ZigBee vs WiFi: Understanding Issues and Measuring Performances of their Coexistence

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***Abstract*—Wireless coexistence is crucial with the explosive development of wireless technologies in recent years. The coexistence issues of IEEE 802.11 b/g and IEEE 802.15.4 have been well studied, however few work focused on 802.11n new features including MIMO, channel bonding and frame aggregation. In this paper, we conducted extensive experiments to understand how 802.11n impact on 802.15.4 and vice versa in a systematic way. We consider primary features of 802.11n both in symmetric and asymmetric scenarios. The goal of our work is to gain more insights into the coexistence issues of 802.11n and 802.15.4 and thus to help protocol design and co-located network deployments**

I. Introduction

The development of diverse wireless technologies has been explosive in the last few decades. Since various network standards such as IEEE 802.11 (WiFi) [1] and IEEE 802.15.4 (ZigBee) [2] share the 2.4 GHz ISM (Industrial Scientific and Medical) band, cross technology interference is inevitable. These two types of networks exploit the same frequency band, and are widely deployed in a number of common applications in which they have to coexist in close proximity. 802.11n, as one of the latest 802.11 standards, supports a maximum 600 Mbps due to several enhancements including MIMO (Multiple Input and Multiple Output), FA (Frame Aggregation) and channel bonding. Its coexistence with other ISM band technologies is crucial to the wide deployment of 802.11n applications.

In the past few years, coexistence issues between legacy 802.11b/g and 802.15.4 have been widely investigated through experiments [3]–[9]. It is shown that the throughput of WiFi and Zigbee degrade heavily when they are co-located, therefore various protocols have been proposed for WiFi to survive in the presence of Zigbee and vice versa [10]–[14]. However, all the work are based on legacy 802.11b/g, few of them consider 802.11n [7], [8]. Nowadays, 802.11n networks are being ubiquitous and have new features (MIMO, FA and channel bonding) different from legacy 802.11b/g. One cannot help asking how 802.11n and 802.15.4 impact each other when they are co-located? Shall we design new protocols to make them co-work? or how to deploy them to alleviate the interference from each other? In this paper, we aim to answer these questions via systematic experiments.

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We establish a testbed composed of one 802.11n network and one 802.15.4 network to carry out the experiments. We choose two popular commercial 802.11n wireless cards: Intel5300 and UBNT SR71-A, in order to examine the behaviors of different 802.11n products in the presence of 802.15.4 interference. We focus on new features of 802.11n (MIMO, FA and channel bonding) and check their impact on 802.15.4 and vice versa. We further consider symmetric and asymmetric scenarios, which are formed due to the transmit power discrepancy between 802.11n and 802.15.4 nodes [15]. In the symmetric scenario, the signal from the 802.15.4 sender is strong enough to trigger the CCA (Clear Channel Assessment) check on the 802.11n sender, therefore both 802.11n and 802.15.4 senders can hear each other. While in the asymmetric scenario 802.15.4 sender can hear 802.11n nodes, but 802.11n nodes are oblivious of 802.15.4 sender.

Our primary findings obtained from our experiments are as follows:

(1) In symmetric scenarios, the throughput degradation of 802.11n primarily steps from backoff. Accordingly, the packet losses of 802.15.4 are primarily due to ACF (Access Channel Failure) instead of corruption. Different 802.11n wireless cards have different behaviors when they operate at single-stream and double-stream modes.

(2) FA and channel bonding have impact on the coexistence. The 802.15.4 network has better performance in terms of PDR (Packet Delivery Ratio) when the 802.11n network operates at 40 MHz or at smaller FA levels.

(3) In asymmetric scenarios, 802.15.4 has no impact on 802.11n. However, the PDR of 802.15.4 decreases to almost zero. The packet losses are due to both ACF and corruption.

From these observations, we gain some insights into network protocol design and co-located network deployments. Some implications are:

(1) It is preferred for 802.15.4 protocol to differentiate the different packet loss types (channel-access-failed or corrupted), thus to improve the PDR of 802.15.4 under the interference of 802.11n.

(2) The parameters of 802.11n (20 MHz/40 MHz, FA levels) should be selected carefully when 802.11n and 802.15.4 are co-located, to make them co-exist well.

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The remaining of the paper is organized as follows. A brief overview of 802.11n and 802.15.4 are given in Section II. We describe the experimental setup and methodology in Section III, and present experimental results in Section IV. Section V introduces the related work and Section VI concludes the paper.

II. BACKGROUND

A. 802.11n overview

TABLE I: 802.11n bit rate at 20 MHz/LGI

MCS	stream	modulation	bit rate (Mbps)	MCS	stream	bit rate (Mbps)
0	1	BPSK	6.5	8	2	13.0
1	1	QPSK	13.0	9	2	26.0
2	1	QPSK	19.5	10	2	39.0
3	1	16-QAM	26.0	11	2	52.0
4	1	16-QAM	39.0	12	2	78.0
5	1	64-QAM	52.0	13	2	104.0
6	1	64-QAM	58.5	14	2	117.0
7	1	64-QAM	65.0	15	2	130.0

Compared to legacy 802.11b/g, 802.11n provides enhancements to both physical and MAC layers. Primary modifications include MIMO, frame aggregation and channel bonding [16], [17].

MIMO: MIMO uses multiple transmit and receive antennae to achieve higher throughput. The key techniques are spatial multiplexing and spatial diversity. With spatial multiplexing, multiple transmit antennae are used to transmit independent data streams. The current standard allows for maximum four spatial streams. With spatial diversity, each transmit antenna transmits a single stream. It leverages the independent fading over multiple-antenna links to enhance signal diversity. The 802.11n standard defines MCS (Modulation and Coding Scheme) to comprehensively consider the permutations of the factors determining data rate such as modulation, coding rate and number of spatial streams. It supports up to 32 MCS indices, here in Table I we only list MCS 0-15 at 20 MHz/LGI (Long Guard Interval). MCS 0-7 correspond to single streams, and MCS 8-15 are double streams. Each MCS index yields a different PHY bit rate.

Frame aggregation: Frame aggregation amortizes the channel contention and backoff delays by transmitting multiple frames in a single transmission opportunity on the channel. Multiple data frames,*i.e.*, MPDUs (MAC Protocol Data Units), are combined into an aggregate frame A-MPDU in this operation. It supports 32 FA levels, defined as the number of MPDUs in an A-MPDU.

Channel bonding: 802.11n introduces two different channel bandwidths, 20 MHz and 40 MHz. Channel bonding simultaneously uses two adjacent 20 MHz channels to transmit data, thus doubles the rate in theory.

B. 802.15.4 overview

The 802.15.4 standard is designed for low power and low data rate wireless sensor networks operating at the 2.4 GHz ISM band [2]. The standard defines 16 channels within this band, each 2 MHz wide with 3 MHz inter-channel guard bands, which are overlapped with the operating channels of 802.11n at 2.4 GHz band.

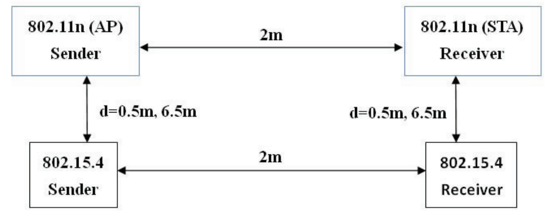


Fig. 1: Network topology

The 802.15.4 adopts CSMA/CA as its MAC protocol [2]. The sender senses the channel before sending a packet. The time granularity that the sender senses the medium is as long as a slot time ($= 320\mu s$). After that, CCA is performed over eight symbol periods to determine whether the channel is available. If CCA succeeds, the packet is sent. Otherwise, if CCA fails, the node carries out the binary exponential backoff. The procedure repeats if the CCA continues to fail. The sender would declare an ACF after failing to access the channel for certain times and the packet is abandoned. In this case, the packet is lost due to ACF.

III. EXPERIMENT SETUP AND METHODOLOGY

A. Experiment Scenarios

We consider diverse experiment scenarios in order to gain deep insights into the coexistence issues between 802.11n and 802.15.4 networks.

The network topology is shown in Fig. 1. We use two 802.11n nodes equipped with the same type of wireless cards to build a 802.11n network, where one acts as AP mode, the other is a station. Although limited to only two nodes, the configuration can be considered general and representative of situations with more than two 802.11n nodes. In fact, according to the CSMA/CA mechanism, only one 802.11n node may transmit at a time and thus interferes with the 802.15.4 network regardless of the number of 802.11n nodes that are involved.

The experiments are conducted at a basement garage at TJU campus. To ensure that our environment is controlled and our experiments are repeatable, we verify that there is little interference external to our testbed by scanning the 2.4 GHz frequency band. We conduct all our experiments at weekends or at late night when the potential for interfering traffic is at a minimum.

Since the transmit power of 802.11n node is much larger than that of 802.15.4 node, the discrepancy between their transmit powers leads to two distinct interference scenarios: symmetric and asymmetric one [15]. We consider both symmetric and asymmetric scenarios in our experiments We change the distance d between 802.11n network and 802.15.4 network to generate symmetric and asymmetric scenarios. In symmetric scenarios, d is set to 0.5 meters so that both 802.11n nodes and 802.15.4 nodes can hear each other. The transmit power of 802.15.4 sender is set to the maximum level 31. In asymmetric scenarios, d is set to 6.5 meters and the transmission power of 802.15.4 sender decreases to the minimum level 0. In this case, 802.15.4 nodes can hear 802.11n but not vice versa.

B. Experiment Methodology

In our experiments, for 802.11n network the sender operates in AP mode and the receiver in station High Throughput mode.

We examine the impact of 802.11n traffic at single-stream (MCS 0-7) and double-stream (MCS 8-15) mode on 802.15.4, and vice versa. To do so, We disable the bit rate adaptation scheme in the driver and fix MCS for each run. The 802.11n nodes operate at WiFi channel 11. The 802.15.4 nodes change their channel from 19 to 26, where channel 21 to 24 overlap with WiFi channel 11 and others are adjacent channels.

We also measure the channel bonding feature of 802.11n. In addition, to see how FA affects the performance, we set FA level to 1, 8, 16, 24 and 32 respectively. In these experiments, MCS 5 and 12 are selected, standing for single stream and double streams respectively.

We use *Iperf* tool [18] to generate UDP traffic with a fixed packet size of 1500 bytes. To measure the worst-case impact on the 802.15.4 network, we configure *Iperf* to transmit as quickly as possible.

C. 802.11n settings

We use two popular commercial 802.11n wireless cards to examine the difference among products. One is Intel WiFi link 5300 (Intel5300) wireless card, and the other is UBNT SR71-A.

Intel5300. The Intel WiFi Link 5300 is an IEEE 802.11a/b/g/n wireless network adapter that operates at both 2.4 GHz and 5 GHz frequency bands. It supports 3×3 MIMO, FA and channel bonding. Two laptops equipped with Intel5300 wireless cards are used as the 802.11n nodes. Laptops are DELL Latitude D630 with Intel duo 1.7 GHz CPU, 1GB RAM, running Ubuntu 10.04 LTS distribution with linux kernel version 2.6.18.

UBNT SR71-A. SR71-A wireless cards have Atheros 9610 chipsets, and support 3×3 MIMO, FA and channel bonding too. They are embedded in a programmable platform, UBNT RouterStation Pro. This platform runs Open-WRT open source OS, and has 680 MHz CPU, 128 MB RAM and 16 MB flash.

D. 802.15.4 settings

The 802.15.4 network consists of motes equipped with Jennic 802.15.4-compatible radios. Jennic is designed for industrial applications with a low-power high-performance transceiver module [19]. Jennic has a 32-bit RISC microprocessor supporting a single-task basic operating system, 192 KB ROM and 96 KB RAM.

The sender sends 100-byte packet in a back-to-back way in order to send packets as fast as possible. During each run, the 802.15.4 sender sends 10,000 packets. The MAC-layer ACK and retransmission are disabled to obtain accurate packet loss rate.

E. Performance metrics

802.15.4 packet reception distribution. From the view of 802.15.4 receiver, the received packets are categorized into three types: valid, channel-access-failed and corrupted packet. The valid packets are those received successfully. The channel-access-failed packets are those lost due to ACF, which happens when the 802.15.4 sender keeps sensing the channel busy. The corrupted packets are those lost due to corruption. If the preamble of the packet is corrupted, then the packet cannot be decoded at all. While if somewhere in the payload is corrupted, the CRC error happens and the packet is dropped. Packet reception distribution refers to the percentage of the three types of packets.

802.15.4 PDR (Packet Delivery Ratio). PDR is defined as the ratio of the number of received valid packets over the number of sent during the experiment.

802.11n busy percentage. Suppose the measured 802.11n throughput at MCS k is B_k, and the data rate at that MCS is R_k, then Busy percentage at MCS k is defined as B_k/R_k. This metric indicates the channel occupation time of 802.11n to some extent. When it is busy with transmission, there is no chance for 802.15.4 nodes to send packets.

802.11n normalized throughput degradation. We measure the average throughput of 802.11n for MCS 0-15, in the absence of 802.15.4 interference as a baseline. In this case, the link quality is good enough that the loss rate is almost zero. We further define the normalized throughput degradation as the throughput decrement divided by the baseline throughput.

IV. Experiment results

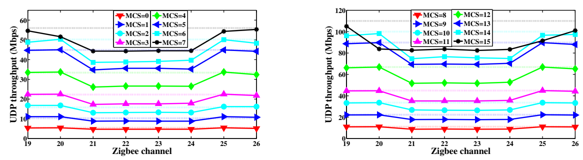
In this section, we examine the coexistence issues of 802.11n and 802.15.4 in controlled environment without external interference. The goal is to obtain the insights into the impact of 802.11n features on 802.15.4 and vice versa. We first carried out the experiments in symmetric scenarios and then repeated them in asymmetric scenarios. We focus on primary techniques of 802.11n, *i.e.*, MIMO, FA and channel bonding.

A. MIMO

We first analyze the impact of 802.15.4 on 802.11n, and then the impact of 802.11n on 802.15.4. We compare the difference between two types of 802.11n nodes: Intel5300 and UBNT SR71-A.

1) Impact of 802.15.4 on 802.11n: In symmetric scenarios 802.11n sender senses a high-level 802.15.4 signal above its CCA threshold. Both of the 802.11n and 802.15.4 senders can hear each other. According to CSMA/CA mechanism, one node senses the channel before its transmission. If the channel is idle, it sends packets after a random backoff time. Otherwise, it backoffs for a random period of time. Therefore when both 802.11n and 802.15.4 nodes have packets to send, it might trigger their backoff process, thus degrades the throughput.

The behavior of Intel5300 wireless cards. Fig. 2 shows the impact of 802.15.4 on 802.11n UDP throughput for MCS 0-15 with Intel5300 wireless cards. The dashed line in the figure is the average throughput measured without 802.15.4 interference. At non-overlapped 802.15.4 channel 19, 20, 25 and 26, none or little UDP throughput degradation is visible. Whereas at overlapped channel 21 to 24, the UDP throughput decreases. We calculate the normalized throughput degradation for each MCS impacted by 802.15.4 at overlapped 802.15.4



(a) MCS 0-7

(b) MCS 8-15

Fig. 2: The impact of 15.4 on the 11n throughput for MCS 0-15, Intel 5300 wireless cards

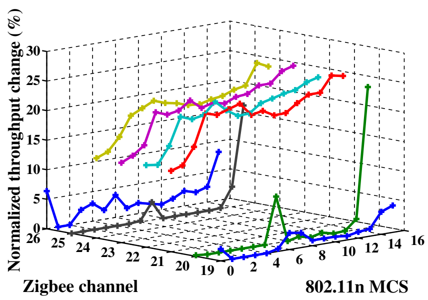


Fig. 3: Normalized 11n throughput degradation in the presence of 15.4 interference

channels. The results are shown in Fig. 3. The maximum normalized UDP throughput degradation is less than 25%. The degradations for double-stream MCS 8-15 are similar, around 20%.

We analyzed traces and found that the packet loss rate of UDP traffic is zero, and there are no retransmissions for any packet. It is the decrease of the sending rate that leads to the throughput degradation at the receiver. Therefore, we deduce that 802.11n sender detects the signal of 802.15.4 and then backoffs. We noted that the throughput of 802.11n at all the overlapped channels are the same, and this holds for the un-overlapped channels. Therefore, we only perform experiments at one overlapped channel later on.

Different modulation and coding mechanisms need different signal strength to decode a packet successfully. The higher the MCS index in the same stream mode, the stronger signal strength required to achieve the same packet error rate. In other words, the higher MCS index is more vulnerable to the interference [20]. Therefore we want to examine the 802.15.4 impact on different MCSs. We plot the throughput of MCS pairs with same PHY bit rate in Fig. 4, where MCS 1 and MCS 8 have bit rate of 13 Mbps, MCS 3 and MCS 9 have bit rate of 26 Mbps, and MCS 4 and MCS 10 have bit rate of 39 Mbps as listed in Table I. It says that the throughput decreases the

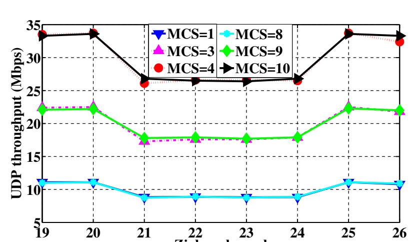


Fig. 4: Impact on 11n throughput for MCSs with same bit rate

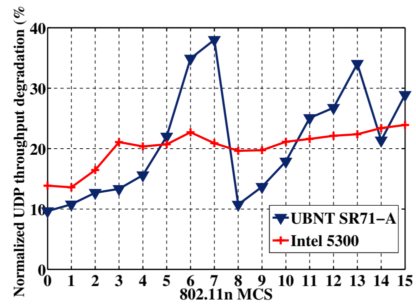
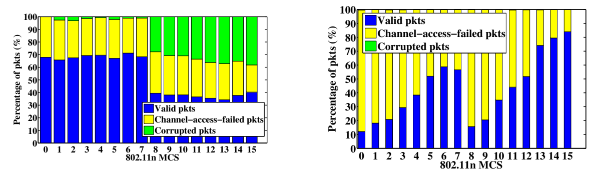


Fig. 5: Normalized UDP throughput degradation in the presence of 15.4 interference



(a) Intel5300

(b) UBNT SR71-A

Fig. 6: Packet reception distribution in symmetric scenario

same way for each MCS pairs. It is worth noting that the MCSs in each pair have different modulation schemes, for instance, the modulation scheme of MCS 1 is QPSK whereas BPSK for MCS 8. This is to say the impact of 802.15.4 on 802.11n UDP traffic is independent of the modulation scheme adopted by 802.11n. This shows that although the signal strength of 802.15.4 is higher than the CCA threshold of 802.11n yet not strong enough to corrupt the packets of 802.11n. Therefore in the presence of 802.15.4 traffic, the 802.11n sender will backoff but the packet loss rate is zero in symmetric scenario.

The behavior of UBNT SR71-A. We then repeat the experiments with UBNT SR71-A to understand the behaviors of different 802.11n commercial products. Fig. 5 shows the normalized throughput degradation in the presence of 802.15.4 interference for UBNT SR71-A wireless cards. We can see that the degradation varies with the MCS indices, and is independent on stream modes. For example, the degradation at MCS 0 is about 10%, and increases to about 38% at MCS 7. This holds for double streams. This observation is different from that of Intel5300. We will see later in Sec IV-A2 that these two types of 802.11n devices have different impact on 802.15.4 too. We will try to explain this phenomena there.

2) The Impact of 802.11n traffic on 802.15.4: We now turn to the impact of 802.11n traffic on 802.15.4 network. We first examine the results in symmetric scenarios and then in asymmetric scenarios.

Symmetric scenario. In symmetric scenarios, 802.11n nodes and 802.15.4 nodes can hear each other.

Fig. 6 illustrates the packet reception distribution of 802.15.4 in the presence of 802.11n traffic. Fig. 6a and Fig. 6b show the results for Intel5300 and UBNT SR71-A respectively. The two types of 802.11n devices have different impact on 802.15.4. For Intel5300 wireless cards, the PDR of 802.15.4 keeps at around 70% for single-stream MCSs, and decreases to below 40% for double-stream MCSs. In other words, the PDR

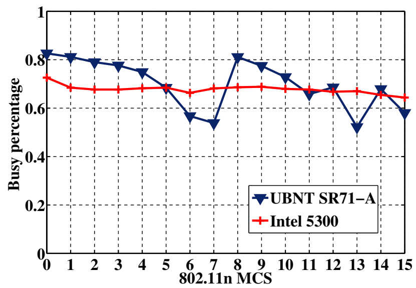


Fig. 7: Busy percentage of different 11n wireless cards in symmetric scenario

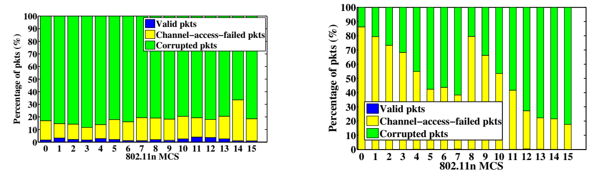
of 802.15.4 depends on the number of 802.11n space streams. In addition, for single-stream MCSs, the number of corrupted packets is almost zero, and the packet losses are due to ACF. Whereas for double-stream MCSs, the packet losses are due to both ACF and corruption.

However, from Fig. 6b we can see that for UBNT SR71-A, the PDR of 802.15.4 varies with MCS indices, or the PHY data rate. For example, the 802.15.4 PDR is only 10% at 802.11n MCS 0, and increases to about 60% at MCS 6, even upto over 80% at MCS 15. Furthermore, the packet losses are due to ACF, since the number of corrupted packets is almost zero. This indicates that UBNT SR71-A 802.11n and 802.15.4 can hear each other and backoff well. Since the slot time of 802.11n is 9 μs, which is much shorter than that of 802.15.4 (320 μs) [15]. In this case, 802.11n node has more opportunities to succeed in channel competition. Therefore 802.15.4 keeps sensing the channel busy, and loses packets due to ACF.

To understand the different impact between Intel5300 and UBNT SR71-A, we plot their busy percentage in Fig. 7. It shows that the busy percentage decreases with the increase of MCS indices inside one space stream mode (single-stream or double-stream) for UBNT SR71-A. That is to say, UBNT SR71-A leaves more time (white space) for 802.15.4 at higher MCS indices (*i.e.*, higher bit rate). From Fig. 5, we can see for UBNT SR71-A, the throughput at higher MCS indices decreases more than that at lower MCSs, *i.e.* it is more sensitive to 802.15.4 interference at higher MCSs inside one space stream mode. This result again explains why the PDR of 802.15.4 is higher at high 802.11n MCSs inside one space stream mode, as shown in Fig. 6b. However, it is hard to explain the impact of Intel5300 on 802.15.4. Its busy percentage keeps almost the same for all 802.11n MCSs, but the PDR decreases from 70% to 40% from single-stream to double-stream MCS. It might be due to the implementation of Intel5300 wireless cards.

Asymmetric Scenario. In asymmetric scenarios, 802.11n senders cannot detect 802.15.4 signals and hence do not defer their transmissions even when there exist ongoing 802.11n transmissions. Therefore the performance of 802.15.4 degrades severely in the presence of 802.11n in asymmetric scenario. We will show our results below.

Fig. 8 shows the packet reception distributions in the presence of Intel5300 and UBNT SR71-A 802.11n traffic respectively. We can see that PDR is almost zero in both Fig. 8a and Fig. 8b, *i.e.*, the 802.15.4 traffic is suppressed by 802.11n severely. Since 802.11n sends packets ignoring the existence of the 802.15.4, and the traffic is set to be saturated to examine the worst case, there is little idle slot time left for 802.15.4. Moreover, when the 802.15.4 senses idle channel and sends the packet, it might collide with 802.11n packets, since 802.11n node does not backoff at all. That is why the percentage of corrupted packets is high above 80% for Intel5300 and some high MCS indices in each stream mode for UBNT SR71-A. However, for UBNT SR71-A, at low MCS indices in each steam mode, for instance MCS 0-4 and MCS 8-10, the channel-access-failed packets are over 50%, whereas the channel-access-failed packets are less than 20% for Intel5300.



(a) Intel5300

(b) UBNT SR71-A

Fig. 8: Packet reception distribution in asymmetric scenario

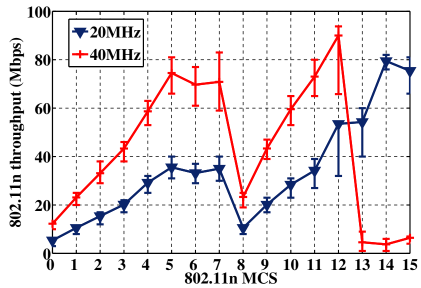
In summary, the primary results considering 802.11n MIMO are given in the following.

(1) In symmetric scenarios, the throughput degradation of 802.11n primarily steps from backoff. 802.11n throughput decreases less than 25% for Intel5300 wireless nodes and less than 40% for UBNT SR71-A. Different types of 802.11n devices have different behaviors while co-existing with 802.15.4 network. In the presence of Intel5300 interference, the PDR of 802.15.4 can still keep at about 70% at single-stream mode, whereas the PDR decreases to about 40% at double-stream mode. In the presence of UBNT SR71-A interference, the PDR varies from 10% to 80% with different MCSs.

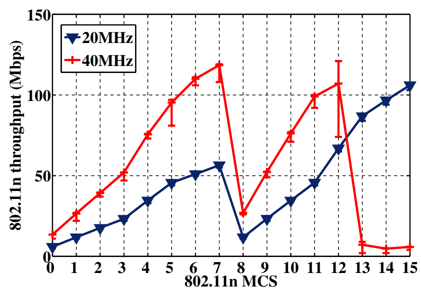
(2) In symmetric scenarios, in the presence of Intel5300 interference, packet losses of 802.15.4 are primarily due to ACF or corruption. In the presence of UBNT SR71-A interference, packet losses of 802.15.4 are primarily due to ACF.

(3) In asymmetric scenarios, the PDR of 802.15.4 is almost zero. In the presence of Intel5300 interference, 80% packets sent are corrupted by 802.11n traffic, near 20% packets cannot be sent at all due to ACF. In the presence of UBNT SR71-A interference, the percentages of corrupted packets and channel-access-failed packets vary with MCS indices.

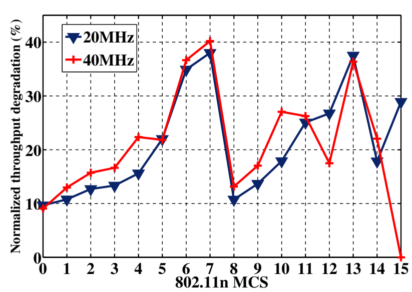
Implications: In asymmetric scenarios, it is hard for 802.15.4 to survive under the interference of 802.11n, since its PDR is almost zero. The packet losses are due to ACF and corruption. In symmetric scenarios, the throughput of 802.15.4 degrades heavier than that of 802.11n. The packet losses of 802.15.4 is primarily due to ACF. For the corrupted packets, it might be possible to recover via error recovery mechanisms as in [15], however it is useless for channel-access-failed packets. Therefore, protocol design should consider both types of packet loss to improve the throughput of 802.15.4.



(a) Symmetric scenario



(b) Asymmetric scenario



(c) Normalized throughput degradation

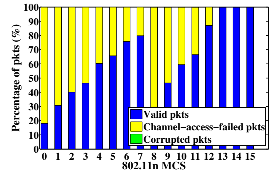
Fig. 9: Throughput of 11n in the presence of 15.4 interference

B. Channel bonding

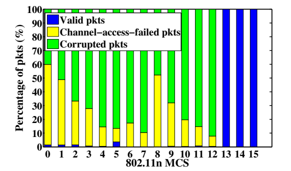
802.11n supports channel bonding which combines the adjacent two 20 MHz channels into one 40 MHz channel, thus to achieve more data rate. We adopted UBNT SR71-A nodes in these experiments. 802.11n and 802.15.4 networks operate in overlapped channels.

Impact of 802.15.4 on 802.11n. Fig.9 shows 802.11n throughput in the presence of 802.15.4 interference in symmetric and asymmetric scenarios, and the normalized throughput degradation in symmetric scenarios. We can see that in both scenarios, 802.11n throughput at 40 MHz almost doubles that at 20 MHz except at MCS 13-15. This is because that 802.11n at 40 MHz needs higher signal strength to achieve the same delivery ratio than at 20 MHz, especially at higher data rates. In this case, the transmit power is not high enough to support high delivery ratio required at MCS 13-15. That is also why the throughput degradation at 40 MHz is a little bit higher than that at 20 MHz.

Impact of 802.11n on 802.15.4. Fig. 10 shows the packet reception distribution of 802.15.4 in the presence of 802.11n at 40 MHz in symmetric and asymmetric scenarios. In symmetric scenarios, there are almost no corrupted packets and the packet losses are due to ACF. The percentage of valid packets (*i.e.*, PDR) varies with MCS indices from 20% to 100%, a little bit better than that in the presence of 802.11n at 20 MHz. On the other hand, in asymmetric scenarios, the PDR of the 802.15.4 is almost zero, whereas 100% at MCS 13-15, since the throughput of 11n at those MCSs is very low. In addition, the packet losses are due to ACF and corruption. The percentages of channel-access-failed and corrupted packets vary with MCS indices.

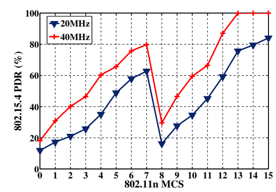


(a) In symmetric scenarios

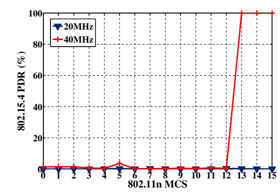


(b) In asymmetric scenarios

Fig. 10: Packet reception distribution of 15.4 in the presence of 11n at 40 MHz

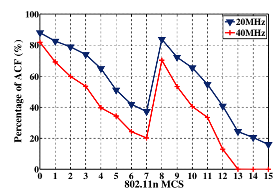


(a) Symmetric scenarios

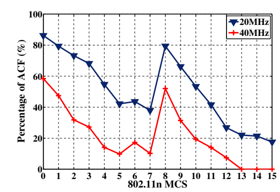


(b) Asymmetric scenarios

Fig. 11: The PDR of 15.4 at 11n 20/40 MHz in symmetric and asymmetric scenarios

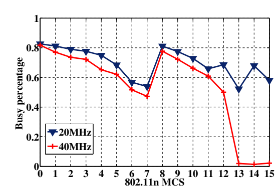


(a) Symmetric scenarios

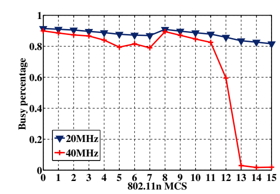


(b) Asymmetric scenarios

Fig. 12: Percentage of channel-access-failed packets of 15.4 at 11n 20/40 MHz in symmetric and asymmetric scenarios

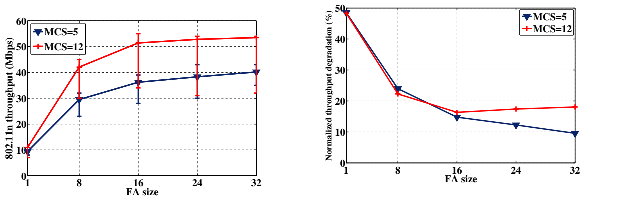


(a) Symmetric scenarios



(b) Asymmetric scenarios

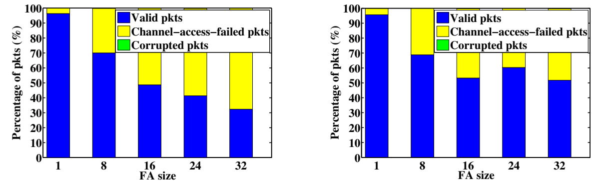
Fig. 13: Busy percentage of 11n at 20/40 MHz in symmetric and asymmetric scenarios



(a) Throughput

(b) Normalized throughput degradation

Fig. 14: Throughput of 802.11n at different frame aggregation sizes



(a) MCS 5

(b) MCS 12

Fig. 15: Packet distribution of 802.15.4 in the presence of 802.11n at different frame aggregation in symmetric scenarios

As a comparison, we plot the PDR of 802.15.4 in the presence of 802.11n at 20 MHz and 40 MHz respectively in Fig. 11. Fig. 12 is the percentage of channel-access-failed packets of 802.15.4 at 20 MHz and 40 MHz respectively. We can see that the trends are similar at both 20 MHz and 40 MHz. The PDR of 802.15.4 in symmetric scenarios at 802.11n 40 MHz is higher than that at 20 MHz, although the 802.11n throughput at 40 MHz is larger than that at 20 MHz. To explain this observation, we compare 802.11n busy percentage at 20 MHz and 40 MHz in Fig. 13. The busy percentage of 802.11n at 40 MHz is lower than that at 20 MHz. This is because 802.11n node sends packets back-to-back in our experiments. Given fixed packet length, the higher bit rate, the shorter transmission time to transmit a packet. That is to say 802.11n node at 40 MHz leaves more time for 802.15.4 node to transmit packets. Therefore, 802.15.4 can obtain higher PDR at 40 MHz. The primary reason is that 802.11n at 40 MHz is more vulnerable to 802.15.4 interference than that at 20 MHz.

In summary, 802.15.4 can achieve higher PDR in the presence of 802.11n at 40 MHz than at 20 MHz in symmetric scenarios, but at the cost of more throughput degradation of 802.11n at 40 MHz.

Implications: It is preferred that 802.11n networks work at 40 MHz while coexisting with 802.15.4 network in symmetric scenarios. However, in asymmetric scenarios, the throughput of 802.15.4 is still almost zero. Protocols need to deal with this problem.

C. Frame aggregation

We adopted UBNT SR71-A nodes in FA experiments. The 802.11n and 802.15.4 networks operate at overlapped channels. 802.11n supports FA to achieve higher data rate. FA allows a sender to send up to 32 MPDUs at one transmit opportunity, which improves link utilization efficiently.

Impact of 802.15.4 on 802.11n. Fig. 14 shows the throughput of 802.11n at different FA levels in symmetric scenarios. We select MCS 5 and 12 to stand for MCSs at single-stream and double-stream modes respectively. It shows that 802.11n throughput at both MCS 5 and 12 increases with the frame aggregation sizes. In the presence of 802.15.4, the throughput degradation at smaller FA levels (1-16) is much higher than that at larger FA levels. This can be explained as follows. With FA mechanism, packets (MPDUs) are grouped into one A-MPDU. In one transmission opportunity, packets inside one A-MPDU are sent back-to-back without contending the channel. The smaller FA level, the smaller A-MPDU size, thus the shorter transmission time occupied. However, in order to send an A-MPDU, the 802.11n node has to contend the channel with 802.15.4 node. Therefore the 802.11n node with smaller FA level has to contend channel for more times with 802.15.4 nodes, since it has more A-MPDUs to send. In this case, 802.15.4 node has more opportunities to occupy the channel. That is why the throughput of 802.11n degrades more at smaller FA levels.

Impact of 802.11n on 802.15.4. Fig. 15 shows the packet distribution of 802.15.4 in the presence of 802.11n at different FA levels in symmetric scenarios. We can see that the number of corrupted packets is almost zero, and the PDR of 802.15.4 decreases with the increasing FA level. That is because that the longer the packets, the more time to transmit, thus the smaller time left to 802.15.4. The trends at MCS 5 and MCS 12 are the same.

In summary, 802.11n and 802.15.4 can coexist well at smaller FA levels, at the cost of the throughput degradation of 802.11n.

Implications: In order to balance the throughput of both 802.11n and 802.15.4, the FA level should be selected carefully.

V. Related work

802.11 impact on 802.15.4. There are many studies on the legacy 11b/g impact on 15.4, and on how to survive for 15.4 network in the presence of 802.11 interference. Liang *et al.* [15] first examine the interference patterns between Zigbee and WiFi networks at the bit-level granularity and design BuzzBuzz to mitigate WiFi interference through header and payload redundancy. Huang *et al.* [21] propose a novel approach that enables Zigbee links to achieve assured performance in the presence of heavy WiFi interference. It develops WISE, which can achieve desired trade-offs between link throughput and delivery ratio. Zhang *et al.* [22] present CCS (Cooperative carrier signaling), that exploits the inherent cooperation among ZigBee nodes to harmonize their coexistence with WiFi WLANs. CCS exploys a separate ZigBee node to emit a carrier signal (busy-tone) concurrently with the desired ZigBees data transmission, thereby enhancing the ZigBees visibility to WiFi.

Few of existing work considers 11n. Petrova *et al.* [23] investigate 11g/n impact on Zigbee, considering the packet delivery of Zigbee operating at different channels in the present of 11g/n. Fiehe *et al.* [8] study 802.11n performance and impact of interferers on the 2.4 GHz ISM band. However, interferers are 11b/g and interfering signal generators rather than Zigbee. Polepalli *et al.* [7] present the 802.11n impact on 15.4 but in a very coarse granularity. Our work examine the coexistence issues of 11n and 15.4 in a systematic way.

802.15.4 impact on 802.11. It has been found that 802.11 is vulnerable to the 15.4 interference too. Gummadi *et al.* [13] study the impact on 802.11b/g networks of RF interference from devices such as Zigbee and cordless phones that increasingly crowd the 2.4 GHz ISM band. Rahul *et al.* [24] present SWIFT, the first system where high-throughput sideband nodes are shown in a working deployment to coexist with unknown narrowband devices, while forming a network of their own. Weeble [12] is a distributed and state-less MAC protocol that solves the coexistence problem. It considers only WiFi nodes with high power or low power, how to avoid the starvation of low power WiFi nodes. [5] compares the 11g and 11n impact to Zigbee. It considers the increasing throughput of 11g/n impact at overlapping channels and fixed throughput at different channels. Angrisani *et al.* [4] investigate coexistence issues between 11b and 15.4 wireless networks, but not involving 802.11n. Wang *et al.* [11] propose WiCop to address the WBAN-WiFi coexistence problem by effectively controlling the temporal white-spaces between consecutive WiFi transmissions.

Different from the existing work, we studied the coexistence issue between 11n and 15.4, focusing on 11n new features including MIMO, FA and channel bonding.

VI. Conclusion

In this paper, we carried out extensive experiments to study the interference between 802.11n and 802.15.4 networks when they are co-located. From the experiments, we obtain some interesting findings. For example, in symmetric scenarios the throughput degradation of 802.11n primarily steps from backoff, whereas the packet losses of 802.15.4 are primarily due to ACF instead of corruption. The 802.15.4 network has better performance in terms of PDR when the 802.11n network works at 40 MHz or at smaller FA levels. We believe our work is helpful in co-located network deployment and protocol design to deal with the coexistence issues.

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