Understanding the Indoor Interference between IEEE 802.15.4 and IEEE 802.11b/g via Measurements

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Abstract—**IEEE 802.15.4 and IEEE 802.11b/g work in the same 2.4GHz ISM (Industrial Scientific and Medical) band, their coexistence is crucial to ensure both of them work efficiently under the interference of each other. In this paper we investigated the above issue through extensive indoor measurements in a systematic way. The experimental results show that (1) 802.11b interferes to 802.15.4 in a larger frequency range but with less interference strength, compared to that of 802.11g; (2) 802.15.4 also has serious impact on the performance of 802.11b/g; (3) different modulation methods of 802.11b/g have different impacts on the link performance of 802.15.4; (4) There are obvious interference ranges for 802.15.4 to 802.11b/g. We believe the measurement results are valuable for the real world deployment and design of the network integrated 802.15.4 and 802.11b/g.**

Keywords- IEEE 802.15.4; IEEE 802.11b/g; Interference

I. INTRODUCTION

IEEE 802.15.4 (Zigbee) is a low-power and low-cost technology used in wireless sensor networks. Together with IEEE 802.11b/g (WiFi) [1] , they have been widely applied in many areas from smart home to industries. IEEE 802.15.4 and IEEE 802.11b/g work in the same 2.4GHz ISM (Industrial Scientific and Medical) band, their coexistence is crucial to ensure both of them work efficiently under the impact of each other.

The IEEE 802.15.4 physical layer uses two frequency bands in the 868/915 MHz and 2.4GHz bands. In this paper we only consider the 2.4GHz band. It offers 16 channels in the 2.4GHz band, and the raw transmission data rate is 250kbps using offset quadrature phase shift keying (O-QPSK) modulation.

IEEE 802.11b/g has 11 channels. IEEE 802.11b utilizes direct sequence spread spectrum (DSSS) using complementary code keying (CCK) modulation; whereas IEEE 802.11g is based on the orthogonal frequency division multiplexing (OFDM) modulation technique and the CCK modulation for backward compatibility with 802.11b. Both of them support multiple data rates at physical layer, for example there are 1, 2, 5.5 and 11Mbps for 802.11b.

There have been many works on the coexistence of 802.11b/g and 802.15.4. According to [1][2][4][5], 802.15.4 has little impact on the 802.11 performance, but 802.11 have a serious impact on the 802.15.4 performance if the channels of them are overlapped [1][3][4][5]. However, most of them (a) are performed in simulation or analyzed in theory, which lack verification in real worlds; (b) focus on how 802.15.4 can survive with the interference of 802.11b/g which has much higher transmission power. There are also some measurement-based studies, but they only consider the achievable link throughput and/or channel distance [5][6].

In this paper, we investigate the interference between 802.11b/g and 802.15.4 through extensive measurements in a systematic way. We measured the link performance of 802.15.4 under the interference of 802.11b/g, as well as the link performance of 802.11b/g under the interference of 802.15.4.

Different from the existed work, we consider more impact factors including different physical layer data rates and modulation methods of 802.11b/g. We also investigate the frequency ranges where WiFi interferes to Zigbee and vice versa.

The main results are as follows:

(1) 802.11b interferes to 802.15.4 in a larger frequency range but with less interference strength, compared to that of 802.11g.

(2) 802.15.4 also has serious impact on the performance of 802.11b/g.

(3) Different modulation methods of 802.11b/g have different impacts on the link performance of 802.15.4.

(4) There are obvious interference ranges for 802.15.4 to 802.11b/g.

The remainder of the paper is organized as follows: Section II gives the measurement method we used. Section III shows the results and analysis of the experiments. Our conclusion is

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[1] We shall use IEEE 802.15.4 and Zigbee; IEEE 802.11b/g and WiFi exchangeable in this paper.

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drawn in Section IV.

II. MEASUREMENT METHODOLOGY

In order to measure how WiFi and Zigbee interfere with each other accurately, we try to find a place where there is not any other devices working in the same frequency band except the ones used in the experiments. It is hard to find such a place nowadays on campus. Fortunately, we eventually found one located in a new building (Building 26) in Tianjin University. Before each experiment, we scanned each channel of 2.4GHz carefully to ensure there were not other WiFi/Zigbee devices active in the surroundings. We did all the experiments in a corridor in that building.

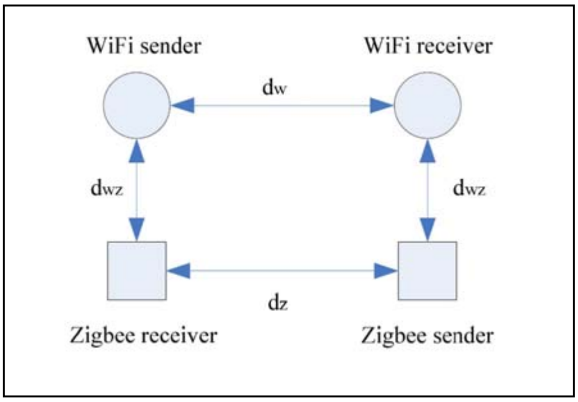

Figure 1. Basic network topology for experiments

A test-bed was established to investigate the potential interference effect of IEEE 802.15.4 on IEEE 802.11b/g and vice versa. The basic network topology is shown in Fig. 1. There are two WiFi nodes and two Zigbee nodes in total. The distance between the WiFi nodes is d_w, and d_z is the distance between the Zigbee nodes. We set $d_w = d_z$. Note that we made the two wireless links parallel, and the traffic flowed on them are in a reverse direction. In this way, the receiver will be interfered mostly by the sender from the other wireless link. The distance between the two wireless links is d_{wz}. We will change the distance d_w and d_{wz} during the experiments according to different goals.

WiFi nodes are set to ad-hoc mode. We leverage Iperf to generate UDP traffic. For more accurate results, the physical layer (PHY) data rate of WiFi is fixed to one of the data rates, and UDP rate is set to twice of the PHY data rate. WiFi channel is fixed to its channel 1 and the Zigbee channel is its channel 12 so that they overlap each other [3][6].

For all experiments in this paper, Zigbee nodes are configured to non-beacon enabled mode, and no ACK in MAC. In this mode, there is no beacon or ACK, so that we can calculate the throughput and loss rate accurately. We designed two Zigbee sending mode. In mode 1, in order to avoid packet loss due to sending buffer overflow, the packets are sent one by one, i.e. a packet will not be sent until the last packet has been sent out (Zigbee node will indicate it). In mode 2, the packets are generated in a fixed interval to obtain an accurate data rate.

The Zigbee node is made of Jennic JN5139 module which has a 16MHz 32-bit RISC CPU, 192KB ROM and 96KB RAM, with a fully compliant 2.4GHz IEEE 802.15.4 transceiver [7]. The WiFi node uses WiZiTJU, a powerful wireless router made by us [8]. It is an embedded device with Linux kernel 2.4.26 and equipped with an IEEE 802.11b/g wireless card. We can set the wireless card parameters such as transmit power, channel via its driver MadWiFi [9].

A. Performance metrics

To gain more insight into the interference between the IEEE 802.11b/g and IEEE 802.15.4, we collected the following performance metrics.

Throughput: link throughput of WiFi or Zigbee. It is the data receiving in the receiver successfully in unit time. When calculating Zigbee throughput, we only consider the payload and ignore the header of MAC and PHY. WiFi throughput can be obtained directly from Iperf at the receiver.

PRR (Packet Received Ratio): the ratio of received packets to the sent packets.

ACF (Access Channel Failure): the number of packets dropped due to channel contention failures in one second. It can reflect the channel busy status to some extent.

III. MEASUREMENT RESULTS AND ANALYSIS

In this section, we describe the experiments in details and analyze the experimental results.

In order to show how the Zigbee link performance is degraded under the WiFi interference, we firstly measured the Zigbee link throughput without any WiFi sources as a baseline. We also tried to find the best packet length leading to the maximum link throughput in this experiment.

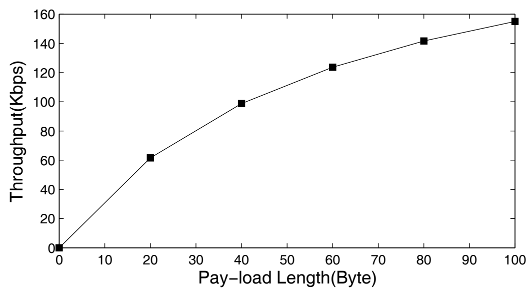

Figure 2. Throughput of Zigbee with different payload size

The Zigbee sender sent 10,000 packets in each experiment to the receiver with mode 1. The payload length (data part without packet header) changed from 0 to 100 bytes by a step of 20 bytes. The link throughput is shown in Fig.2. We can see from Fig. 2 that the throughput increases with the payload length almost linearly. The maximum throughput is achieved at payload size of 100 bytes which is almost the maximum payload size supported by 802.15.4. At this point, the throughput is near 155 kbps, which is reasonable considering the overhead at MAC layer and the listening in the channel contention procedure.

A. Performance of Zigbee at different channels under the same WiFi interference

In order to study interference frequency range of WiFi to Zigbee, we set WiFi channel to 11, and make Zigbee channel changes from 11 to 26.

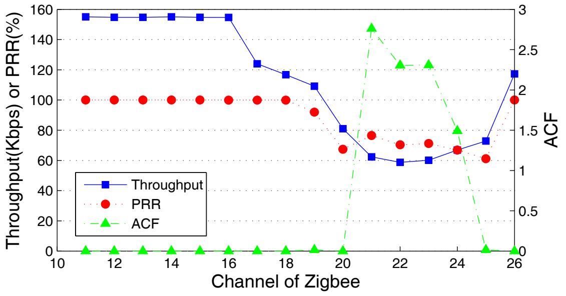

Figure 3. The performance of Zigbee at different channels under 802.11b interference

1) Under IEEE 802.11b at 11Mbps

Fig.3 shows the performance of Zigbee at different channels under 802.11b interference. We can see that Zigbee throughput reduced from channel 17. There is 16MHz bandwidth from Zigbee channel 17 to the left edge of WiFi channel 11, and 27MHz to the center frequency of WiFi channel 11. PRR of Zigbee has decreased from channel 19 to 25, with bandwidth of 17MHz to the center frequency of WiFi channel 11. ACF is high from channel 21 to channel 24. This bandwidth is 7MHz. Thus, we can get three ranges of interference strength which are 27MHz, 17MHz and 7MHz from Zigbee channel to the center frequency of WiFi respectively. The closer the frequency interval from Zigbee channel to WiFi channel, the stronger the interference.

2) Under IEEE 802.11g at 54Mbps

For 802.11g, there are no three ranges of interference. All the three metrics become deteriorated from channel 21 to 24. It is about 8MHz from the center frequency of WiFi. The throughput and PRR are worse than them under 802.11b. So the frequency range of 802.11b can interfere is larger than that of 802.11g, but the interference strength of 802.11g is stronger than 802.11b.

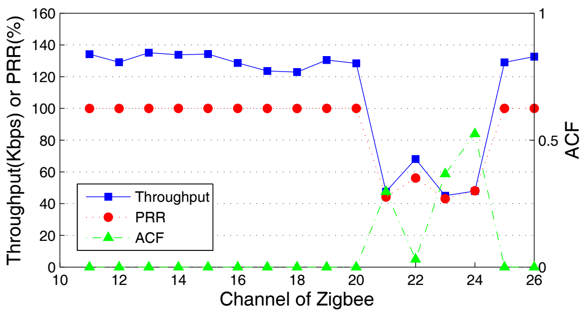

Figure 4. The performance of Zigbee at different channels under 802.11b interference

B. Performance of Zigbee under different data rates of WiFi and vice versa

1) Performance of Zigbee under WiFi

In this experiment, the distance between the two nodes d_w and d_z as in Fig.1 is set to 5m, and d_{wz} is 1m. Both the transmit power (tx-power) of WiFi sender and Zigbee sender are set to their maximum values, i.e. 27dBm and 0dBm respectively in our test-bed. Zigbee sends packets using mode 1. We measured the Zigbee link throughput, PRR and ACF under different PHY data rates of 802.11b/g. The results are shown in Fig.5 and Fig.6.

Fig.5 illustrates the link performance of Zigbee under 802.11b interference. Zigbee link has the lowest throughput when the PHY data rate of 802.11b is 1Mbps. Zigbee link achieves the highest throughput when 802.11b is 5.5Mbps. Generally, the performance of Zigbee improves with the increasing PHY rate except the point of 5.5Mbps. The performance of Zigbee under 802.11b PHY data rate of 5.5Mbps and 11Mbps (DSSS/CCK) outperform that under 802.11b PHY data rate of 2Mbps (DSSS/DQPSK). Zigbee was interfered most seriously when 802.11b is at 1Mbps (DSSS/DBPSK). Therefore we can deduce that the modulation method is the primary factor that causes the degradation of Zigbee performance.

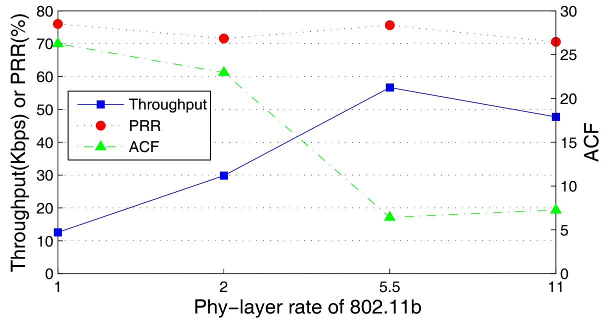

Figure 5. Zigbee link performance under multiple data rates of 802.11b

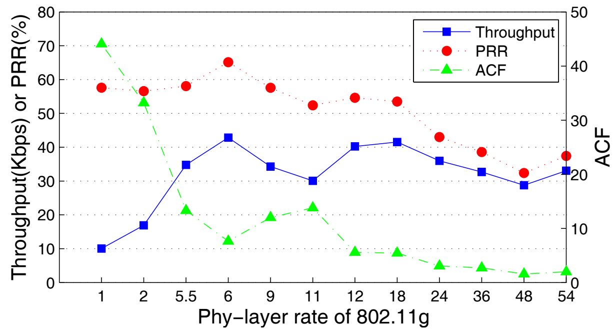

Figure 6. Throughput of Zigbee under different PHY data rate of 802.11g

In addition, the packet loss is primarily due to the following reasons:

a) channel contention using CSMA/CA.

b) interferece by WiFi sources..

The PRR of Zigbee is almost invariable and above 70% for four PHY rates of 802.11b. But the ACF decreases when the throughput increases. Thus, the channel contention is the main reason for the performance reduction of Zigbee under 802.11b.

In the experiment of Zigbee performance under 802.11g, the throughput of Zigbee have small waves except 1Mpbs, 2Mpbs, 5.5Mbps and 11Mbps. In Fig.7 it is clear that Zigbee performance is nearly invariant because all these rates of 802.11g use OFDM modulation. Thus, different modulation methods of WiFi have different interference to Zigbee. At the point of 1Mbps, Zigbee have the lowest throughput of 10Kbps, but at 5.5Mbps, throughput achieves the highest rate up to 34.7Kbps. Zigbee has only 6.5% to 22.4% performance gains relative to the rate in interference-free environment. In the data we recorded, the packet loss rate increases from 14% to 61% when the rate of WiFi increases from 1Mbps to 54Mbps.

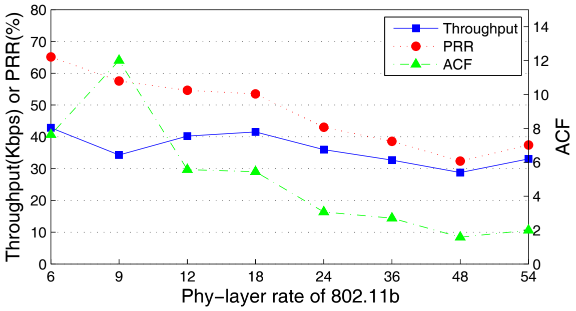

Figure 7. Throughput of Zigbee under 802.11g using OFDM

For all OFDM rates, the PRR and ACF both decrease with the PHY rate of WiFi increasing. The Zigbee node sends data faster but more packets are loss at receiver since the WiFi interference. We then conjecture the Zigbee cannot work effectively under high PHY data rate of 802.11g.

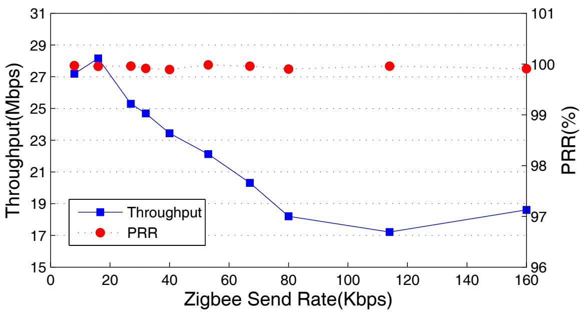

Figure 8. WiFi performance under different Zigbee rate

Zigbee throughput is lower under interference of 802.11g than that under 802.11b even at the same PHY data rate. The Zigbee throughput is 56Kbps and becomes the highest when 802.11b PHY data rate is 5.5Mbps. For all DSSS rates in 802.11g, Zigbee throughput also achieves the highest when the WiFi rate is 5.5Mbps. But it is only 35Kbps. This phenomenon also can be observed at the other rates of DSSS. We conjecture that the sending mode of wireless NICs at 802.11b rates is not exactly the same with that at DSSS rates of 802.11g.

2) Performance of WiFi under Zigbee

In this experiment, we only run 802.11g and the PHY data rate is 54Mbps. The Zigbee node sends packets with Mode 2. For each experiment, Iperf run for 40s and only data recorded during 10s to 40s is used. All other parameters are the same as in the last experiment.

In Fig.8 we can see that WiFi link throughput increases with Zigbee rate decreasing. The lowest rate of WiFi is 17.2Mbps, about 52% of the throughput in the interference-free environment. The PRR of WiFi is almost 100%. Thus, the interference of Zigbee to WiFi is contributed almost only by the channel contention. Zigbee has also impact on WiFi when WiFi nodes are in the interference range of Zigbee nodes.

C. Performance of Zigbee under WiFi with different distance and vice versa

In order to observe the interference with different distance between Zigbee and WiFi, we carried out this experiment in a corridor in the building.

1) Performance of Zigbee under WiFi

For the limited width, we changed d_z and d_w to 2m, and increased the d_{wz} from 5m to 50m with a step of 5m. The WiFi nodes used 802.11g with PHY rate set to 54Mbps. The tx-power of WiFi sender is set down to 11dBm. The tx-power of Zigbee sender is 0dbm. At each distance, we first scanned the channel energy, and then sent 10,000 packets with Mode 1.

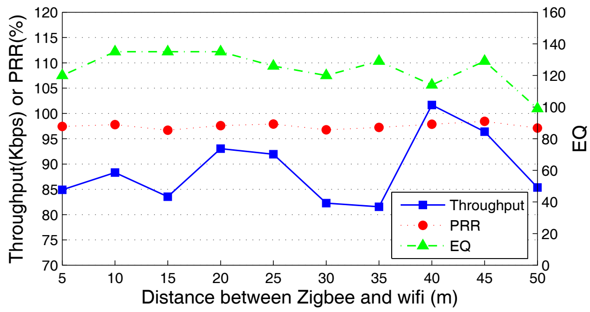

Figure 9. Zigbee performance under WiFi interference with different distance

The ED (Energy Detect) is the highest energy obtained after scanning a channel in 138.24ms. In Fig.9 ED recedes little with the distance increasing generally. We think this is because that the tx-power of WiFi is too high so that the transmission range is much longer than the length of the corridor (about 60m). The strength of interference cannot cause the Zigbee link have packet loss and only channel contention influences on the Zigbee performance since the PRR is almost 100%. Zigbee rate has rough and wavy growth as the distance between Zigbee nodes and WiFi nodes increases. We consider the reason may be that the signal of WiFi reflects and overlaps in the corridor and forms a regular interference environment.

2) Performance of WiFi under Zigbee

In this experiment, the d_z and d_w are also 2m, and the d_{wz} is from 1m to 45m by a step of 1m. We changed the tx-power of WiFi to 27dbm and the tx-power of Zigbee to - 24dbm so that at the end of the corridor the WiFi node cannot hear the Zigbee node. Zigbee sent packets continuously using mode 2 with a fixed interval of 5ms. Other configurations are the same as in the last experiment.

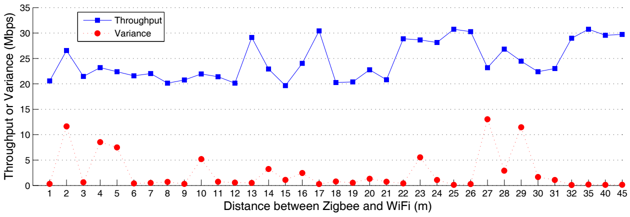

Figure 10. WiFi performance in different distances from Zigbee nodes

As shown in Fig.10, WiFi throughput increases with the distance from Zigbee increasing in general. At the worst case, the throughput of WiFi is 19.57 Mbps and about 59% of that in an interference-free environment. It is 30.7Mbps and highest when the distance is 35m. At some points, the Zigbee node cannot interfere WiFi nodes drastically even the distance is not long. However at some other points, the rate of WiFi shook seriously. This phenomenon might also due to the signal reflection in the corridor. We suppose the confusion of signal may be more serious in a room since the furniture. Thus, in an indoor scenario, the interference does not always decrease with the increasing of the distance between the device and the interference source.

IV. CONCLUSIONS

We studied the interference between IEEE 802.11b/g and IEEE 802.15.4 in this paper. The main contributions of the paper are: (1) extensive measurements of the impacts of IEEE 802.11g on IEEE 802.15.4 and vice versa in a systematic way; (2) 802.11b interferes to 802.15.4 in a larger frequency range but with less interference strength, compared to that of 802.11g; (3) IEEE 802.15.4 also has drastic interference on IEEE 802.11b/g; and (4) Different PHY data rate of IEEE 802.11b/g has different impact on IEEE 802.15.4 depending on their modulations. In the future work, we will investigate the interferences between 802.15.4 and 802.11 in outdoor environment, and also consider 802.11n, the new 802.11 standard.

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