COFFEE: Coexist WiFi for ZigBee Networks - A Frequency Overlay Approach

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1 INTRODUCTION

The 2.4 GHz ISM band is becoming increasingly over crowded with the ubiquitous usage of WiFi and ZigBee systems. WiFi Access Points (APs) are widely used in urban area for ubiquitous Internet access. Most of them, such as IEEE 802.11g [7] system, are leveraging OFDM communication scheme, and working at the frequency band from 2.402 to 2.482 GHz. The OFDM systems divide the 20 MHz bandwidth into 64 orthogonal subcarriers, and use 52 of them for data transmission. Meanwhile, the Wireless Senor Networks (WSNs) are also applied for real time and long term environmental monitoring in urban area such as urban sensing (*e.g.*, City See) [10], as well as medical health care applications [13]. Unfortunately, the WSNs also select the crowded 2.4 GHz ISM band for communications, which is an over crowded spectrum band.

Many solutions have been proposed to address the coexistence problem of these two heterogeneous networks. Zhang *et al.* [19] exploit a powerful ZigBee node to trigger the WiFi node backing off. While Huang *et al.* proposed a solution beyond coexistence [5] for the ZigBee networks by learning the traffic pattern of WiFi networks, and utilize the idle time to transmit ZigBee packets. Liang *et al.* [9] studied the interference pattern between WiFi and ZigBee networks and proposed the multi-header and RS coding solution to increase the error-resilience capability for ZigBee node. However, all these solutions fall into time domain techniques. Since the band width of ZigBee networks is only 2 MHz, and its data rate is 250 kbps, it takes about 4 ms to transmit one ZigBee packet. While for the WiFi networks, the data rate could be up to 54 Mbps. It takes about only 400 μs to transmit one WiFi packet. Thus a long lasting 2 MHz narrow band signal, say ZigBee, will inevitably blocks a short time 20 MHz wide band signal, say WiFi.

Most of the status quo solutions fall into time domain techniques, and suffer from the two basic constraints. First, handling the two systems in time domain will inevitably affect the performance of WiFi system, especially when WiFi transmissions are in very high rate. Backing off even a slight duration of time would lead to significant throughput reduction for WiFi systems. Second, although some techniques such as interference cancellation (IC) techniques [2] [15] have been applied for collision resolution, it will need significant discrepancy in signal strength. Also, the IC scheme also needs very accurate channel response matrix value, which is difficult to achieve especially when collision happens.

To avoid the inherent drawbacks in time domain techniques, a few seminar works begin to investigate the frequency domain methods. He *et al.* proposed MPAP [4] to avoid the mutual interference with narrow band ZigBee networks leveraging non-continuous OFDM in IEEE 802.11g WiFi networks. And Zhang *et al.* [18] proposed ASN to enable partial spectrum sharing in wireless LANs. However, those solutions need brand new design for WiFi systems, which could not work with the legacy system. Moreover, strong coordinations or network management are also needed.

To enable efficient coexistence for WiFi and ZigBee networks in frequency domain, the following challenges have to be properly addressed. First, we have to enable the WiFi nodes switch between the normal transmission mode and the coexistence mode seamlessly. Any modification of the subcarrier usage has to be recognized and properly handled without interrupting WiFi data transmissions. Second, there should be a brand new data processing scheme for subcarrier nullifying patterns. The receiver should recognize this modification and handle subcarrier nullifying patterns correctly. And inevitably, such modification should also be compatible with standard WiFi data transmissions.

In this paper, we propose a frequency overlay approach COexist wiFi For zigbEE (COFFEE) networks. The proof-of-concept design enables the WiFi networks to efficiently coexist with ZigBee networks. With COFFEE, the WiFi and ZigBee networks can transmit data simultaneously without interfering each other seriously. The implementation is done with USRP, an open source software radio platform, where the impact of various factors, *e.g.*, the SNR values, modulation schemes, *et al.*, are illustratively examined. The evaluation results show that COFFEE could improve network throughput nearly 3 folds comparing to the coexistence technologies in time domain. Even when WiFi node would never share transmission time for ZigBee nodes, COFFEE could still enable the concurrent ZigBee transmissions with only 10% to 15% throughput reduction.

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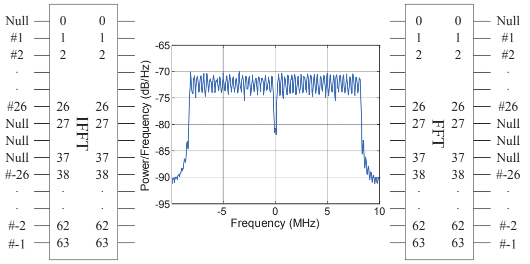


Figure 1: Schematic of OFDM System.

The rest of this paper is organized as follows. We first provide a brief introduction of WiFi and ZigBee technologies in Section 2. And the design details of COFFEE system in Section 3. The implementation and evaluation of COFFEE is presented in Section 4 and Section 5. Finally, we review the related work in Section 6 and conclude our work in Section 7.

2 PRELIMINARIES

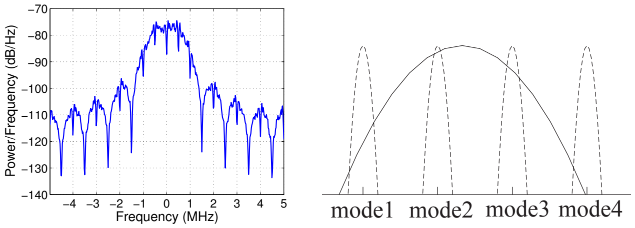
In order to enable coexistence for WiFi and ZigBee networks, we need to investigate details of these two systems. Their salient features as well as import schemes are presented in the following subsections.

2.1 WiFi Overview

The IEEE 802.11 standard [7] defines several physical layer (PHY) specifications for WiFi networks, which are almost ubiquitous in urban areas. Due to the high spectrum efficiency of OFDM systems, we mainly focus our research for IEEE 802.11g networks, which operate at the 2.4 GHz ISM band[7].

The IEEE 802.11g standard specifies the PHY entity for an Orthogonal Frequency Division Multiplexing (OFDM) system, which divides a 20 MHz channel into 64 subcarriers, and uses 52 subcarriers for data transmission. 4 out of 52 subcarriers are dedicated to pilot signals, so as to make the coherent detection robustly against frequency offsets and phase noises. The pilot signals are put in subcarriers numbered in -21, -7, 7 and 21. Each subcarriers are independent to each other. There are four different modulation schemes (*e.g.* BPSK, QPSK, *et al.*). First, a data stream is stripped into bits, with different number of bits assigned to each subcarrier according to modulation scheme. After that, an assignment of modulated bits forms an OFDM symbol which is shown in Fig. 1. To this end, the frequency domain signal of the OFDM symbol is converted to a time domain OFDM symbol by an Inverse Fast Fourier Transform (IFFT) process. Thus, the modulated time domain signal is sent to the RF module.

The receiver firstly determines the exact sample where the packet starts, and performs Carrier Frequency Offset (CFO) as well as channel estimation with PHY layer preambles. After that, the signal is passed to a Fast Fourier Transform (FFT) module for frequency domain processing. The data symbols are then converted to frequency domain signal, corrected for the carrier frequency offset, and demodulated for the originally sending data packets.



(a) PSD of ZigBee Signal **(b) Overlapping Patterns**

Figure 2: PSD and Channel Overlap Patterns of ZigBee.

2.2 ZigBee Overview

The PHY layer of ZigBee networks operating in the 2.4 GHz ISM band is specified in IEEE 802.15.4 standard [6], which is widely used in low rate wireless networks. According to the standard, the PHY layer bytes are divided into two 4-bit symbols. Then, each symbol is mapped to 1 of the 16 nearly orthogonal pseudo-random noises (PN), which is a 32-chip sequence. The chip sequence is modulated onto the carrier using offset quadrature phase-shift keying (O-QPSK) and transmitted at 2 Mchips/s. Thus, the data rate of ZigBee networks is 250 kbps. In showing the modulation scheme with visual impressions, the power spectrum density (PSD) of ZigBee signal is shown in Fig. 2a.

The IEEE 802.15.4 standard defines 16 channels with 2 MHz bandwidth in ISM band. The central frequencies in MHz of these channels are represented as follows:

$$F_c^{ZigBee}(k) = 2405 + 5(k - 11), k = 11, 12, ..., 26$$

Meanwhile, IEEE 802.11 standard defines 13 channels with 20 MHz bandwidth in ISM band, with central frequencies in MHz:

$$F_c^{WiFi}(k) = 2412 + 5(k - 1), k = 1, 2, ...13$$

Since 52 out of 64 subcarriers are utilized in WiFi networks, the occupied frequency is 18.75 MHz bandwidth. Therefore, for any WiFi channel, there are four channel overlapping patterns with ZigBee as illustrated in Fig. 2b.

3 SYSTEM DESIGN

The overall system architecture is shown in Fig. 3. We describe each of these components in detail.

3.1 Dealing with Frequency Overlapping Mode

According to the channel allocation as specified in IEEE 802.11 [7] and IEEE 802.15.4 [6], there are four frequency overlapping modes as described in section 2.2. For each overlapping mode, we need to formally address the issue of subcarrier allocation.

The subcarrier allocation mode of standard IEEE 802.11 WiFi and COFFEE are shown in Fig. 4. The standard subcarrier allocation mode for WiFi is labeled as ‘Standard’ in Fig. 4. Subcarriers numbered -26 to 26 are used as data subcarrier except -21, -7, 7 and 21 which are used as pilot subcarrier.

In order to enable coexistence for WiFi and ZigBee networks, the subcarriers that overlapped with ZigBee channel should be nullified, *i.e.* do not allocate any data or pilot data to them. The four different

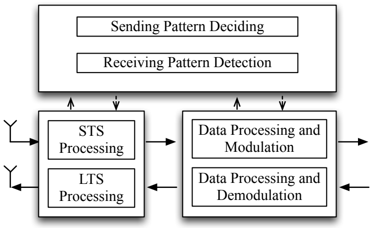


Figure 3: System Architecture.

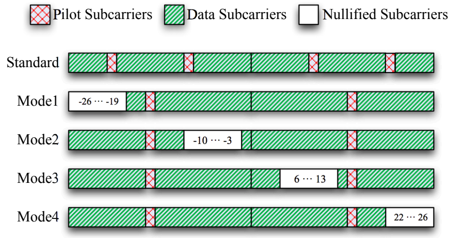


Figure 4: Subcarrier Nullifying Mode.

channel overlapping patterns corresponds to four different subcarrier nullification modes. We illustrate the subcarrier nullification modes in Fig. 4, which are labeled as 'Mode1', 'Mode2', 'Mode3' and 'Mode4' respectively. Specifically, we nullify subcarriers numbered -26, -25, -24,-23, -22, -21, -20 and -19 in 'Mode1'. Subcarriers numbered -10 to -3 are nullified in 'Mode2'. In 'Mode3', we nullify subcarriers numbered 6 to 13. Finally, there are 6 subcarriers are nullified in 'Mode4', *i.e.* 21, 22, 23, 24, 25 and 26. It should be noted that the subcarrier used as pilot should also be nullified. To hold the phase tracking capability, we redesign the pilot structure as shown in Fig. 4, *i.e.* subcarriers numbered -16 and 16 are used as pilot subcarrier.

In addition to the redesigning of 'Pilot', the structure of preamble should also be carefully addressed.

3.1.1 Short Training Symbol. The Short Training Symbol (STS) in IEEE 802.11 WiFi networks consists of 12 subcarriers, which is modulated by the elements of $S_{-26:26}$ [7]. Nonzero amplitude exists in spectral lines being indexed with multiple of 4, which forms a periodicity of $T_{FFT/4} = 0.8us$ (*i.e.* 16 complex samples). The WiFi receiver exploits this property to detect an incoming packet.

To enable subcarrier nullifying for the overlapping ZigBee channels, COFFEE nodes should not use the subcarriers specified in subcarrier nulling mode. Hence, we simply set the value of subcarriers overlapped with ZigBee signal to zero based on standard STS.

3.1.2 Long Training Symbol. The long training symbol (LTS) consists of 53 subcarriers (including a zero value at DC) according to IEEE 802.11 standard [7]. The receiver uses the known LTS to perform channel and fine frequency offset estimation. To enable coexistence with ZigBee networks for our COFFEE nodes, some of the subcarriers are set to zero according to nulling pattern at the transmitter. Since different subcarrier nulling pattern leads to different sequence of LTS, we utilize this feature for the receiver node to detect the subcarrier nulling pattern.

3.2 Overlapping Mode Detection and Recognition

To eliminate the interference between WiFi and ZigBee networks, COFFEE sender should decide which subcarrier nulling mode should be used before data transmission.

Before transmitting data, a COFFEE node should sense the channel status. If the energy of all the subcarriers overlapped with all the four ZigBee channels is lower than a threshold, then the transmitter will use the 'Standard' mode, *i.e.* uses all the available subcarriers. While for the case that, the energy of the overlapping ZigBee channels is higher than a threshold, the transmitter will use the corresponding subcarrier nulling mode, where the transmitter will pass this information to STS/LTS processing block, and then to the data processing and modulation block. Otherwise, the channel is busy and the transmitter will defers its transmission.

For the COFFEE receiver side, we explorer the spectrum feature of received signal to identify the overlapping mode. The incoming packet is firstly detected with energy detection. Normally, WiFi packets are detected by auto correlation with STS. However, auto correlation can not work properly due to the interference of ZigBee signal. Note that, the spectrum feature of different overlapping mode is different with each other. When subcarriers are interfered by ZigBee signal, there amplitude various severely than other subcarriers. The illustration of this feature is shown in Fig. 5. The upper figure plots the spectrum of received signal when WiFi and ZigBee are coexist together. The lower figure shows the amplitude various for different overlapping mode. It can be seen that, the amplitude various of 'Mode2' is much higher than others.

In this way, the COFFEE node could enable coexistence for ZigBee networks effectively.

3.3 Data Processing and mod/demodulation

When the incoming samples as well as subcarrier nullification mode information are passed to data processing block, the FFT is applied first in accordance with IEEE 802.11 standard. Then, the frequency domain data of each subcarrier are mapped to data sequence accordingly, such that, subcarriers being nullified would not make further data processing.

3.3.1 Pilot Subcarriers. In standard mode, four subcarriers are dedicated to pilot signals in order to make the coherent demodulation robust against residual carrier frequency error and phase noise [7]. These pilots are arranged symmetrically to simplify the process of phase tracking. Specifically, these pilots are put in subcarrier -21, -7, 7, and 21. To maintain this property in different overlapping mode, we reduce the number of pilot subcarrier from 4 to 2 and rearrange the position of pilot in subcarrier -16 and 16 as shown in Fig. 4.

3.3.2 Data Subcarrier. We modify the interleaving and deinterleaving processes in COFFEE. The interleaving depth determines the robustness to burst interferences. Note that, we have nullified certain subcarriers, thus the number of subcarriers for data transmission does not comply with standard system. The interleaving

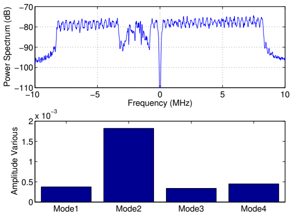


Figure 5: Illustration of overlapping mode detection.

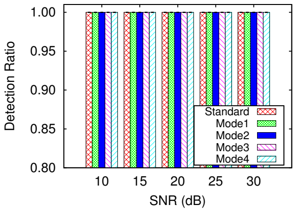


Figure 6: Overlapping mode detection of COFFEE without the presence of ZigBee signal.

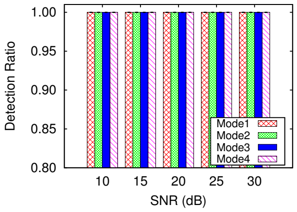


Figure 7: Overlapping mode detection of COFFEE when WiFi and ZigBee with the same SNR.

depth in IEEE802.11 standard is 16. However, in COFFEE system, the interleaving depth should be set according to the number of available data subcarriers. For subcarrier nulling mode 'Mode1', 'Mode2' and 'Mode3', 8 consecutive subcarriers are nullified. After subtracting 2 pilot subcarriers, there are 42 available subcarriers for data transmission. Such that, we could set the interleaving depth to 14. Meanwhile, the interleaving depth of subcarrier nulling pattern 'Mode4' is slightly different, which needs 44 data subcarriers, thus the interleaving depth is set to 11 accordingly.

4 IMPLEMENTATION

We use USRP N200 software radio platform with SBX daughterboard to evaluate COFFEE performance. In COFFEE design, we need full control of the WiFi physical layer, thus we build the prototype with USRP N200. The evaluations are performed with real trace data collected from these customized software radio platforms.

According to IEEE 802.11 OFDM standard series, the sampling frequency of COFFEE is set to 20 MHz. We implement 8 data rates according to different modulation and coding schemes, *i.e.* 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. Since certain subcarriers are nullified to enable coexistence for ZigBee networks, the attainable data rate varies with different subcarrier nullification patterns. We also implement the OQPSK PHY layer of ZigBee networks according to IEEE 802.15.4 standard [6], and the signal bandwidth is set to 2 MHz.

5 EXPERIMENTAL RESULTS

To evaluate the performance of COFFEE comprehensively when WiFi and ZigBee coexist together, we conduct experiments under different modulation schemes, *i.e.*, SNR and channel settings. For WiFi network, we evaluate BPSK, QPSK and 16QAM modulations with 1/2 convolution channel coding. We select WiFi and ZigBee payload length to 512 and 20 Bytes respectively, which are typical settings for WiFi and ZigBee networks. In order to achieve different SNR level both for WiFi and ZigBee networks, we adjust the TX gain of SBX daughterboard. The different overlapping modes are achieved by varying the central frequency of ZigBee. For each experiment setting, we collect 10 traces, and the reported experimental results are averaged over all these 10 traces.

5.1 Micro-Benchmark

We firstly evaluate the micro-benchmark of COFFEE and ZigBee implementation, *i.e.* the performance of COFFEE and ZigBee under different modulation schemes, where SNR and carrier frequency also vary for illustrative evaluations. For micro-benchmark experiments, all the traces are collecting at least 100 packets both for WiFi and ZigBee. Since we use 10 traces for each evaluation, 1000 packets are collected for each experiment setting. In evaluating the coexistence performance between WiFi and ZigBee networks, we set the concurrent WiFi and ZigBee transmissions in every 2 ms.

The Performance of Overlapping Mode Detection We evaluate the performance of overlapping mode detection under various experiment settings, *i.e.* different SNR and overlapping modes. We record the setting of each experiment as ground truth. Then, the receiver detects the overlapping mode of received signal with our proposed scheme. We define detection ratio as: $D_R = N_C/N_R$, where N_C is number of correctly detected packets, and N_R is the number of total received packets.

The performance of overlapping mode detection are shown in Fig. 6 and Fig. 7. Fig. 6 shows the overlapping mode detection results without the interference of ZigBee signal. Fig. 7 shows the detection results when WiFi and ZigBee with the same SNR. We can find that the receiver can always detects the overlapping mode correctly for almost all the experiment settings. When the SNR of ZigBee is lower than that of WiFi, the detection results are similar to Fig. 7. So, we omit the results for limit of space.

The Performance of COFFEE when Overlapping with ZigBee We then study the performance of COFFEE and ZigBee networks when they coexist together. In our evaluations, the SNR difference between WiFi and ZigBee networks is set by the value ranging from 0 dB to 10 dB[1].

The PDR of ZigBee is shown in Fig. 8. It could be seen that when the SNR gap is 0 dB, and the PDR of ZigBee is close to that of ZigBee baseline as shown in Fig. 8a. Such that, COFFEE could successfully nullify the overlapping subcarriers and effectively mitigate the interferences to ZigBee networks. However, when the SNR gap is greater than 5 dB, the PDR of ZigBee drops due to the out of band interference of WiFi signal. Even when the SNR gap is as high as 10 dB, the PDR of ZigBee could still be around 30%.

5.2 Macro-Benchmark

In this section, we evaluate the end-to-end throughput gain of COFFEE. To measure throughput, we generate different traffic patterns for performance comparisons. For 'TDMA' traffic, the WiFi and ZigBee packets are scheduled for interference-free transmission.

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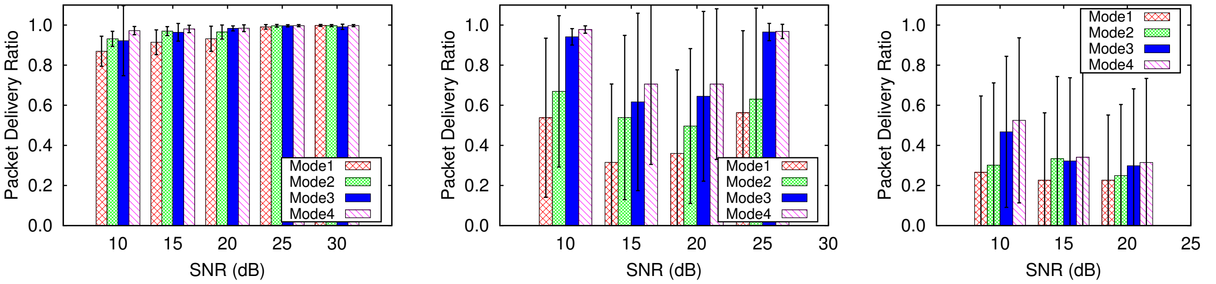
[1] Typically, the SNR value of WiFi is larger than ZigBee. In this experiment, we also obey this rule for evaluations.



(a) When SNR gap is 0 dB. **(b) When SNR gap is 5 dB.** **(c) When SNR gap is 10 dB.**

Figure 8: Performance of ZigBee networks when ZigBee and WiFi coexist together. SNR gap is the SNR difference between WiFi and ZigBee receiver. The x-axis labels the SNR of ZigBee. SNR of WiFi equals to the SNR of ZigBee plus SNR gap.

While for 'COFFEE' traffic, we generate WiFi and ZigBee packets concurrently. The backoff time for WiFi and ZigBee networks is set to 500 μs. The packet length of WiFi and ZigBee are set to 512 and 20 Bytes, which are typical settings for these networks. We evaluate three modulation schemes (BPSK, QPSK, and 16QAM) for WiFi. The SNR value gap between WiFi and ZigBee is set to 25 dB, and the overlapping mode is set to 'mode2'. In this work, we use the following method to measure the throughput of WiFi and ZigBee with different transmission scheme. One USRP node is set for WiFi transmission, and the other one is set for ZigBee transmission. For each experiment configuration, the receiver collets 10 traces over real wireless channels.

The throughput of WiFi and ZigBee networks are shown in Fig. 9a and Fig. 9b respectively. The label 'TDMA' is used for scheduled WiFi and ZigBee transmissions, where packets in TDMA mode. While the label 'COFFEE' means WiFi and ZigBee are transmitting packets concurrently, where COFFEE is applied to achieve the coexistence form WiFi and ZigBee networks.

To examine the throughput gain clearly, we evaluate the throughput gain of COFFEE in Fig. 9c. The throughput gain for ZigBee is about 2×. And the throughput gain of WiFi can as high as 3×. Note that, the throughput gain of WiFi is higher when 16QAM modulation scheme is applied, because it could take less time for WiFi to transmit with higher data rates.

6 RELATED WORK

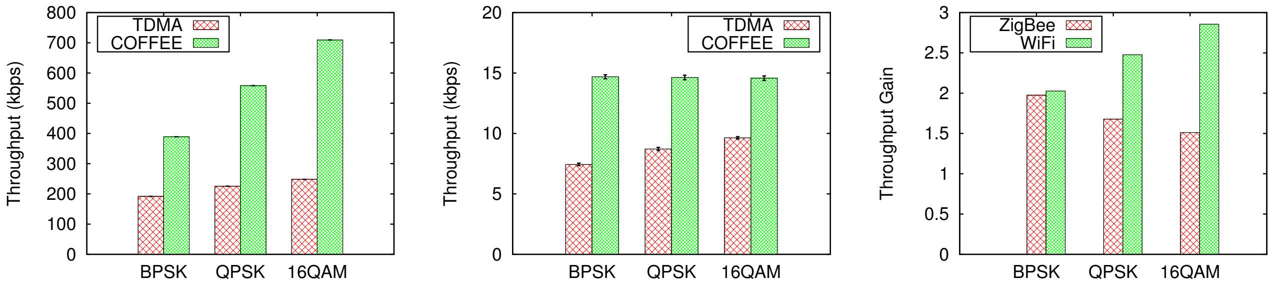
Previous solutions can be classified into two main categories: time domain solutions and frequency domain solutions.

6.1 Time domain solutions

Zhang *et al.* [19] proposed a mechanism called Cooperative Busy Tone (CBT) to enable the coexistence for WiFi and ZigBee networks. CBT specifies a separate ZigBee node to schedule a busy tone concurrently with the desired transmission, thereby causing the nearby WiFi device sense the ZigBee device to defer its transmission. Wang *et al.* [16] uses a fake WiFi PHY preamble-header broadcast to mute other WiFi interferers, and uses repeated WiFi PHY preamble to mute other WiFi interferers throughout the duration of ZigBee active period. Huang *et al.* [5] presents a Pareto model to characterize the white space in WiFi traffic, where a ZigBee frame control protocol called WISE is developed to achieve traded-offs between link throughput and delivery ratio. WISE predicts the WiFi traffic based on the Pareto model, and intelligently adapts frame size to maximize the throughput efficiency with assured packet delivery ratio. Kannan *et al.* proposed an off-line strategy to quantify the level of link burstiness due to interference, known as the β-factor, from RSSI traces [14]. ZigBee nodes then use this information to estimate the expected duration of the interference and defer outgoing packet transmissions to reduce the retransmission cost. Liang *et al.* [9] examines the interference pattern between ZigBee and WiFi networks at the bit-level granularity. Then, Multi-Header and TinyRS are proposed to increase the detection probability and helps to decode corrupted payload respectively. However, all of the time domain solutions need the WiFi transmitter to defer its transmission and wait during ZigBee transmission, which leads to severe spectrum under utilization, since it takes more than 10 times longer to transmit a ZigBee packet than WiFi. More importantly, the time domain solutions will suffer from the channel interference level, as well as the inaccuracy of the channel state information.

6.2 Frequency domain solutions

Rahul *et al.* [12] presents SWIFT to enable high-throughput wideband nodes to coexist with unknown narrowband devices. Poston *et al.* [11] demonstrated the feasibility of NC-OFDM using a software radio based prototype, which was implemented by directly nulling the subcarriers of an OFDM communications system. Gollakota *et al.* [1] enables 802.11n to communicate in the presence of high-power cross-technology interference. He *et al.* [4] proposed MPAP to avoid the mutual interference with narrow band ZigBee networks leveraging non-continuous OFDM in 802.11g WiFi networks. Gollakota *et al.* [2] exploits interference cancellation technique to redesign the carrier sensing mechanism to improve the performance of wireless local area networks. Halperin *et al.* [3] and Kun *et al.* [15] use interference cancellation technique in multiuser MIMO scenario. Li *et al.* [8] proposed Collision-Resistant Multiple Access (CRMA) to achieve high efficiency. In CRMA, each transmitter views the OFDM physical layer as multiple orthogonal but sharable channels, and independently selects a few channels for transmission. In addition, Zhang *et al.* [18] propose adaptive subcarrier nulling (ASN) to enabling partial spectrum sharing in wireless LANs. ASN builds on



(a) Throughput of WiFi networks. **(b) Throughput of ZigBee networks.** **(c) Throughput gain of COFFEE.**

Figure 9: Throughput performance comparison between TDMA and COFFEE.

the 802.11 OFDM PHY, allowing the radio to sense, transmit, detect and decode packets through spectrum fragments. However, most of them fail to tailor the coexistence techniques for ZigBee networks, *e.g.* the transmission rate, SNR value, *etc.*, which will inevitably lead to throughput loss.

COFFEE differs from those solutions mentioned above in the following two aspects:

(1) COFFEE can effectively utilize the OFDM subcarriers when WiFi transmitters are backing off, which improve the spectrum utilization considerably. Besides, COFFEE can enable concurrent transmission disregard of the traffic load of WiFi networks and improve the throughput performance for both of them.

(2) COFFEE is tailored for the coexistence for WiFi and ZigBee networks, the impact of varies factor on the performance of WiFi and ZigBee networks are examined comprehensively.

7 CONCLUSION

In this paper, we investigate the coexistence problem between WiFi and ZigBee networks in frequency domain to maximize the spectrum utilization. We propose COFFEE, a frequency overlap approach, to enable the WiFi networks to efficiently detect the presence of ZigBee networks and identify the overlapping modes. With COFFEE, the WiFi and ZigBee networks can transmit data concurrently and maximize the spectrum utilization. We implement COFFEE with USRP software radio platform using commercial compatible implementations of WiFi and ZigBee. Our evaluation results show that COFFEE could improve the throughput gain of WiFi as high as 3× more than that when WiFi and ZigBee transmit packet alternatively.

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