IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 29, 2019, accepted September 11, 2019, date of publication September 17, 2019, date of current version October 1, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2941963

Coexist WiFi for ZigBee Networks With Fine-Grained Frequency Approach

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This work was supported in part by the National Key Research and Development Plan under Grant 2017YFB0801702, in part by the NSFC under Grant 61625205, Grant 61632010, Grant 61772546, Grant 61772488, and Grant 61520106007, in part by the Key Research Program of Frontier Sciences, CAS, under Grant QYZDY-SSW-JSC002, in part by the NSFC under Grant NSF ECCS-1247944 and Grant NSF CNS 1526638, in part by the NSF of Jiangsu For Distinguished Young Scientist under Grant BK20150030, in part by the Fundamental Research Funds for the Central Universities under Grant WK2150110014, and in part by the Anhui Provincial Natural Science Foundation under Grant 1908085QF296.

ABSTRACT The widely deployed WiFi APs and ZigBee devices make the coexistence for these two networks more pervasive than ever. Previous solutions focus on the contention resolution in time domain, but would lead to the underutilized frequency resources. However, for frequency domain schemes, to enable efficient coexistence for WiFi and ZigBee networks, the WiFi nodes or ZigBee nodes have to select the appropriate channel for transmission. Such scheme will need strict cooperations among these two independent systems, and could not work with the conventional legacy systems seamlessly. In this paper, we propose a frequency overlay approach named COFFEE (COexist wiFi For zigbEE networks), where subcarriers interfering with ZigBee transmissions are nullified by WiFi. According to our basic evaluations, due to the relatively robust feature in WiFi/OFDM design, nullifying small portion of subcarriers would affect the WiFi performance slightly, but could improve the capability for coexistence significantly. Thus by using COFFEE, WiFi and ZigBee nodes can transmit their packets concurrently without any coordination. Also, COFFEE and conventional legacy WiFi systems could work together seamlessly. Furthermore, we implement COFFEE with USRP software radio platform and evaluate the performance under real wireless network scenarios. The extensive evaluations show that compared to the coesistence schemes in time domain, COFFEE is able to increase the network throughput by more than 300%. Even when the ZigBee node never knows the transmission time of WiFi packet, it still can provide concurrent lossless transmission by using COFFEE with only 10% to 15% WiFi throughput reduction.

INDEX TERMS Coexistence, WiFi, ZigBee, OFDM.

I. INTRODUCTION

The demand for information has brought prosperity to network systems such as WiFi and zigbee, which have also crowed the 2.4GHz ISM band where these networks operate at. The WiFi Access Points (APs) are widely used for ubiquitous Internet access. Benefit from the high frequency utilization, most of existing WiFi system, such as IEEE 802.11g [1] system, are using OFDM communication scheme, and operating at the frequency range of 2.402 $\sim$ 2.482 GHz. An OFDM channel occupies a 20 MHz bandwidth and is divided into 64 orthogonal subcarriers, and use 52 of them for data transmission. On the other hand, the Wireless Sensor Networks (WSNs) beginning to play an increasingly important role in long-term and real-time environmental monitoring in urban areas, (*e.g.*, City See) [2], as well as health-care applications [3]. Unfortunately, the WSNs also communication at the

The associate editor coordinating the review of this manuscript and approving it for publication was Irfan Ahmed.

crowed 2.4 GHz ISM band, making such band more crowded.

The coexistence problem between these two heterogeneous networks has attracted the attention of many researchers. Zhang and Shin [4] design an enhanced ZigBee node to trigger the back-off scheme of WiFi node by broadcasting a high-power beacon. Huang *et al.* presented a solution beyond coexistence [5] for ZigBee networks by learning the traffic pattern of WiFi networks, and leverage the idle interval for ZigBee communications. While Liang *et al.* [6] investigated the model of interference between WiFi and ZigBee networks and designed a packet structure with multi-header and RS coding to improve the robustness of ZigBee networks. All the above solutions solve the coexistence problem in time domain, and have an unavoidable shortcoming. Specifically, the ZigBee network has the bandwidth of only 2 MHz, with the data rate of 250 kbps, one ZigBee packet will take about 4 ms to transmit. While for WiFi networks with the data rate up to 54 Mbps, the WiFi packet will lasting to only 400 μs. Therefore, the ZigBee packet with long lasting time will inevitably interferes the WiFi packet with short packet duration.

Although address the coexistence problem of heterogeneous networks in the time domain has been a popular method in the past decade, two basic constraints limit their performance. First, coexist two networks in time domain will inevitable degrade the performance of WiFi network, especially when WiFi transmit at high data rate. Backing off even a slight time slot would result in significant throughput reduction for WiFi system. Second, although some techniques such as interference cancellation (IC) [7], [8] have been used for collision resolution, these methods work only when there is a significant gap in signal strength. Besides, the IC technique also needs high accuracy channel estimation, which is difficult to obtain especially when collision occurs. Moreover, all the above methods require modification on ZigBee nodes. By considering the large amount of ZigBee nodes, such hardware or software modification will take a significant amount of time, which is not acceptable for large-scale coexistence network deployment.

To avoid the inherent drawbacks of such time domain coexisting schemes, some recent studies began to exploit the methods in frequency domain. He *et al.* leverages the non-continuity of OFDM in IEEE 802.11g WiFi networks, and proposes MPAP [9] to avoid its interference on narrow band ZigBee networks. Similarly, Zhang *et al.* proposed ASN [10] to enable partial spectrum sharing in WLANs. Unfortunately, these schemes still unsuitable for large-scale coexistence network. For example, ASN [10] requires strong coordination among ASN nodes. This centralized network structure is difficult to adapt to the need for large-scale network. On the other hand, MPAP [9] designs a virtual network card to let MPAP nodes to replace WiFi and ZigBee nodes. However, this modification still involves large amount of ZigBee nodes and hardly to be adopted by the large-scale coexistence network.

To coexist WiFi and ZigBee networks efficiently in frequency domain, some unavoidable challenges must be addressed properly. First, the WiFi nodes have to switch between standard communication mode and coexistence mode seamlessly. Any adjustment of subcarrier usage must be known by the WiFi nodes and properly processed without interrupting their data transmissions. Second, a new data processing algorithm is needed for subcarrier nullifying patterns. Receiver must know such adjustment and handle the subcarrier nullifying patterns suitably. Obviously, such adjustment also has to be compatible with the legacy WiFi systems.

In this paper, we present COFFEE (COexist wiFi For zigbEE), a frequency overlay approach, which enables the WiFi networks to coexist with ZigBee networks efficiently. By using COFFEE, WiFi and ZigBee networks can transmit their packets simultaneously without causing serious interference. We implement the prototype of COFFEE on USRP N200 platform, and test the impact of various parameters, such as the SNR values, modulation schemes, *et al.*. The evaluation results show that COFFEE can improve the network throughput nearly 300% comparing to the previous time domain coexistence schemes. Even when ZigBee nodes never known the transmission time information of WiFi node, COFFEE can still enable the concurrent ZigBee communications with only 10% $\sim$ 15% througput reduction of WiFi networks. In summary, our contribution is two-fold:

1) We propose a frequency domain scheme COFFEE, which utilizes the spectrum resources in frequency domain. By applying COFFEE, the WiFi and ZigBee networks can coexist together with efficient spectrum utilization. COFFEE doesn't need any modification in ZigBee networks. Besides, COFFEE can switch between legacy devices and COFFEE nodes seamlessly for WiFi and ZigBee networks.
2) We focus on the issues of WiFi and ZigBee networks coexistence and propose certain customized techniques to improve the efficiency of both networks. Further, we provide specific guidelines to enable effective coexistence for WiFi and ZigBee networks with comprehensive experimentations.
3) Comparing with previous works, COFFEE only needs to modify the software of WiFi node slightly, rathen than modify the hardware of wireless nodes, and is suitable for large-scale coexistence network deployment.

The rest of this paper is organized as follows. We first introduct WiFi and ZigBee technologies briefly in Section II. Then the motivation is described in Section III, followed by the technique details of COFFEE design in Section IV. The implementation and evaluation of COFFEE is presented in Section V and Section VI. After that, we discuss some related issue and compare COFFEE with some related work in Section VII and Section VIII. Finally, we conclude our work in Section IX.

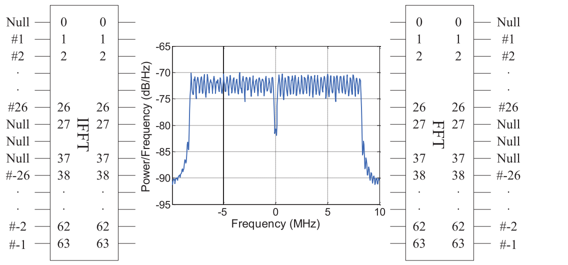
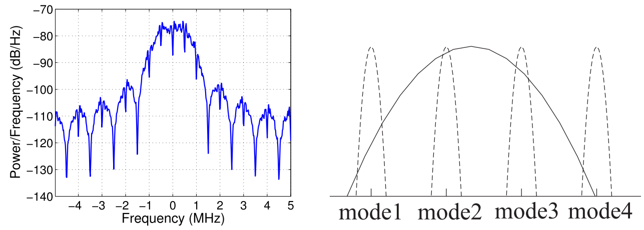


FIGURE 1. Illustration of OFDM System.



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

FIGURE 2. PSD and channel overlap patterns of ZigBee.

II. PRELIMINARIES

In order to solve the problem of the coexistence for WiFi and ZigBee networks, we need to investigate technique details of both networks first. In this section, we present the salient features and some important schemes of WiFi and ZigBee networks.

A. WiFi OVERVIEW

As an ubiquitous network in urban areas, WiFi networks' physical layer (PHY) specifications are defined by the IEEE 802.11 standards. In this paper, we focus our research on IEEE 802.11g network which operate in the 2.4 GHz ISM band [1], since the high spectrum efficiency of OFDM modulation it used.

According to the IEEE 802.11g standard, WiFi network applies Orthogonal Frequency Division Multiplexing (OFDM) as its PHY entity. The WiFi channel occupies a bandwidth of 20 MHz and is divided into 64 subcarriers. WiFi uses 52 subcarriers for data transmission, and 4 out of these subcarriers are allocated to pilot signals (numbered in $-21, -7, 7$ and 21), so as to make the WiFi networks robustly against to frequency offsets and phase noises. All subcarriers are independent to each other, and four different modulation schemes (*e.g.*, BPSK, QAM, 16 QAM and 64 QAM) are designed to adapt different demand of throughput. To transmit a WiFi packet, the data stream is converted into bits at the beginning, depending on the modulation scheme, each subcarrier will be assigned a different number of bits. Then, the modulated bits are assigned to form an OFDM symbol as it illustrated in Fig. 1. After that, the frequency domain OFDM symbol is converted to time domain by doing an Inverse Fast Fourier Transform (IFFT) operation. Finally, such modulated OFDM symbol is feed to the RF front-end and broadcast to the air consequently.

When a packet is incoming, the receiver firstly identifies its start edge, and estimates the Carrier Frequency Offset (CFO) as well as channel state information (CSI) by leveraging the PHY layer preambles. After that, the time domain signal is converted to frequency domain by operating a Fast Fourier Transform (FFT). And the signal processing such as CFO correction, demodulation, and CRC checking will be performed followed by.

B. ZIGBEE OVERVIEW

ZigBee network is a widely used low-rate wireless network which operates in the 2.4 GHz ISM band, its PHY layer is specified in IEEE 802.15.4 standard [11]. According to IEEE 802.15.4, the PHY layer bytes are divided into two 4-bits symbols, and each symbol is mapped to 1 of 16 nearly orthogonal pseudo-random sequences (PN), which forms a 32-chips sequence. The chip sequence is then modulated onto the carrier by using Offset Quadrature Phase-Shift Keying (O-QPSK) and transmitted at the rate of 250 kbps. Fig. 2a illustrates the Power Spectrum Density (PSD) of ZigBee signal.

According to IEEE 802.15.4 standard, 16 ZigBee channels are allocated in ISM band, each has the bandwidth of 2 MHz. The central frequencies of these channels can be calculated as follows:

$$F_c^{ZigBee}(n) = 2405 + 5(n-11)(MHz), \quad n = 11, 12, \ldots, 26$$

On the other hand, there are 13 WiFi channels defined by IEEE 802.11g standard, each with the bandwidth of 20 MHz. The central frequencies of each WiFi channel are represented as follows:

$$F_c^{WiFi}(n) = 2412 + 5(n-1)(MHz), \quad n = 1, 2, \ldots 13$$

As we discussed above, WiFi networks use 52 out of 64 subcarriers for data transmission, therefore the occupied frequency is 18.75 MHz. As a result, for any WiFi channel, there are four channel overlapping patterns with ZigBee as shown in Fig. 2b.

III. MOTIVATION

With the pervasive usages of IOT (Internet Of Thing) deployment, ZigBee networks are widely existed around office buildings, homes, and even outdoors in urban area, where the interference between WiFi and ZigBee networks is becoming more severe than ever [6], [12], [13]. In this section, we examine the performance of WiFi and ZigBee networks when they interfere with each other.[1] Also, we transmit WiFi packets by intentionally nullifying subcarriers that would interfere with ZigBee networks. We are to investigate two major concerns in the following experimental evaluations.

First, we need to know the packet loss rate when some subcarriers are nullified. This setting is based on the simple fact that, if the SNR value is high enough, the packet

[1] Here interference means there is a relatively significant packet loss rate when either network is involved.

loss rate would not drop significantly. Since OFDM/WiFi transmissions could effectively mitigate selective frequency effects, some nullified subcarriers would possibly not affect the system performance much.

Second, we need to know the ZigBee system delivery ratio even when the interfering subcarriers are nullified by WiFi system. Since these subcarriers could not be perfectly nullified and there are still residual interference among subcarriers, the performance of ZigBee transmissions should also be evaluated.

In this section, we first make basic observations for the above concerns. Since this evaluation is in preliminary stage, many design concerns are not addressed. We only need to show the effectiveness of the proposed subcarrier nullification scheme, and consider the details for system design after the proposed solution is verified by some basic experiments. We show the design details in Section IV.

A. EXPERIMENT SETUPS

We implement the PHY layer of WiFi and ZigBee networks according to IEEE 802.11g and IEEE 802.15.4 respectively. In general, the sampling frequency of WiFi node is 20 MHz, and it can provide data rate with 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. The sampling frequency of ZigBee node is 2 MHz, and the data transmission rate is 250 kbps.

We calculate the throughput as follows:

$$Throughput = \frac{N_c \times l}{t_c}$$

where N_c denotes the number of corrected received packets, l denotes the length of packets, and t_c denotes the channel occupation duration for a transmission.

We study the per pair link throughput. The sender node sends 1000 packets to receiver node. The size of WiFi packet and ZigBee packet is 256 Bytes and 20 Bytes respectively which are typical settings for WiFi and ZigBee transmissions [12], [13]. Without loss of generality, we use channel 1 for WiFi networks (with central frequency at 2.412 GHz), and channel 11 for ZigBee networks (with central frequency at 2.405 GHz).

B. FREQUENCY DOMAIN COEXISTENCE

We study the throughput performance when subcarrier nullification is concerned. For ease of comparison, we make two types of design. One is typical settings, where subcarriers are not nullified. And the other one is designed with subcarrier nullification.

1) BASELINE DESIGN

In this scenario, the PHY layer of WiFi nodes strictly complies with the IEEE 802.11 standard. In short, 48 subcarriers are used for data transmission, and 4 subcarriers are used for pilot transmission. We let the WiFi sender and the ZigBee sender transmit packet alternatively. Each of them transmits 1000 packets in our evaluation. Also, the SNR values of WiFi and ZigBee sender are ranging from 1 to 30 dB.

As depicted in Fig. 3 and Fig. 4, the attainable throughput of WiFi nodes is much less than the nominal throughput, about 63% for BPSK(1/2) and 15% for 64QAM(3/4) respectively. The severe decline of throughput is caused by the channel contention of ZigBee nodes. The 'baseline' schemes in the caption of Fig. 3 and Fig. 4 refer to the OFDM implementation according to the IEEE 802.11g standard, when WiFi and ZigBee networks coexisted together. However, the bandwidth of ZigBee node is only 2 MHz, while the WiFi node's is 20 MHz. A narrow band network blocks a wide band network, which results in low channel utilization. This could be unacceptable especially for the crowded 2.4 GHz ISM band.

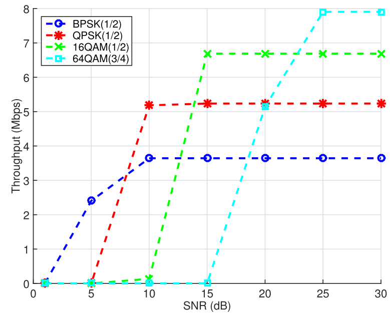


FIGURE 3. Throughput of baseline WiFi scheme.

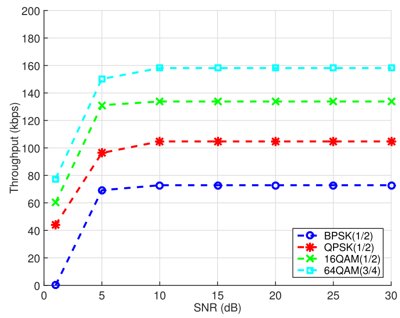


FIGURE 4. Throughput of baseline ZigBee scheme.

2) SUBCARRIER NULLIFICATION

We then implement a WiFi networks with subcarrier nullifications. Specifically, the value of the subcarriers that overlapped with ZigBee channel are set to 0. In this case, the subcarriers numbered −26, −25, −24, −23, −22, −21, −20 and −19 are nullified. In the case with subcarrier nullifying, WiFi packet contains 42 data subcarriers and 2 pilot subcarriers.

In this scenario, both WiFi sender and ZigBee sender could transmit packets simultaneously without interfere with each other. Since the transmit power of WiFi nodes usually are 10 ∼ 100 times higher than ZigBee nodes [6], we let the power of WiFi node 15 dB higher than ZigBee node.

The throughput of WiFi and ZigBee networks are illustrated in Fig. 5 and Fig. 6. Remember that, the SNR of WiFi signal is 15 dB higher than ZigBee signal. So, the SNR of ZigBee signal varying from 1 to 30 dB, while the SNR of WiFi signal varying from 16 to 45 dB. As depicted in Fig. 5, when the SNR of ZigBee is greater than 25 dB, there is a

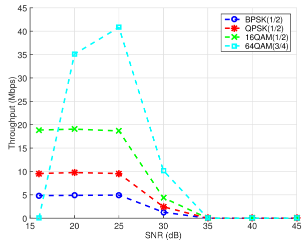


FIGURE 5. Throughput of WiFi when subcarrier nullification is applied.

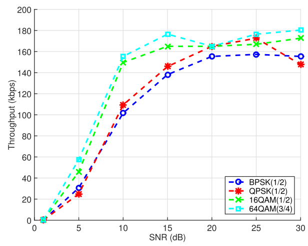


FIGURE 6. Throughput of ZigBee when WiFi subcarrier nullification is applied.

significant decrease in WiFi throughput. The main reason is, when the power of ZigBee networks becomes stronger, especially stronger than 10 dB, the interference to WiFi networks becomes significant.

To clearly make comparisons between the baseline and subcarrier nullification scheme, we select the throughput of WiFi networks when SNR is 25 dB and the throughput of ZigBee networks when SNR is 10 dB. The throughput gain of WiFi networks is defined as (Throughput of WiFi when subcarrier nullification is applied to WiFi) / (Throughput of baseline WiFi scheme). While the throughput gain of ZigBee networks is defined as (Throughput of ZigBee when subcarrier nullification is applied to WiFi) / (Throughput of baseline ZigBee scheme). As shown in Fig. 7, it can be clearly seen that the WiFi nodes with subcarrier nullification can achieve a throughput nearly 5 times higher than that without subcarrier nullification. The throughput gain of ZigBee networks is lower due to the high interference of WiFi nodes.

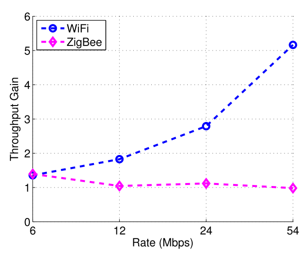


FIGURE 7. Throughput Gain when WiFi subcarrier nullification is applied.

We can conclude that, coexistence for WiFi and ZigBee networks in frequency domain can improve the attainable throughput for both of them. To realize such a network design, we have to properly deal with the challenges in designing such a coexistent network.

1) We should ensure that the WiFi nodes can switch its state between the standard transmission mode and subcarrier nullifying mode seamlessly. Any modification of subcarrier usage should be known and properly processed without causing any interruption of WiFi communication.
2) We have to design a new data processing schemes for different subcarrier nullifying patterns. Such subcarrier nullifying mode must be recognized by the receiver and be handled properly. Moreover, the mode modification should be compatible with the standard WiFi networks.

IV. SYSTEM DESIGN

The main challenge to enable coexistence for WiFi and ZigBee networks is to detect and nullify the overlapping subcarriers while keeping the salient feature of OFDM systems. We achieve this goal by redesigning three key components of OFDM communication systems:

- dealing with frequency overlapping mode
- overlapping mode detection and recognition
- signal processing and packet mod/demodulation

The architecture of COFFEE system is illustrated in Fig. 8, The technique details of these components will be described as follows.

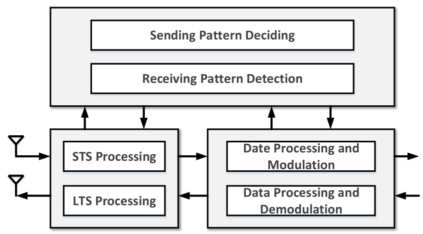


FIGURE 8. System architecture.

A. DEALING WITH FREQUENCY OVERLAPPING MODE

As we discussed in section II-B, according to the IEEE 802.11g [1] and IEEE 802.15.4 [11] protocols, there are four channel overlapping models in WiFi and ZigBee coexistence scenarios. Therefore, we have to carefully re-allocate the subcarriers for each overlapping mode.

Fig. 9 illustrates the subcarrier allocation scheme of standard IEEE 802.11g WiFi and COFFEE. For standard WiFi

FIGURE 9. Subcarrier nullifying mode.

system, the subcarriers numbered $-26 \sim 26$ are used for data transmission (*e.g.* Data Subcarrier) except four subcarriers (No. -21, -7, 7 and 21) which are allocated for pilot signal transmission(*e.g.* Pilot Subcarrier).

In order to make the coexistence for WiFi and ZigBee networks possible, we need to nullify the WiFi subcarriers which collided with ZigBee channel, *i.e.* do not assign any data or pilot signal to them. According to different channel overlapping patterns, we classify the subcarrier nullification schemes into four modes and label them as 'Model $1 \sim 4$' in Fig. 9. Specifically, in 'Mode 1', we nullify the subcarriers numbered from -26 to -19. Subcarriers numbered from -10 to -3 are nullified in 'Mode 2' while the No.6 $\sim$ No. 13 subcarriers are nullifed in 'Mode 3'. And for 'Mode 4', we nullify the subcarriers of No. $21 \sim 26$. COFFEE nullifies 8 subcarriers for 'Model $1 \sim 3$' and clears the bandwidth of 2.5 MHz except 'Model 4', in which WiFi only overlaps part of ZigBee's spectrum. It should be noted that each ZigBee channel occupies 2 MHz bandwidth, the extra 500 kHz bandwidth COFFEE nullifies can provide proper redundancy for preventing the interference caused by Doppler shift. It should be noted that in these modes, the pilot subcarriers are also nullified as well as data subcarriers. Therefore, in order to ensure the phase tracking capability, we reallocate the pilot subcarriers as shown in Fig. 9. Specifically, we allocate the subcarrier No. -16 and No. 16 for pilot signal transmission. Accordingly, the preamble structure also need to be addressed carefully due to the redesigned 'Pilot Subcarrier'.

1) SHORT TRAINING SYMBOL

According to IEEE 802.11g protocol, the Short Training Symbol (STS) in WiFi is designed to provide information to help the WiFi receiver to detect an incoming packet. It contains 12 subcarriers, which are modulated by the elements of $S_{-26:26}$ [1]. The Non-zero amplitude values exist in spectral lines which are indexed with multiple of 4, and forms a periodicity of $T_{FFT/4} = 0.8\mu s$ (*i.e.* 16 samples).

To ensure the subcarriers which are overlapped with ZigBee channels are nullified, Such subcarriers specified in subcarrier nulling modes should not be used in COFFEE. To this end, we force the value of these overlapped STS subcarriers to zero.

2) LONG TRAINING SYMBOL

According to IEEE 802.11g standard [1], the Long Training Symbol (LTS) contains 53 subcarriers (including a zero value at DC). It can be used by receiver to perform symbol synchronization, channel estimation, as well as frequency offset compensation. Similar with the STS, some of the subcarriers are set to zero depends on different nullifying pattern at the sender, and provide the capability of coexistance between ZigBee networks and COFFEE nodes. Since different subcarrier nullifying pattern causes different LTS sequences, COFFEE leverages this feature to recognize the subcarrier nulling pattern at the receiver side. The detail description of pattern detection will be described in the following subsection.

B. OVERLAPPING MODE DETECTION AND RECOGNITION

To avoid the interference between WiFi and ZigBee networks, COFFEE sender needs to determine which subcarrier nullifying mode can be applied before its transmission. To this end, COFFEE node should listen to or sense the channel or subcarrier occupancy before transmitting any packet. If the amplitude variance of all subcarriers which may overlapped with ZigBee channels is lower than a given threshold, then COFFEE node considers there is no conflict happen and transmits signal by using the 'Standard' mode, *i.e.* leverages all data and pilot subcarriers. However, if the variance of one overlapping ZigBee channel exceeds such threshold, COFFEE node will apply the corresponding subcarrier nullifying mode, and feeds the mode information to 'STS/LTS Processing Block', and the 'Signal Processing and Packet Modulation Block' consequently. Otherwise, COFFEE node considers the channel is busy and defers its transmission.

When server as a receiver, COFFEE identifies the overlapping mode by leveraging the spectrum feature of the received signal. COFFEE first detects the incoming packet by using energy detection. Normally, WiFi packet can be detected by performing the delay and auto-correlation operation with STS. However, due to the ZigBee interference, this method can not work well. When packet has been detected, COFFEE performs a 256-point FFT to calculate the spectrum feature of the incoming packet. Note that the spectrum features among overlapping modes are different with each other. When a subcarrier is interfered by ZigBee signal, its amplitude changes more significantly than other subcarriers. Fig. 10 illustrates such feature. The upper sub-figure shows the spectrum of the conflicted WiFi and ZigBee packet, while the lower figure sub-figure plots the amplitude various for different overlapping mode. Obviously, the amplitude various of 'Mode 2' is much higher than other modes, and COFFEE will leverage the 'Mode 2' subcarrier nullifying scheme consequently and enable the coexistence for ZigBee networks effectively. We remind readers that the 256-point FFT operation requires only a small amount of computational resources (the time complexity is $O(N \times logN)$) and cost few time (about few microseconds). Therefore, it does not cause serious impact on the typical WiFi packet demodulation. However, to the control frames (*e.g.* RTS, CTS and ACK) which may need fast response (about $10\mu s$), the time cost of FFT may cause serious impact on them and we regard this problem as our future work.

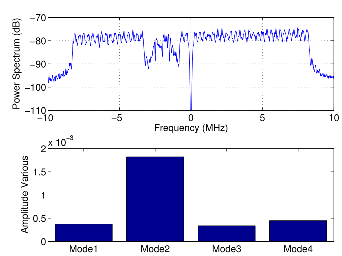


FIGURE 10. Illustration of overlapping mode detection.

C. SIGNAL PROCESSING AND PACKET MOD/DEMODULATION

When the subcarrier nullification mode information and incoming samples are feed into data processing block. COFFEE will perform the packet detection and symbol synchronization again by leveraging the STS and LTS. According to the conclusion of our previous work, the STS and LTS can still be used for packet detection and symbol synchronization even if several subcarriers are nullified [14]. After that, a FFT operation is performed first to transform the time domain symbol into frequency domain. Then the frequency domain data of each subcarrier are mapped to bit sequence accordingly and do further processing except the nullified subcarriers.

1) PILOT SUBCARRIERS

In standard mode, four pilot subcarriers are allocated to enhance the robustness of the coherent demodulation against the residual CFO and phase noise [1]. These pilots are arranged symmetrically (No. −21, No. −7, No. 7 and No. 21) to imporve the performance of phase tracking. To maintain their property in overlapping modes, COFFEE reduces the pilot subcarrier number (from 4 to 2) and rearrange the pilot symbol in subcarriers indexed −16 and 16 as illustrated in Fig. 9.

2) DATA SUBCARRIER

We further adjust the interleaving and de-interleaving processes in COFFEE. The depth of interleaving determines the system robustness to burst interference. Since we have nullified some subcarriers in COFFEE, thus the number of data subcarrier does not as same as it in standard WiFi system. In IEEE 802.11g standard, the interleaving depth is 16, however, in COFFEE, the interleaving depth should be adjusted depends on the number of available data subcarriers. For subcarrier nullifying 'Mode 1', 'Mode 2' and 'Mode 3', COFFEE nullifies 8 consecutive subcarriers. Therefore, 42 subcarriers can be used for data transmission. In this case, the interleaving depth is set to 14. Meanwhile, there are 44 data subcarriers when COFFEE applies 'Mode 4' subcarrier nulling pattern, and the interleaving depth should be slightly different, which is set to 11 accordingly.

V. IMPLEMENTATION

We implement COFFEE on our USRP N200 software radio platform with SBX daughterboard, and evaluate the system performance via real-world experiments. According to IEEE 802.11g, the sampling rate of COFFEE is set to 40 MHz. depending on different modulation and coding schemes, 8 data rates are implemented, *i.e.* 6, 9, 12, 18, 24, 36, 48 and 56 Mbps. Since some subcarriers are nullified to enable coexistence for ZigBee communication, the actual data rate would varies among different subcarrier nullifying patterns. We also implement the O-QPSK PHY layer of ZigBee networks with the bandwidth of 2 MHz based on IEEE 802.15.4 [11]. In order to minimize the interference caused by frequent WiFi and Bluetooth communication during the day, all experiments were conducted in the midnight and there are only nodes communicate in the 2.4 GHz band.

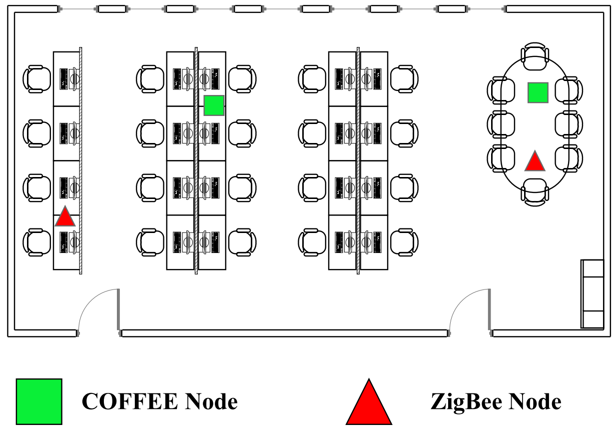


FIGURE 11. Experiment Setup: The room size is 13*m* × 7*m*, the green squares represents COFFEE nodes, the red triangles represents ZigBee nodes. All nodes are implemented on USRP N210.

VI. EXPERIMENTAL RESULTS

We conduct the real-world experiments in a 13 $m \times 7$ m office room, Fig shows the floor plan of the office, where the green squares represent COFFEE nodes, while the red triangles represent ZigBee nodes. The LOS path between COFFEE nodes is blocked by the screen of the desk and the communication is in a multipath environment. In order to make a deep sense of how COFFEE performs on the coexistence of WiFi and ZigBee, the experiments are conducted under various parameters, such as modulation schemes, SNR levels, as well as channel settings. For WiFi network, we test the BPSK, QPSK and 16 QAM modulation with 1/2 convolution channel coding. The packet length of WiFi and ZigBee are set to 256 and 20 Bytes respectively, which are typical settings for both networks. In order to obtain WiFi and ZigBee signals with different SNR level, we adjust the TX gain of USRP. The overlapping modes are implied by varying the channel of ZigBee communication. For each experimental setting, we collect 10 traces, and average all these 10 traces as the reported experimental results.

A. MICRO-BENCHMARK

We first test some micro-benchmark of COFFEE and ZigBee prototypes. In this experiment, we vary the signal modulation, SNR and carrier frequency of both COFFEE and ZigBee, and test their performance. In each evaluation we collect 10 traces, and for each trace, at least 100 packets for both WiFi and ZigBee are collected. Therefore, 1000 packets are collected for each experimental configuration. Both WiFi and ZigBee nodes transmit their signals concurrently in every 2 ms to eveluate the coexistence performance.

1) THE PERFORMANCE OF OVERLAPPING MODE DETECTION

We evaluate the performance of COFFEE on overlapping mode detection under different SNRs and overlapping modes. In each experiment, we record the setting as the ground truth. Receiver identifies the overlapping mode of the incoming packet by using our proposed scheme. The detection ratio is defined as: $D_R = N_C/N_R$, where N_C is number of correctly identified packets, while N_R refers to the number of total received packets.

Fig. 12 and Fig. 13 show how COFFEE performs in overlapping mode detection. Fig. 12 shows the overlapping mode detection results when ZigBee signal cause no interference, while Fig. 13 illustrates the detection ratio when WiFi and ZigBee suffer the same SNR. Both figures show that, for most of the experiment setting, COFFEE can always identify the correct overlapping mode, even when ZigBee signal is weaker than WiFi.

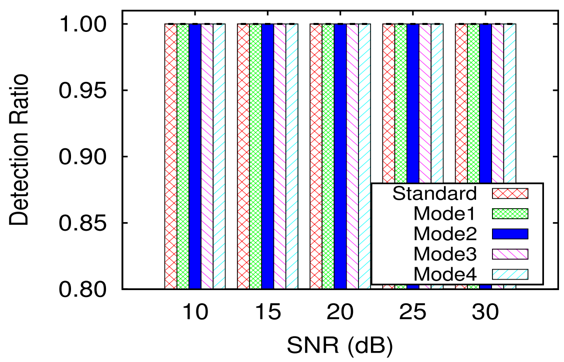


FIGURE 12. Overlapping mode detection of COFFEE without the presence of ZigBee signal.

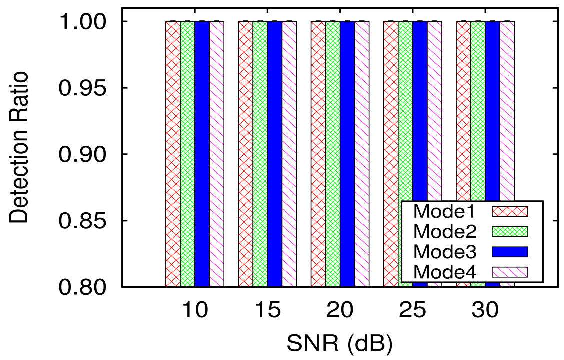


FIGURE 13. Overlapping mode detection of COFFEE when WiFi and ZigBee with the same SNR.

2) THE PERFORMANCE OF COFFEE AND ZigBee

To verify the correctness and illustrate the base line performance for COFFEE and ZigBee system, we study packet delivery ratio (PDR) and packet detection for both implementations.

The PDR of implemented ZigBee system is shown in Fig. 14. In this evaluation, we set different carrier frequency for ZigBee system, where different overlapping mode could be used for evaluation. When SNR is greater than 10 dB, the PDR of ZigBee is above 0.9. As shown in Fig. 15, the implemented ZigBee system could also effectively detect all receiving packets across different SNR settings. Also, as depicted in Fig. 16, the COFFEE system could also detect all packets perfectly with different SNR settings.

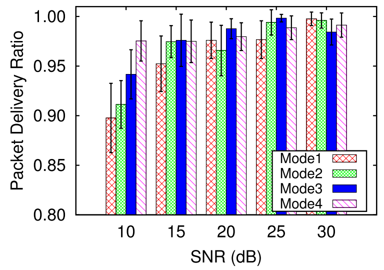


FIGURE 14. Benchmark performance of ZigBee networks.

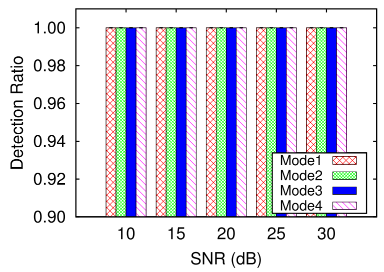


FIGURE 15. Packet detection probability of ZigBee.

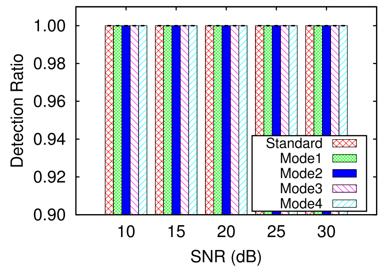
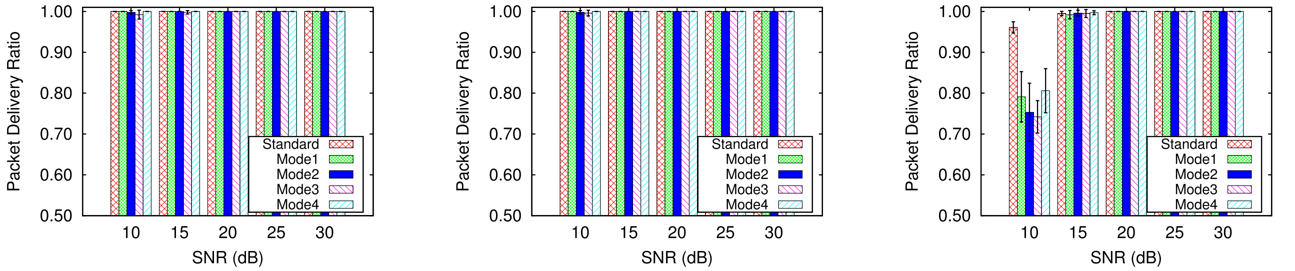


FIGURE 16. Packet detection probability of COFFEE.

Fig. 17 shows the PDR of implemented COFFEE system. Noted that, 'Standard' mode of COFFEE strictly complies with the IEEE 802.11g standard. As depicted in Fig. 17, the PDR of COFFEE could be close to 1, when SNR value is greater than 15 dB for BPSK, QPSK and 16QAM modulation schemes. When SNR is about 10 dB, the PDR of WiFi with 16QAM modulation is less than that with modulation BPSK and QPSK due to 16QAM modulation is less resilient to noise.

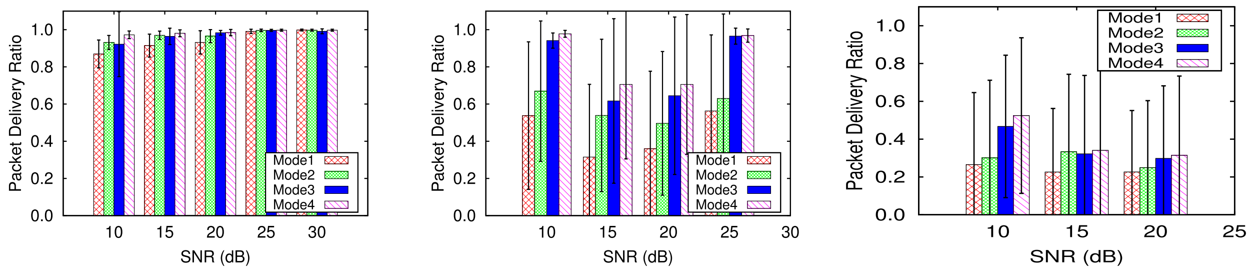
3) THE PERFORMANCE OF COFFEE WHEN OVERLAPPING WITH ZigBee

We then investigate the performance of COFFEE when it coexists with ZigBee networks. In this experiment,



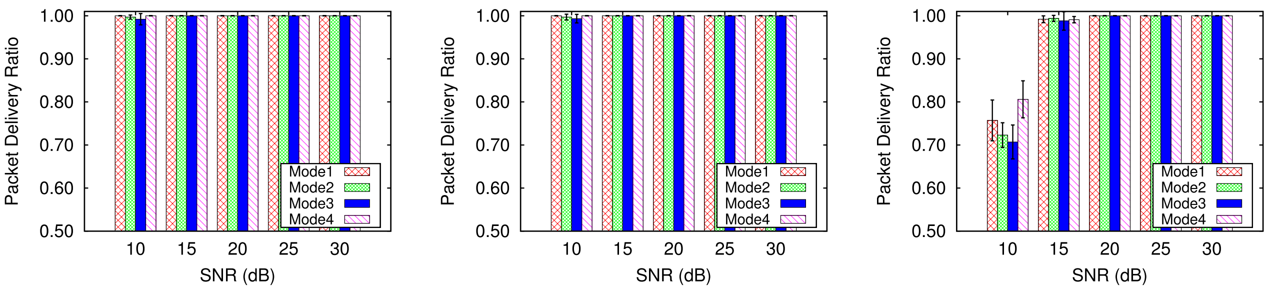
(a) When WiFi modulation is BPSK. (b) When WiFi modulation is QPSK. (c) When WiFi modulation is 16QAM.

FIGURE 17. Benchmark performance of WiFi networks.



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

FIGURE 18. 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.



(a) When WiFi modulation is BPSK. (b) When WiFi modulation is QPSK. (c) When WiFi modulation is 16QAM.

FIGURE 19. Performance of WiFi networks when the SNR of WiFi is same as the SNR of ZigBee.

the SNR gap between WiFi and ZigBee siganls is set from 0 dB $\sim$ 10 dB.[2]

The Packet Delivery Ratio (PDR) of ZigBee can be seen in Fig. 18. When ZigBee and WiFi has the same signal strength, the PDR of ZigBee is similar to its baseline which shown in Fig. 18a. This means that, COFFEE can successfully nullify the overlapping subcarriers and eliminate the interference to ZigBee network effectively. When the SNR gap exceeds 5 dB, the PDR of ZigBee drops caused by the out of band interference of WiFi network. However, ZigBee still can achieve the PDR of about 30% even when the SNR gap is up to 10 dB.

As depicted in Fig. 19 and Fig. 21, COFFEE could decode nearly all WiFi packets correctly, even when there exist a concurrent ZigBee transmission. However, as depicted in Fig. 19c, when the SNR of WiFi is same to that of ZigBee, the PDR of WiFi drops to 75%. This phenomena suggests us to use lower transmission rate for WiFi, such that, higher PDR could be achieved.

As shown in Fig. 23, the ZigBee could make significant effects on the PDR of WiFi when the transmission power is similar to that of WiFi, with 16QAM modulation schemes.

4) THE PERFORMANCE OF FREQUENCY OFFSET ESTIMATION

We also evaluate the performance of frequency offset estimation under different frequency offsets. We deliberately introduce known carrier frequency offset by mismatching the

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

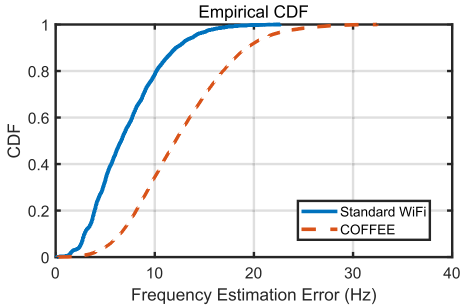


FIGURE 20. The performance of frequency offset estimation.

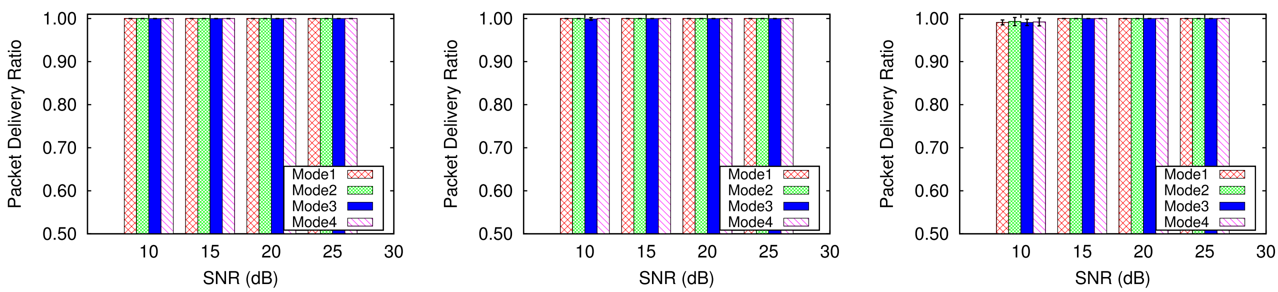
carrier frequency of transmitter and receiver, since the true frequency offset can not be known. The value of the introduced CFO is from 500 Hz to 10 kHz at intervals of 500 Hz. In each setting, 1000 WiFi packets and 1000 COFFEE packets are transmitted. Specifically, the WiFi packet contains four pilot subcarriers, while the COFFEE packet contains two subcarriers and the modified preamble.

Fig.20 shows the CDF of estimation error of both WiFi and COFFEE. The CFO estimation error of COFFEE is slightly larger than standard WiFi. This is because (a) most of the frequency offsets can be estimated and compensated by using STS and LTS, the pilot symbols are only used to approximate the residual frequency offsets. Therefore, the performance of CFO estimation of COFFEE is not significantly deteriorated compared to standard WiFi. (b) COFFEE only has two pilot subcarriers, therefore the estimated CFO suffers a larger variance, resulting in a larger estimation error. (c) The modified preamble degrades the accuracy of estimated channel state information, which also affects the CFO estimation of COFFEE. Fortunately, such slightly increased estimation error does not cause serious interference with the decoding of COFFEE.

5) A SIMULATION STUDY

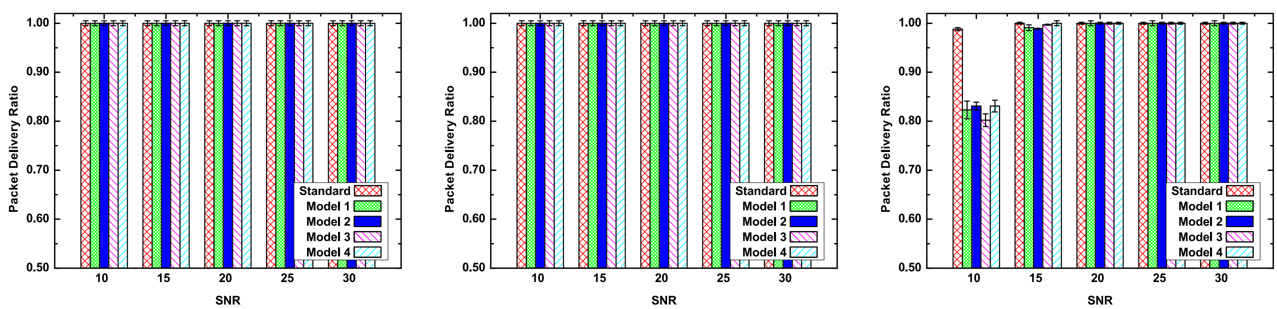
Considering that our experimental results may not be sufficient to demonstrate the performance of COFFEE in a multipath environment, we tested the COFFEE performance under a Rayleigh channel through simulation in Matlab. In this simulation, we designed Rayleigh fading channels for both COFFEE-COFFEE links and ZIGBEE-COFFEE links by using Jakes model, each Rayleigh channel contains five paths with different attenuation factors and delay, and the maximum Doppler shift is set to 100 Hz. Both WiFi and ZigBee have the similar SNR. The simulation parameters are shown in Tab. 1 and the results are shown in Fig. 22.

As can be seen from the figure, when WiFi uses BPSK and QPSK modulation, COFFEE can decode almost all packets, no matter which mode is applied. When WiFi adopts 16-QAM modulation, COFFEE also can achieve the similar PDR as legacy WiFi at high SNR ($\geq 15\ dB$), and only suffers about 20% performance degradation at low SNR ($\leq 10\ dB$). The reasons for this result are as follows.



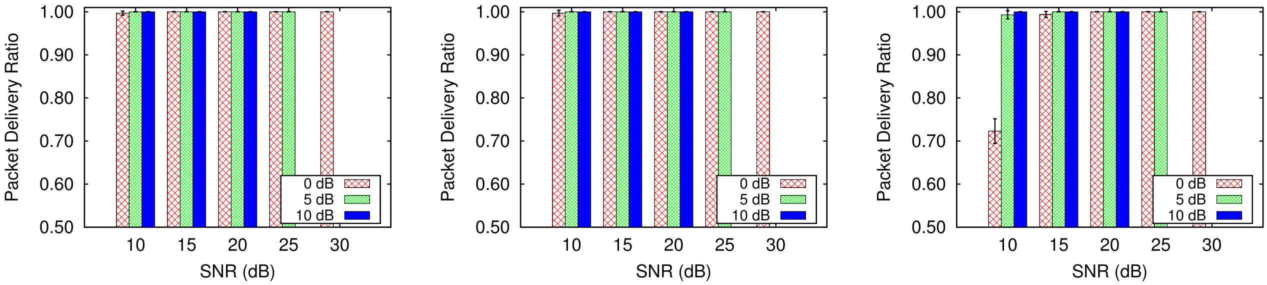
(a) When WiFi modulation is BPSK. (b) When WiFi modulation is QPSK. (c) When WiFi modulation is 16QAM.

FIGURE 21. Performance of WiFi networks when the SNR of WiFi is 5 dB higher than the SNR of ZigBee. The x-axis labels the SNR of WiFi. SNR of ZigBee equals to the SNR of WiFi minus 5 dB.



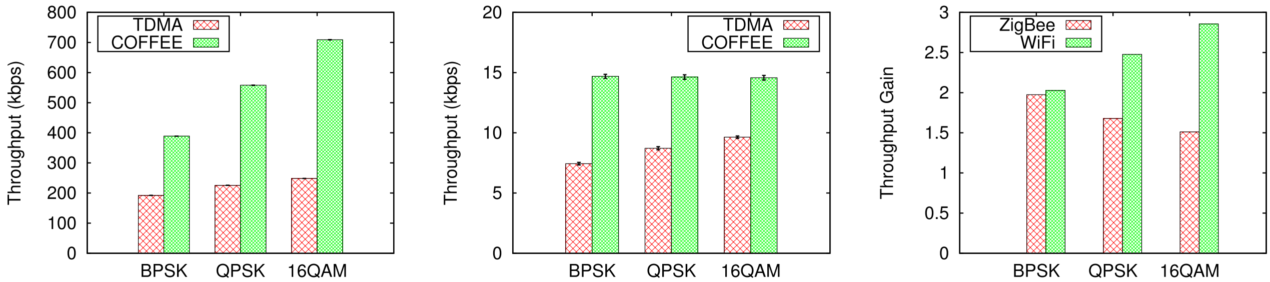
(a) When WiFi modulation is BPSK. (b) When WiFi modulation is QPSK. (c) When WiFi modulation is 16QAM.

FIGURE 22. Simulation of WiFi networks when the SNR of WiFi is the same as the SNR of ZigBee.



(a) When WiFi modulation is BPSK. (b) When WiFi modulation is QPSK. (c) When WiFi modulation is 16QAM.

FIGURE 23. **Performance of WiFi networks when the overlap mode is 'mode2'.**



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

FIGURE 24. **Throughput performance comparison between TDMA and COFFEE.**

- The OFDM overcomes inter-symbol interference (ISI) caused by multipath effect by inserting a Cyclic Prefix (CP) before each symbol. The multipath will not cause serious interference to OFDM communication as long as the maximum multipath delay does not exceed the length of CP (*e.g.* $0.8\mu s$). Although COFFEE nullifies some subcarriers which are overlapping with ZigBee channel, the length of CP does not be modified. Therefore, it will not cause significant drop in multipath resistance of COFFEE.
- The 16-QAM modulation requires a higher SNR rather than BPSK and QPSK. The subcarrier nullification and pilot rearrangement weak the noise resistance of COFFEE, resulting in a decrease in PDR at low SNR consequently.

This result is consistent with our experiment result and demonstrates that COFFEE works well in environments with multiple paths.

It should be noted that COFFEE is designed for typical communication environments such as offices and warehouses. For some extreme cases with dramatic frequency selective fading, the channel gain on the non-nullified subcarriers may be very small, which in turn leads to performance degradation in COFFEE consequently. Leverage the spatial diversity of signals may help solve this problem through collaboration among multiple nodes and we regard it as our future work.

B. MACRO-BENCHMARK

In this experiment, we evaluate the end-to-end throughput gain of COFFEE. To this end, we apply two different traffic patterns for performance evaluations. The first pattern is the 'TDMA' traffic, in which WiFi and ZigBee packets are transmit successively to avoid interference. The second pattern is the 'COFFEE' traffic, in which WiFi and ZigBee nodes transmit their packets at the same time. We set the back-off time of WiFi and ZigBee networks to 500 μs, and the packet length of WiFi and ZigBee are setting to 256 and 20 Bytes, respectively. Three modulation schemes (BPSK, QPSK and 16-QAM) are evaluated for WiFi, and the SNR gap between WiFi and ZigBee is set to 25 dB. our default overlapping mode is 'Mode 2'. To measure the throughput of WiFi and ZigBee under various transmission parameter, we use one USRP to transmit WiFi packet and another USRP to transmit ZigBee packet. For each experiment configuration, 10 traces are collected by the receiver. Each trace contains 200 ms signal data on one 20 MHz WiFi channel. We store these traces on disk and process them offline.

TABLE 1. **Simulation parameters: C-C Link stands for the link between two COFFEE nodes, Z-C Link represents the link between ZigBee transmitter and COFFEE receiver.**

C-C Link	Delays (us)	0	0.01	0.013	0.02	0.043
	Gains (dB)	0	-1.9	-2.2	-4.9	-8.1
	Doppler (Hz)	100				
Z-C Link	Delays (us)	0	0.021	0.023	0.031	0.046
	Gains (dB)	0	-5.1	-5.2	-6.5	-8.2
	Doppler (Hz)	100				

Fig. 24a and Fig. 24b show the throughput of WiFi and ZigBee respectively. The scheduled WiFi and ZigBee transmissions which follows the TDMA mode, is label as 'TDMA'. While the label 'COFFEE' refers to WiFi and ZigBee nodes transmit their packets concurrently, and COFFEE is applied to coexist both WiFi and ZigBee networks. It can be seen that both throughput of WiFi and ZigBee have been improved greatly.

To investigate the throughput gain in more detail, we show the throughput gain of COFFEE in Fig. 24c. As this figure shown, the throughput of ZigBee is increased about 2×, while the WiFi throughput is improved to nearly 3×. Note that, the throughput gain of WiFi can be higher when 16-QAM modulation scheme is applied, since it takes less time for WiFi transmission with higher data rates.

VII. DISCUSSION

A. THE IMPACT OF DOPPLER EFFECT

Doppler shift is a very common phenomenon that usually occurs when transmitter and receiver are moving. Excessive frequency shifts can cause carrier frequency offset on the received signal, which may affect the performance of mode detection of COFFEE. In order to counter the interference caused by the Doppler shift, COFFEE adds the redundancy when nullifies the subcarriers. Specifically, COFFEE nullifies a 2.5 MHz bandwidth for each overlapping ZigBee channel, instead of 2 MHz. For the WiFi and ZigBee network which work on the 2.4 GHz band, the Doppler shift is only 8 Hz when the relative speed is 1 m/s. COFFEE adds an extra bandwidth of 500 Hz, making it easy to handle any Doppler shifts that can occur in indoor environments. Moreover, as a mature communication technology, WiFi and ZigBee signals also retain a certain ability to resist Doppler shift. For example, by using the preamble, WiFi can accurately estimate the CFO up to 625 kHz [15].Therefore, COFFEE is capable of providing coexistence communication between WiFi and ZigBee networks.

B. THE OUTDOOR SCENARIO

The outdoor environment is another important component of smart city. Although the ourdoor wireless communication has the advantage of less multipath, there are still some challenges need to be solved.

The first challenge is the interference from distant wireless signal. COFFEE can only ensure that the modified WiFi sent by itself will not interfere with ZigBee network. However, in ourdoor communication, due to the lack of obstruction, the distant signal may still have sufficient energy to jam the ZigBee communication even after long-distance propagation. The second challenge comes from other modulated signals working in the 2.4 GHz band, such as Bluetooth and Wireless USB. Moreover, recent research indicates that RFID siganl may shifted to the 2.4 GHz band via harmonic backscattering [16]. The presence of these interfering signals will undoubtedly reduce the performance of COFFEE. The third challenge is the Doppler effect. In outdoor environment, the communication devices may moving with a high speed rather than the low speed in indoor scenario. Therefore the resulting Doppler shift is much more serious. Although COFFEE reserves redundant bandwidth for anti-Doppler shift, it is not enough to cope with such high frequency shift.

C. THE IMPACT OF OTHER INTERFERENCE SOURCES

There are four common wireless networks work in the 2.4 GHz ISM band, the WiFi, ZigBee, Bluetooth and cordless phone. COFFEE deal with the coexistence problem between WiFi and ZigBee via modifying the WiFi node. In this section, we briefly discuss how these interference sources affect COFFEE and ZigBee respectively.

The first interference comes from the legacy WiFi nodes that do not use COFFEE algorithm. These legacy WiFi nodes will compete for channels with the COFFEE nodes. When they compete for the channel, the COFFEE node will defer its own transmission, while the ZigBee node will undoubtedly be subject to severe WiFi signal interference. ZigBee nodes also compete for channels, but this does not cause a serious impact on ZigBee nodes or COFFEE nodes. However, as the number of occupied ZigBee channel increases, the number of available WiFi subcarrier in COFFEE decreases, which will cause the throughput degradation of WiFi network. Bluetooth uses Frequency-Hopping Spread Spectrum (FHSS) and splits the 2.4 GHz ISM band into 79 1 MHz channels, and hop among these 79 channels 1600 times per second in a pseudo-random pattern. recent research shows that Bluetooth will not cause significant interference to ZigBee communication since the probability of frequency collision between them is only 1/79 [17], [18]. Besides, as a low power communication technique, the impact of Bluetooth on WiFi communication is very weak in most cases. Cordless phone, on the other hand, do not use a standard protocol. Some phones use Direct Sequence Spread Spectrum (DSSS), while others use FHSS, and use a channel bandwidth of 5 $\sim$ 10 MHz. Due to its wider channel and higher power, the cordless phone can completely stop a WiFi network, as well as ZigBee [19]. As a result, the coexistence between cordless phone and other network is an open challenge.

VIII. RELATED WORK

Many solutions have been proposed to address the issue of coexistence for WiFi and ZigBee networks. In this paper, we classify these solutions into two main categories: time domain solutions and frequency domain solutions.

A. TIME DOMAIN SOLUTIONS

Zhang and Shin [4] proposed an algorithm called Cooperative Busy Tone (CBT) to avoid the interference for WiFi and ZigBee networks. CBT designed an enhanced ZigBee node to broadcast a busy tone before the desired ZigBee transmission, thereby making the nearby WiFi nodes sense the existence of ZigBee node and defer their transmission. Wang *et al.* [20] designed a fake WiFi PHY preamble-header. By broadcasting such fake preamble, it can mute other WiFi nodes throughout the whole period of ZigBee transmission. Huang *et al.* [5] utilized a Pareto model to characterize the white space in WiFi traffic, and developed

WISE, a ZigBee frame control protocol to achieve trade-off between link throughput and packet delivery ratio. Based on the learned Pareto model, WISE can predict the traffic situation of WiFi and adjust the frame size intelligently to maximize the throughput with certain PDR. By learing from the RSSI traces, Kannan *et al.* proposed an off-line strategy, which can estimate the burstiness of the link due to the interference, known as the β-factor. The β-factor can be used for ZigBee nodes to approximate the expected interference time and defer their packet transmissions to reduce the cost of re-transmission. Liang *et al.* [6] investigate the interference pattern between WiFi and ZigBee networks from a bit-level perspective, and apply Multi-Header, as well as TinyRS to improve the packet detection rate and PDR of the corrupted payload respectively. However, nearly all these time domain solutions require the WiFi nodes to defer their transmission until ZigBee transmission completed, which causing a severe spectrum under-utilization, since the time cost to transmit a ZigBee pacekt is 10 times longer than that of WiFi. More importantly, the performances of these time domain solutions are limited by several factors such as the channel interference level, and the inaccuracy of channel estimation result.

B. FREQUENCY DOMAIN SOLUTIONS

Rahul *et al.* [21] proposed SWIFT to enable high-throughput wide-band nodes to coexist with unknown narrow-band devices. Poston and Horne [22] demonstrated the feasibility of NC-OFDM on interference mitigation by designing a software radio prototype, which was implemented by nulling the OFDM subcarriers directly. Similarly, He *et al.* [9] proposed MPAP to avoid the interference on ZigBee networks by leveraging non-continuous of OFDM in 802.11g WiFi networks. Gollakota *et al.* [12] enabled 802.11n communication works well even in the presence of high-power cross-technology interference. Their additional work [7] leverages the interference cancellation technique to improve the WLAN performance. Halperin *et al.* [23] and Kun *et al.* [8] applied interference cancellation technique in multi-user MIMO scenarios. Li *et al.* [24] proposed Collision-Resistant Multiple Access (CRMA) to improve the system efficiency. In CRMA, the physical layer of OFDM is regarded as multiple orthogonal but shareable channels, and few channels are selected for independent transmissions. Moreover, Zhang and Shin [10] proposed the Adaptive Subcarrier Nulling (ASN) algorithm to enable partial spectrum sharing in WLANs. Based on the 802.11 WiFi PHY, ASN allows the radio to sense, transmit, detect and decode packets via the fragmented spectrum. However, most of these solutions fail to tailor the coexistence techniques for ZigBee networks, *e.g.* the data rate, SNR level, *etc.*, which will causing throughput loss inevitably.

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

1) COFFEE can effectively utilize the WiFi band resources which would be wasted due to the back-off of WiFi transmitters, and improves the overall spectrum utilization significantly. Besides, COFFEE also enables the concurrent ZigBee communication despite the traffic load of WiFi networks and improves the throughput gain for both networks.
2) COFFEE is tailored for the coexistence for WiFi and ZigBee networks, the impact of varies factors on the performance of WiFi and ZigBee networks have been evaluated comprehensively.

IX. CONCLUSION

In this paper, we investigate the coexistence problem between WiFi and ZigBee networks from the frequency domain perspective, and propose COFFEE, a frequency overlap algorithm to enable the coexistence between WiFi and ZigBee, and maximize the spectrum utilization as well. By using COFFEE, WiFi nodes can efficiently detect the presence of ZigBee transmissions and identify their corresponding overlapping modes. Moreover, by using COFFEE, both networks can transmit their data concurrently. We implement COFFEE on our USRP platform and test its performance through real-world experiments. The experimental results show that COFFEE can improve the throughput of WiFi around 3× than that when WiFi and ZigBee follow the TDMA scheme. Even the transmission time information of WiFi node does not be shared to ZigBee node, COFFEE can still enable the concurrent lossless ZigBee transmission with only 10% ∼ 15% WiFi throughput reduction.

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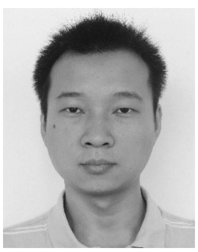

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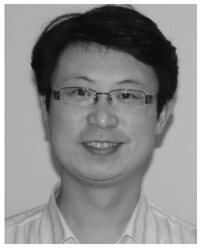

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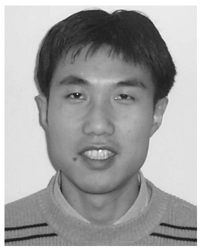

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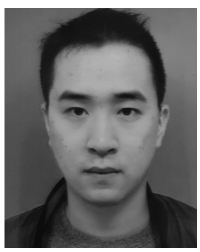

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