi interference and the sensing application's tolerance of PLR that exceeds limit occasionally. For example, in an environment with very stable WLAN traffic profile, T_{update} can be assigned a large value so as to reduce the frequency of power adjustment. After every T_{update} (e.g. 10 seconds), the coordinator calculates the number of packet losses, denoted as PLR_{Total}:

$$PLR_{Total} = 1 - \frac{N_R}{DSN_{Last} - DSN_{First}} , \qquad (1)$$

where N_R is the number of received packets within T_{update}, DSN_{First} and DSN_{Last} are the data sequence numbers (DSN) for the first and last received packets during T_{update}, respectively. If PLR_{Total} is higher than PLR_{High}, an ATPA command packet is sent to the ZigBee client to increase its transmit power level. Otherwise, if PLR_{Total} is lower than PLR_{Low}, an ATPA command packet with a message to reduce the transmit power is sent. It is noted that ATPA command packets are sent at the maximum transmit power so as to ensure higher delivery rate.

The ZigBee client mote first selects the maximum power level (0 dBm) as the initial transmit power. During the running time, it adjusts its transmit power level based on the received ATPA commands. Considering the power level adjustment happens in every T_{update} seconds, a binary search algorithm is applied to speed up the adjustment mechanism in finding the lowest transmit power that satisfies the PLR requirement. The pseudo code of ATPA binary search scheme is depicted in Fig. 3. As shown in Table 1, each output power level is represented with an integer index. We denote L_{High} and L_{Low} as the two search index limits; $Index_{Max}$, $Index_{Min}$, and $Index_{Cur}$ as the maximum, minimum and current power level index, respectively.

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Input: L_High, L_Low, Index_Max, Index_Min, and Index_Cur
Initial phase:  L_High = Index_Max ;  L_Low = Index_Min ;
If to increase transmit power:
   If (L_High = L_Low)      { L_High = Index_Max };
   L_Low = Index_Cur ;
   Index_Cur = ⌈(L_High + L_Low) / 2⌉;
If to decrease transmit power:
   If (L_High = L_Low)      { L_Low = Index_Min };
   L_High = Index_Cur ;
   Index_Cur = ⌊(L_High + L_Low) / 2⌋;
```

Fig. 3. Binary search algorithm of ATPA

As shown in Fig.3, the binary search algorithm is implemented with two index limits, i.e., L_{High} and L_{Low} (initialized with $Index_{Max}$ and $Index_{Min}$, respectively), which progressively narrow the search range. If the received ATPA command is to increase the transmit power, the current operating power level index, $Index_{Cur}$, is selected as L_{Low}. On the other hand, if the received ATPA command is to decrease the transmit power, the $Index_{Cur}$ is chosen as L_{High}. The intermediate power level index between the L_{High} and L_{Low} is obtained and the corresponding transmit power is selected at the ZigBee client. Compared to linear search that adjusts the power level by level, whose worst case requires N-1 iterations (N is the number of the power levels supported in the mote.), the binary search is substantially more efficient with a worst case of $\lceil log_2(N) \rceil$.

The ZigBee coordinator sends back ATPA commands to trigger the binary search operation and power adjustment until the PLR_{Total} is between the two PLR boundaries, i.e., PLR_{High} and PLR_{Low}. Once the external interference changes and the PLR requirement is not satisfied any more, a new ATPA power increase/decrease command will be generated and transmitted to trigger another binary search operation and transmit power adjustment.

4 Performance Evaluation Results and Discussion

In order to validate the performance improvement of the proposed ATPA mechanism, we performed an extensive set of experiments using the testbed shown in Fig. 1. For comparison, ZigBee's performance was also assessed when the transmit power of the ZigBee client mote was set at the maximum or minimum values. PLR and the energy consumption of the CC2420 transceiver in the packet transmission process were evaluated. For transmitting each ZigBee packet, the energy consumed by CC2420 can be expressed as:

$$E = A_i * V_{cc2420} * \frac{L_Z}{R_Z}, \quad (2)$$

with A_i denoting the current consumption of power level i (shown in Table 1), V_{CC2420} the supply voltage of 1.8V, L_Z the ZigBee packet length, and R_Z the transmit bit rate. Our custom-made ZigBee client firmware calculates the number of ZigBee packets transmitted at each power level so that the total energy consumption in the experiment can be calculated. In each experiment, the ZigBee client mote is programmed to send out 10000 data packets with 100 bytes/packet at 30ms intervals. The D-ITG generates UDP traffic with different segment payload, segment rate and IDT distribution, which are converted to varying IEEE 802.11g Wi-Fi interference by the WR. The corresponding results are illustrated and discussed in Figs. 4 to 9. All the data points are marked with a 95% confidence interval.

In Fig. 4 and Fig. 5, ZigBee's performance evaluation results are shown when the transmitted packets are not acknowledged, thus there is no packet retransmission. The required PLR (PLR_{High}) is set to be 10% and PLR_{Low} is assigned the value of 9%. D-ITG generated UDP traffic with constant segment IDT, payload size of 1400 bytes and different segment generation rates: 300 segments/second (Test 1), 500 segments/second (Test 2), and a combination of 300 segments/second in the first half of the experiment and 500 segments/second for the remaining half (Test 3).

As shown in Figs. 4 and 5, although using the minimum transmit power consumes the minimum energy for packet transmission, the ZigBee mote suffers from severe packet losses, resulting in PLRs far beyond the required value. While operating at the maximum power achieves the best PLR, the transmitting mote consumes the most energy. Obviously, if the PLR requirement has already been met, there is little or no use for ZigBee mote to sacrifice more energy in exchange of further PLR improvement. The proposed ATPA provides a simple but efficient trade-off algorithm to reduce the energy consumption while maintaining the required PLR. It can be observed from Fig. 5 that compared to maximum transmit power, ATPA reduces energy consumption from ~15% (Test 2) to ~ 33% (Test 1) depending on the external interference level; the less the interference, the more the energy savings are. In addition, ATPA handles the changing Wi-Fi interference very well as demonstrated in Test 3. The Wi-Fi traffic in Test 3 is an equal combination of traffic used in Test 1 and Test 2. Thus, in Fig. 4, the PLRs of minimum and maximum transmit power in Test 3 have values larger than those in Test 1 but smaller than those in Test 2. Since the transmit power adjustment of ATPA is for saving energy while maintaining the required PLR, the PLRs of ATPA in all three tests are about the same, but the energy consumption of ATPA in Test 3 is between the corresponding values in Test 1 and Test 2, which shows the ATPA adjusts the transmit power when interference changes. ATPA increases transmit power when interference increases so as to maintain the required PLR. ATPA could be particularly effective with bursty interference because it could temporarily boost transmit power when there is increased interference and decrease transmit power when interference goes down.

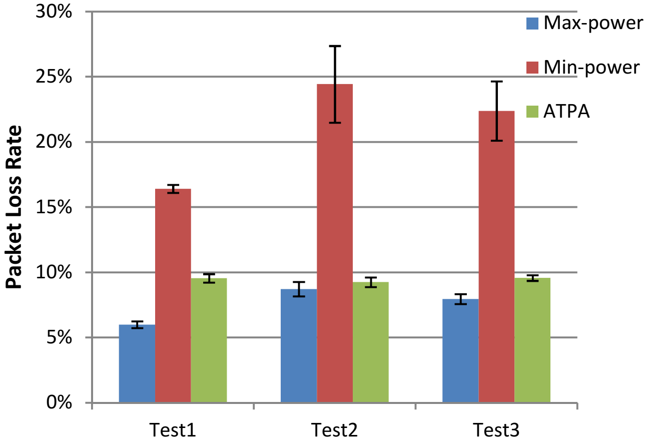

Fig. 4. Packet loss rate comparison of ZigBee without use of packet retransmission under interfering UDP traffic with different packet rates

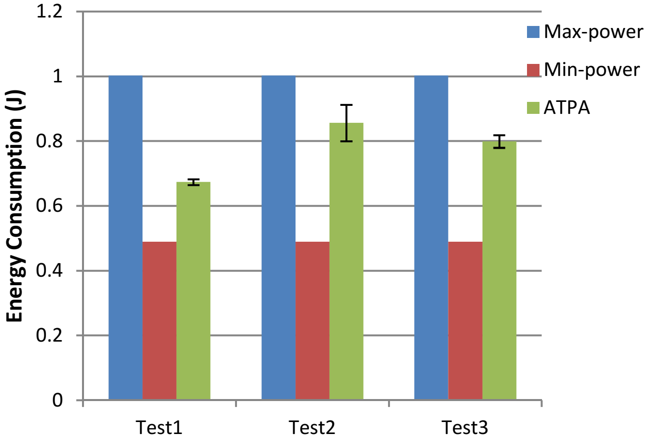

Fig. 5. Energy consumption comparison of ZigBee without use of packet retransmission under interfering UDP traffic with different packet rates

In Figs. 6 - 9, the ZigBee's performance is evaluated when allowing one ZigBee packet retransmission. The results of combining ATPA with our earlier proposed ACK with Interference Detection (ACK-ID) scheme [17] are also illustrated for comparison purposes. By performing interference detection before sending out ACK packets, ACK-ID can effectively reduce ACK losses and ZigBee packet retransmissions, thus consequently reduce the energy consumption in transmitting packets. The PLR_{High} and PLR_{Low} have assigned values of 3% and 2%, respectively. The assigned PLR threshold values are much lower compared to those used in the experiments of Figs. 4 and 5. This is because packet retransmission is adopted in this set of experiments, which significantly decreases PLR. In Fig. 6 and Fig. 7, D-ITG is set to generate traffic with constant UDP segment IDT, payload size of 1400 bytes and different segment rates: 500 segments/second (Test 4), 700 segments/second (Test 5), and a combined traffic with 500

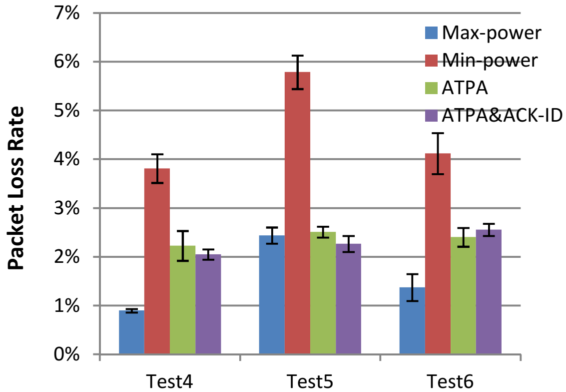

Fig. 6. Packet loss rate comparison of ZigBee with use of packet retransmission under interfering UDP traffic with different packet rates

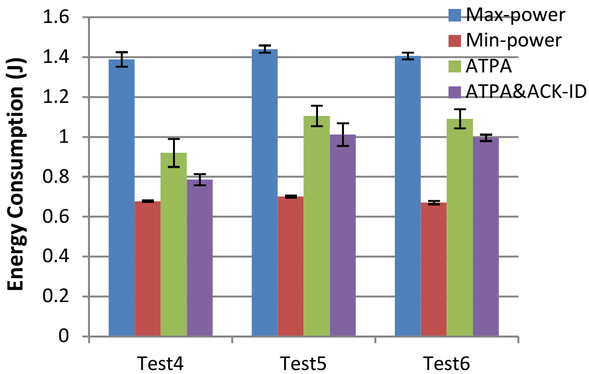

Fig. 7. Energy consumption comparison of ZigBee with use of packet retransmission under interfering UDP traffic with different packet rates

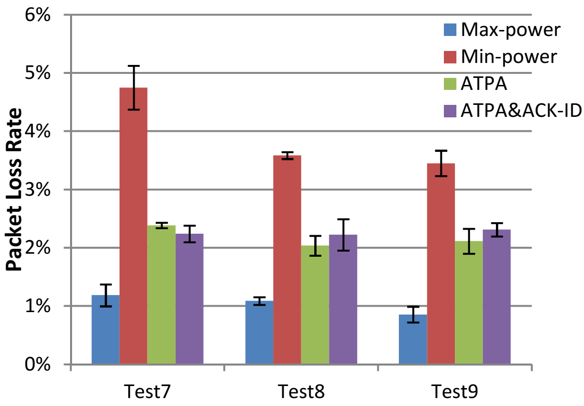

Fig. 8. Packet loss rate comparison of ZigBee with use of retransmission under interfering UDP traffic with payload sizes and arrival rates following three different random distributions

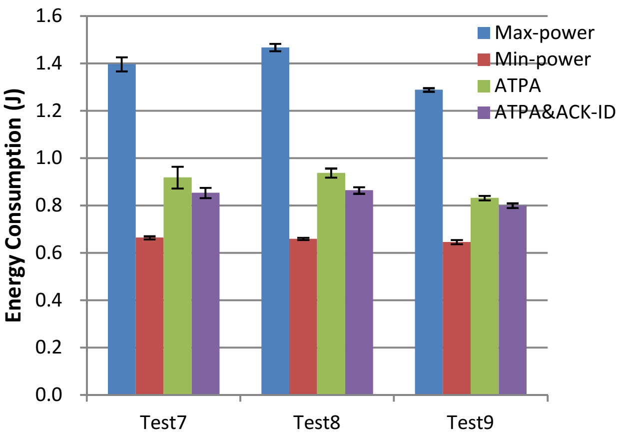

Fig. 9. Energy consumption comparison of ZigBee with use of packet retransmission under interfering UDP traffic with payload sizes and arrival rates following three different random distributions

segments/second in the first half of the experiment and 700 segments/second in the remaining half (Test 6). For the tests shown in Fig. 8 and Fig. 9, the UDP segment's payload size and IDT are both following three different random distributions, i.e., Poisson (Test 7), Uniform (Test 8), and Exponential (Test 9), with mean payload size of 1200 bytes and arrival rate of 600 segments/second. More specifically, uniform distributed traffic has a UDP payload size between 1000 to 1400 bytes, and a segment rate between 400 to 800 segments/second.

From Figs. 6 - 9, it can be seen that ATPA effectively reduces the energy consumption for ZigBee packet transmission while satisfying the predefined PLR requirement when there is varying interference from the collocated WLAN. As discussed in [17], ACK-ID can improve the performance of ZigBee packet transmission in terms of packet retransmission rate, which consequently saves energy. Based on the experimental results, the ACK-ID and ATPA techniques can be implemented together to achieve better usage of bandwidth and energy when there is varying Wi-Fi interference close by.

5 Conclusion

In this paper, we proposed a novel and effective Adaptive Transmit Power Adjustment (ATPA) technique that makes use of the configurable transmit power provided by the sensor nodes to dynamically and rapidly select the optimal transmit power according to the varying external Wi-Fi interference. The performance improvement has been validated and evaluated through extensive experiments carried out in our testbed. The experimental results confirmed that ATPA can improve the performance of ZigBee packet transmission in terms of energy consumption when there is varying interference from the collocated WLAN and in the meantime maintain the required PLR.

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