Supporting WiFi and LTE Co-existence

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***Abstract*—Motivated by the recent push to deploy LTE in unlicensed spectrum, this paper develops a novel system to enable co-existence between LTE and WiFi. Our approach leverages LTE and WiFi antennas already available on smartphones to let LTE and WiFi transmit together and successfully decode the interfered signals. Our system offers several distinct advantages over existing MIMO work: (i) it can decode all the interfering signals under cross technology interference even when the interfering signals have similar power and occupy similar frequency, (ii) it does not need clean reference signals from either WiFi or LTE transmission, (iii) it can decode interfering WiFi MIMO and LTE transmissions, and (iv) it has a simple yet effective carrier sense mechanism for WiFi to access the medium under interfering LTE signals while avoiding other WiFi transmissions. We use USRP implementation and experiments to show its effectiveness.**

I. INTRODUCTION

Motivation: As the world embraces wireless and mobile technologies at an unprecedented rate, wireless traffic is growing exponentially. Given the severely limited license spectrum available, in order to accommodate such an explosive traffic growth, there has been a recent push by many major companies, such as Qualcomm, Huawei, Nokia, Ericsson, T-Mobile, NTT DoCoMo, to deploy LTE in unlicensed spectrum [19], [18], [3], [7] in addition to using existing licensed spectrum. [7] reports Ericsson deployed small cells indoor using unlicensed spectrum and T-Mobile plans production trials in 2015 [7]. Other companies are also pushing LTE to unlicensed spectrum. In fact, 3GPP is now working on standards for LTE in unlicensed 5GHz band.

Deploying LTE in unlicensed spectrum means that LTE will share the same spectrum with the widely used WiFi. It is challenging to support co-existence between LTE and WiFi. LTE has been used in a controlled environment with little interference, and does not have any mechanism to avoid interference. On the other hand, WiFi is mainly used in ISM band where any device can use it without a license, so it uses carrier sense multiple access (CSMA) to avoid interference. If they are used in the same spectrum, it is likely that LTE dominates the spectrum while WiFi devices keep deferring to LTE transmissions. Even if WiFi gets a chance to access the channel (*e.g.*, due to occasionally low LTE interference), WiFi will be easily interfered by LTE as soon as LTE signal becomes stronger, degrading both performance.

One way to support their co-existence is to separate them in either time domain or frequency domain, as used by Qualcomm and Huawei [19], [18], [17]. However, such resource allocation requires accurate estimation of WiFi and LTE traffic demands, which is challenging given the rapid fluctuation of wireless traffic. Moreover, even with accurate demand estimation, only one of them can be active at a given time and frequency, thereby limiting the total throughput.

Opportunities and challenges: We observe that mobile devices are already equipped with both WiFi and LTE antennas and it is theoretically possible to decode WiFi and LTE transmissions even if they transmit at the same time over the same frequency. However, decoding overlapping LTE and WiFi transmissions poses significant challenges:

1. Channel estimation is essential for signal decoding. Traditionally, channel estimation is performed by sending known signals, such as preambles in WiFi and reference signals in LTE. The receiver estimates the channel by taking the ratio between the received signal and the (known) transmitted signal. However, when LTE and WiFi signals overlap without fine-grained coordination, it is difficult to get uninterfered reference signals/preambles from either LTE or WiFi. How to estimate channel without clean reference signals is an open problem.
2. Both LTE and WiFi use OFDM, which transmits data by spreading it over multiple orthogonal subcarriers, due to its robustness to multipath fading and high spectrum efficiency. How should we decode two interfering OFDM signals generated by heterogeneous PHY technologies and not aligned in either frequency or time domain?
3. Smartphones today have one WiFi and one LTE antenna due to limited form factor. The high capacity gain of MIMO will likely push more smartphones to adopt MIMO within each technology. How should we decode WiFi MIMO streams interfered with LTE transmissions?
4. There can be more than one WiFi transmitter in an area, and these transmitters should use carrier sense to avoid interfering each other. But how can a WiFi node access the medium under LTE signals while deferring to other WiFi transmissions?

While there are some prior work on decoding under cross technology interference, they do not address the above challenges. First, both TIMO [10] and ZIMO [32] assume the receiver gets clean reference signal from at least one of the two interfered signals. This assumption significantly simplifies channel estimation. However, such assumption does not hold in the LTE and WiFi context, since LTE transmission is usually continuous and ceaseless and it is hard to get a clean WiFi preamble. Moreover, LTE reference signals are transmitted periodically, and easy to overlap with WiFi transmissions. So it is essential to estimate channel without clean reference signals from either WiFi or LTE. Second, TIMO [10] decodes WiFi frames in the presence of cross-technology interference. However, it requires a WiFi node to know the channel to the cross-technology receiver (*e.g.*, cordless phone) and nulls WiFi interference at that receiver, which is hard to achieve in practice. ZIMO [32] decodes both WiFi and ZigBee signals without nulling, but it exploits that ZigBee signals are much narrower and have lower power than WiFi signals. WiFi and LTE, on the other hand, occupy similar frequency band and have similar power. Third, both TIMO and ZIMO focus on a single WiFi transmission and do not consider supporting WiFi MIMO transmissions. Fourth, neither work considers carrier sense problem among multiple WiFi transmitters.

Our approach: In this paper, we propose letting LTE and WiFi transmitters send together and the receivers decode the overlapping transmissions using a novel decoding scheme. We first consider decoding one WiFi and one LTE signal when they overlap. Our decoding scheme consists of two components: (i) a new method to estimate the channel without clean reference signals from either LTE or WiFi, and (ii) a new decoding algorithm that can decode two interfering OFDM signals that are not aligned in time or frequency. Our channel estimation leverages the fact that even when LTE and WiFi use 20 MHz, their signal bandwidth are 18 MHz and 16.25 MHz, respectively. This means that LTE has 0.875 MHz on each side not interfered by WiFi, and we can use the standard channel estimation for this portion. However, how to estimate the remaining channel is challenging and we cannot rely on extrapolation alone since only 1.75MHz channel is known and is insufficient to extrapolate to get accurate channel estimation for 16.25MHz channel. We utilize interfered signals as well as extrapolation to estimate the remaining LTE and WiFi channels iteratively. Based on the estimated channels, we decode the interfering LTE and WiFi signals by separately transforming the interfered signal using either WiFi FFT size or LTE FFT size. We use an iterative decoding to enhance the accuracy.

Next we extend our channel estimation to the case where WiFi MIMO transmissions interfere with LTE. We introduce a simple and low-cost modification to a few WiFi transmissions that permits estimation of WiFi MIMO channels and supports decoding of both WiFi MIMO and LTE signals.

Then we develop a simple yet effective carrier sense for WiFi transmitters. The carrier sense is performed by projecting the received signal orthogonal to the LTE channel in order to remove the the impact of LTE signal and detect the presence of other WiFi signals. We develop a method to estimate instantaneous LTE channel under interference and support projection-based carrier sense.

We further consider several practical issues, such as synchronization, supporting wider channels, sending WiFi ACKs. We implement our complete approach in a USRP testbed. Our results show that (i) the median MSE of channel estimation is 0.12, (ii) the average throughput gain over time sharing is 87% (close to 100% theoretical gain), (iii) the signal SNR in WiFi MIMO under LTE interference is similar to that under no LTE interference, and (iv) the new carrier sense achieves 0 false positive and false negative when SNR is 6 dB or higher, and 4% and 0.2%, respectively, under 3 – 5 dB SNR.

Our contributions include: (i) a new method to iteratively estimate the WiFi and LTE channels without clean reference signals and decode two interfering cross technology OFDM signals without alignment even when these signals have similar power and occupy similar spectrum; (ii) a new method to estimate the WiFi MIMO channels and decode interfering WiFi MIMO and LTE signals. Our estimation does not require clean reference signals; (iii) a new carrier sense scheme for WiFi to avoid interference with other WiFi signals while co-existing with continuous LTE transmissions; (iv) a prototype implementation that demonstrates the effectiveness of the approach.

II. RELATED WORK

We classify related work into (i) spectrum sharing by avoiding interference, (ii) MIMO for the same technology, and (iii) MIMO for cross technologies.

Interference avoidance: A natural approach to support coexistence between multiple transmissions is to isolate spectrum across different time, frequency, space, thereby avoiding interference. Examples of frequency-based isolation include OFDM subcarrier suppression [24], [12] and fine grained frequency fragmentation [31], [20], [13]. Several approaches use time-domain isolation based on centralized scheduling or distributed carrier sense. [9] describes co-existence challenges for heterogeneous networks in TV white spaces. Our approach allows multiple transmissions to co-exist in the same frequency at the same time over the same area, significantly out-performing the interference avoidance based approaches.

MIMO for the same technology: MIMO has attracted lots of research and development owing to its significant capacity benefit. It has also been widely deployed as evidenced by recent standards (*e.g.*, IEEE 802.11n [2] and 802.11ac [1]). Multi-user MIMO leverages antennas on different nodes to achieve an even higher gain. [8], [30] provide a nice survey on the theoretical advances in multi-user MIMO. There are also several nice experimental research on multi-user MIMO, such as [4], [28], [23], [5]. All of these works support MIMO transmissions within the same technology.

Cross technology MIMO: [10] is the pioneering work on cross technology MIMO. It focuses on decoding WiFi frames, and uses nulling to let the interferer (*e.g.*, cordless phone) decode its signal. Nulling not only requires the WiFi sender to have two antennas while sending one stream, but also requires accurate channel estimation (*e.g.*, from the WiFi sender to the cordless phone receiver in TIMO and from the WiFi sender to the LTE receiver in our context), which is hard to achieve in practice. [32] decodes both WiFi and ZigBee signals, but it exploits that ZigBee signals are much narrower and have lower power than WiFi signals. However, WiFi and LTE occupy similar frequency band and have similar power. Moreover, both TIMO [10] and ZIMO [32] assume that the receiver gets clean reference signals for channel estimation, which does not hold in our context due to continuous LTE transmissions.

III. BACKGROUND

In order to avoid inter symbol interference (ISI) problem, WiFi uses OFDM technique that sends multiple symbols in parallel in different frequency bands (i.e., subcarriers). 20MHz is the most widely used channel width in WiFi. A WiFi node uses carrier sense to avoid interference. Each WiFi frame starts with a preamble, which is a known sequence and allows a receiver to estimate the channel.

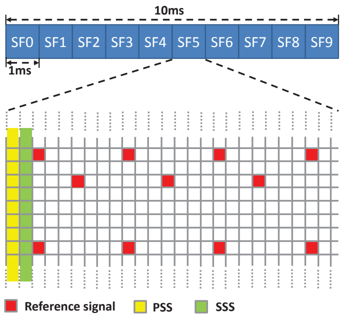

Fig. 1. LTE frame structure

As WiFi, LTE also uses OFDM to address multipath fading. It uses a 20 MHz channel with 2048 subcarriers. As shown in Figure 1, LTE frame transmission is continuous: each LTE frame lasts 10 ms, and consists of ten 1 ms subframes. To support synchronization, an LTE frame has primary synchronization sequence (PSS) and secondary synchronization sequence (SSS) transmitted every 5 ms. PSS enables a UE to synchronize on a per subframe level. PSS uses Zadoff Chu sequences [6] containing 63 symbols. These sequences have a nice property that the correlation between the received sequence and the ideal sequence is highest when the lag is zero and the correlation is zero everywhere else. So a receiver can use correlation to detect the start of the sequence for synchronization purpose. The detection is robust even under low SNR. The LTE reference signals are transmitted frequently. In the frequency domain, they are sent once every 6 subcarriers, which is 90 KHz apart. In the time domain, they are sent once every 3 or 4 OFDM symbols, where each OFDM symbol lasts 71 us. Interpolation is used to estimate the channel of the subcarriers without reference signals.

IV. OUR APPROACH

We propose a novel system design that enables coexistence between LTE and WiFi. We assume the receiver has separate antennas for LTE and WiFi, which is a valid assumption given the capability of smartphones today. When it receives interfering LTE and WiFi signals, it decodes both transmissions as described in Section IV-A. We address an important challenge in decoding – how to estimate channel without clean reference signals. We further extend to decode interfering WiFi MIMO and LTE transmissions in Section IV-B. We design carrier sense to allow a WiFi node to join LTE transmission while avoiding interfering other WiFi transmissions in Section IV-C. We discuss several practical issues in Section IV-D.

A. Decoding One WiFi Signal and One LTE Signal

First, we examine how to decode a WiFi signal and an LTE signal that overlap in both time and frequency. This is challenging because normally such interfered signals will result in collisions. Figure 2 illustrates the network we consider. Note that the WiFi AP and LTE base station may or may not communicate with the same client. When they communicate with different clients, each client applies our technique to decode the signal of its interest.

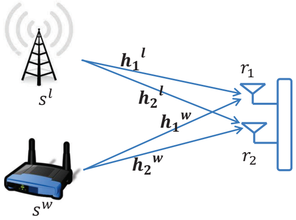

Fig. 2. WiFi-LTE coexistence

We gradually build up our decoding algorithm. We start with the simplest case of decoding when both WiFi and LTE channels are known. Then we consider how to estimate WiFi channel without uninterfered preambles while the LTE channel is known. Finally, we consider joint channel estimation of both WiFi and LTE channels without uninterfered preambles or reference signals from either network. Below we use the superscripts l and w to represent LTE and WiFi, respectively. We use lower case letters to represent time domain signals, and use upper case letters to represent frequency domain signals.

1) Decoding Interfered Signals: Let $X[k]$ be the modulated symbol transmitted in the k-th subcarrier. The transmitted time domain signal $s[n]$ is generated by performing IFFT to $X[k]$, which is $s[n] = \frac{1}{N}\sum_{k=0}^{N-1} X[k]e^{j2\pi kn/N}$. When WiFi signal $s^w[n]$ and LTE signal $s^l[n]$ are transmitted together, these two signals naturally add up in the air and the received signal is the sum of the two time domain signals, namely, $r[n] = \mathbf{h^w} * s^w[n] + \mathbf{h^l} * s^l[n]$, where $\mathbf{h^w}$ and $\mathbf{h^l}$ are the channel impulse responses for WiFi and LTE channels, respectively. This signal is transformed into frequency domain symbol by FFT, but because $s^l[n]$ and $s^w[n]$ are generated by different FFT sizes, it is impossible to transform both signals together. Suppose $Y^w[k]$ is the received frequency domain symbol in the k-th WiFi subcarrier by performing FFT with respect to the WiFi OFDM symbol structure. Then we have $Y^w[k] = H^w[k]X^w[k] + H^l[k]I^l[k]$, where $I^l[k] = \frac{1}{N}\sum_{l=0}^{N-1}(\frac{1}{M}\sum_{i=0}^{M-1} X^l[i]e^{\frac{j2\pi ik}{M}})e^{\frac{-j2\pi lk}{N}}$, X^l is LTE symbol in the frequency domain, N and M are FFT sizes in WiFi and LTE, respectively. [1]

In fact, performing FFT with respect to the WiFi FFT size does not orthogonalize the LTE signal, so it generates undecodable signal $I^l[k]$. Though the LTE signal is not decodable, we can decode the WiFi signal using the two received signals. The received frequency domain symbols at two antennas are:

$$Y_1^w[k] = H_1^w[k]X^w[k] + H_1^l[k]I^l[k]$$
$$Y_2^w[k] = H_2^w[k]X^w[k] + H_2^l[k]I^l[k].$$

Assuming all channel coefficients are known, we can decode $X^w[k]$ as we have two equations involving 2 unknowns: $X^w[k]$ and $I^l[k]$. Note that we do not exploit any structure in LTE OFDM symbol when we decode the WiFi signal, so it works regardless of the alignment of WiFi and LTE OFDM symbols.

The same technique can be applied to decode LTE signal. It first performs FFT with respect to LTE OFDM symbol size, and decodes it using two received signals and known channel coefficients while ignoring the WiFi interference.

2) Estimating WiFi Channel Using Interfered Signals: In general, channel estimation is done by having a sender transmit known reference signals and a receiver estimate the channel based on $Y = H \cdot X$, where Y and X are received and transmitted signal, respectively. But when LTE and WiFi senders transmit without coordination, it is difficult to guarantee that the reference signals are transmitted without interference. We estimate the channel even in the presence of interference by exploiting their frame structures. In this section, we describe how to estimate WiFi channel when the LTE channel is already known using the uninterfered LTE reference signals. We will remove this assumption in Section IV-A3.

We leverage the WiFi preamble that overlaps with LTE signals. If we perform FFT on the received WiFi preamble using the WiFi FFT size, we get:

$$Y_1^w[k] = H_1^w[k]X_p^w[k] + H_1^l[k]I^l[k]$$
$$Y_2^w[k] = H_2^w[k]X_p^w[k] + H_2^l[k]I^l[k], \tag{1}$$

where $X_p^w[k]$ is the known WiFi preamble symbol in the k-th subcarrier, and $I^l[k]$ is unknown LTE interference. Here we have three unknowns $H_1^w[k]$, $H_2^w[k]$ and $I^l[k]$, but only two equations. So it cannot be solved.

To extract an additional constraint required for decoding, we observe that we can leverage the LTE reference signal that interferes with the WiFi signal to remove the LTE interference and estimate the ratio between the two WiFi channels (*i.e.*, $H_2^w[k]/H_1^w[k]$) as follows. Assume the receiver is synchronized with the LTE base station. We will describe in Section IV-D how to synchronize in the presence of WiFi interference. Then the receiver takes the received signal during the expected time of a reference signal and performs FFT with respect to the LTE FFT size and get:

$$Y_1^l[k] = H_1^l[k]X_p^l[k] + H_1^w[k]I^w[k]$$
$$Y_2^l[k] = H_2^l[k]X_p^l[k] + H_2^w[k]I^w[k], \tag{2}$$

where $X_p^l[k]$ is known LTE reference symbol and $I^w[k]$ is unknown WiFi interference. Note k here does not mean the k-th LTE subcarrier, but denotes an LTE subcarrier that overlaps with the k-th WiFi subcarrier. From the two received symbols $Y_1^l[k]$ and $Y_2^l[k]$ and known LTE channel and reference signals, we compute the WiFi channel ratio α_k as

$$\alpha_k = \frac{H_2^w[k]}{H_1^w[k]} = \frac{Y_2^l[k] - H_2^l[k]X_p^l[k]}{Y_1^l[k] - H_2^l[k]X_p^l[k]}. \tag{3}$$

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[1] For simplicity, it is written as if WiFi and LTE OFDM symbols starting samples are aligned, but it is not a requirement for our decoding algorithm.

Plugging α_k into Equation 1, we get

$$\begin{aligned} Y_1^w[k] &= H_1^w[k]X_p^w[k] + H_1^l[k]I^l[k] \\ Y_2^w[k] &= \alpha_k H_1^w[k]X_p^w[k] + H_2^l[k]I^l[k]. \end{aligned} \tag{4}$$

Now the number of unknowns is reduced to 2, so we can solve them to find $H_1^w[k]$ and get $H_2^w[k]$ using $H_2^w[k] = \alpha_k H_1^w[k]$. In this way, we get the WiFi channel coefficients by jointly utilizing the WiFi preamble interfered with an LTE signal and the LTE reference signal interfered with a WiFi signal.

Note that to cancel LTE interference, we need the LTE channel coefficient in an entire WiFi subcarrier. Unlike WiFi, LTE does not send reference signals on all subcarriers. Instead, LTE transmits a reference signal once every 6 subcarriers, where the subcarrier width is 15 KHz. WiFi subcarrier width is 312.5 KHz. Therefore, if a WiFi frame overlaps with the LTE reference signal once in time, regardless of the subcarrier alignment, each WiFi subcarrier overlaps with at least 3 LTE reference subcarriers. We estimate the LTE channel coefficient in a WiFi subcarrier using the average channel coefficients from the three or four LTE reference subcarriers in that WiFi subcarrier. If a WiFi frame is longer and overlaps with the LTE reference signals multiple times, we can estimate the LTE channel in the WiFi subcarrier using the average channel coefficients derived from all the overlapped reference signals.

3) Joint LTE and WiFi Channel Estimation: Next we estimate both LTE and WiFi channels without relying on the uninterfered LTE reference signals. We exploit the fact that LTE and WiFi have different guard bandwidths even when both of them use 20MHz channel. The actual signal bandwidth of LTE and WiFi are 18MHz and 16.25MHz, respectively. As a result, LTE has 0.875MHz spectrum not interfered by WiFi on each side. We call this spectrum boundary LTE channel. Each boundary channel contains 9 LTE reference subcarriers that can be used to estimate the channel of uninterfered portion of the spectrum.

But how do we estimate the channels of the remaining spectrum interfered by the WiFi signal? One natural approach is to use the boundary LTE channels to extrapolate for the channels that are interfered by WiFi. However, extrapolation alone is not enough since only 1.75MHz channel is known and insufficient to extrapolate for estimating 16.25MHz channel. Therefore, we utilize the interfered signal in addition to extrapolation to estimate LTE and WiFi channels. Below we focus on the subcarriers with reference signals. The channel estimate of LTE subcarriers without reference signals are set to the channel estimate of the closest subcarrier with reference signals. For ease of description, we call the i-th LTE subcarrier with reference signals as the i-th LTE subcarrier.

1. **Estimate the boundary LTE channel:** We estimate the boundary LTE channel using the standard channel estimation based on $Y = HX$, where X and Y are transmitted and received signals, respectively, and H is channel estimate. This is possible due to little interference from WiFi.
2. **Estimate the channel of the first LTE subcarrier:** The boundary LTE channel contains 9 reference subcarriers, whose channel is estimated in step 1. We estimate the first LTE subcarrier (with reference signal) that interferes with WiFi using the average of the five reference subcarriers (in the boundary LTE channel) closest to it.
3. **Estimate the channel of the first WiFi subcarrier:** Based on the LTE channel estimate, we estimate the channel of the first WiFi subcarrier by applying the approach described in Section IV-A2. Specifically, we cancel the LTE reference signal on the first LTE subcarrier (with reference) to estimate the WiFi channel ratio using Equation 3. The channel within one WiFi subcarrier is relatively flat. So we use this ratio as the ratio of the entire WiFi subcarrier. Then we use Equation 4 to estimate the channel of the first WiFi subcarrier.

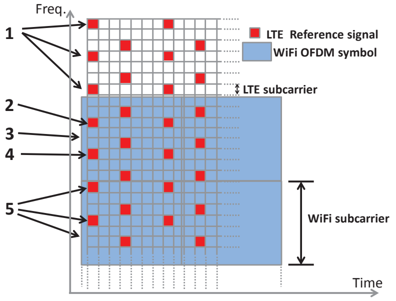


Fig. 3. Channel estimation without uninterfered WiFi preamble and LTE reference signals: 1) estimate LTE channels using uninterfered reference signals in the guardband, 2) estimate LTE channel through extrapolation, 3) estimate the first WiFi subcarrier using the known LTE channel and WiFi preamble, 4) estimate all the LTE subcarriers within the first WiFi subcarrier using known WiFi channel and LTE reference signal, 5) Repeat 2-4 for the remaining channel.

4. **Estimate the channel of all LTE subcarriers within the first WiFi subcarrier:** Next we estimate the next LTE subcarrier using WiFi channel estimate and WiFi preamble. We remove interference from WiFi preamble on the first WiFi subcarrier to compute the ratio of LTE channel as:

$$\alpha_k^l = \frac{H_2^l[k]}{H_1^l[k]} = \frac{Y_2^w[k] - H_2^w[k]X_p^w[k]}{Y_1^w[k] - H_1^w[k]X_p^w[k]},$$

similar to Equation 3. Then we estimate the channel of the LTE subcarrier by plugging α_k^l into the following:

$$\begin{aligned} Y_1^l[k] &= H_1^w[k]I^w[k] + H_1^l[k]X_p^l[k] \\ Y_2^l[k] &= H_2^w[k]I^w[k] + \alpha_k^l H_1^l[k]X_p^l[k]. \end{aligned} \tag{5}$$

where WiFi channel $H_1^w[k]$ and $H_2^w[k]$ are known and LTE reference signal $X_p^l[k]$ is also known, and H_1^l and $I^w[k]$ are the only unknowns and can be solved using the two equations. We use this process to estimate the channel of all LTE subcarriers in the first WiFi subcarrier.
5. **Repeat 2-4 for the remaining channel:** Then we go back to step 2 to estimate the WiFi and LTE channels on the next WiFi subcarrier. The process continues until it reaches the center frequency. Then we start from the other end of the channel and repeat the same process to estimate the other half channel.

Figure 3 illustrates this process. Note that it is conceptual illustration so the number of subcarriers, the subcarrier width, OFDM symbol duration and the reference signal structure do not match with the real LTE and WiFi frame structure.

Improving the channel estimation accuracy: We use two additional techniques to further improve the channel estimation accuracy. First, we use multiple symbols for estimation. When we get the ratio of the WiFi channels using the LTE reference signals in Equation 3, we use multiple reference signals overlapped with one WiFi subcarrier as the average channel ratio. Suppose WiFi frame duration is 1ms. One WiFi subcarrier overlaps with up to 12 LTE reference signals transmitted in different time and frequency (*i.e.*, 3 in time and 4 in frequency). By using all of them, we improve accuracy in channel ratio estimation. Similarly, we also use multiple LTE reference signals to improve LTE channel estimation and 2 OFDM symbols in the standard WiFi preamble to improve WiFi channel estimation.

Second, we use iterative channel estimation. Based on the initially estimated channel, we demodulate and decode WiFi data bits, and then re-modulate the transmitted data symbols. We get new channel estimation by treating known data symbols in the same way as the preamble. This step improves accuracy by bringing the decoded signals to their closest constellation points. If decoding is correct (which is highly likely under a good rate selection), this step allows data symbols to be treated as known reference symbols. With more reference symbols, channel estimation accuracy improves. Given the improved channel estimation, again we demodulate and re-modulate data symbols, and repeat the same process to improve the estimate. This technique can be applied to joint LTE and WiFi channel estimation as well as the WiFi channel estimation with known LTE channel. Note that we do not use LTE data symbols to improve the estimation accuracy because LTE already provides a sufficient number of reference signals. In Section V, we evaluate the tradeoff between complexity and accuracy by varying the numbers of symbols and the number of iterations used for channel estimation.

B. Decoding WiFi MIMO Signals Interfered with LTE Signals

Most smartphones today do not have MIMO due to limited form factors, and our approach in Section IV-A is sufficient for these phones. Given the large capacity gain of MIMO, it is likely that more smartphones will support MIMO in the future. Therefore, in this section, we examine how to support co-existence between WiFi MIMO transmissions that overlap with LTE signals. It is necessary to estimate additional transmitted signal(s) and MIMO channel coefficients. This poses new challenges to decoding by introducing more unknown variables to the linear decoding system. The number of new unknowns increases fast since the number of MIMO channels to estimate increases with the product of numbers of sender and receiver antennas. In this section, we consider 2 × 2 WiFi MIMO transmissions interfering with LTE transmissions and a receiver with 3 antennas to receive up to 2 WiFi MIMO streams and 1 LTE stream. Our approach easily extends to an arbitrary number of WiFi streams.

WiFi channel estimation based on known LTE channel: 2 × 2 WiFi MIMO and LTE coexistence generates three LTE channels H_i^l, and six WiFi channels H_{ij}^w, where i and j are the receiver and the transmitter antenna indices, respectively. In WiFi SISO, we get the WiFi channel ratio based on LTE reference signal interfered with WiFi data signals. In WiFi MIMO, however, we cannot compute the WiFi channel ratios, since we have two different WiFi transmissions. Specifically,

$$\begin{aligned} H_{11}^w[k]I_1^w[k] + H_{12}^w[k]I_2^w[k] &= Y_1^l[k] - H_1^l[k]X_p^l[k] \\ H_{21}^w[k]I_1^w[k] + H_{22}^w[k]I_2^w[k] &= Y_2^l[k] - H_2^l[k]X_p^l[k] \end{aligned}$$

where the symbols on the left-hand side are unknown and the symbols on the right-hand side are known. In order to derive channel ratio, we let only one of the WiFi antennas j transmit during LTE reference signal time. Then we can derive the following channel ratio:

$$\alpha_k^j \triangleq \frac{H_{2j}^w[k]}{H_{1j}^w[k]} = \frac{Y_2^l[k] - H_2^l[k]X_p^l[k]}{Y_1^l[k] - H_1^l[k]X_p^l[k]}.$$

Similarly, we get $\beta_k^j \triangleq \frac{H_{3j}^w[k]}{H_{1j}^w[k]}$.

Once we get the channel ratios, we can estimate the WiFi channel similar to WiFi SISO in Section IV-A2. Specifically, in IEEE 802.11n WLAN, each MIMO transmit antenna sends a channel estimation preamble (*i.e.*, Long Training Field (LTF)) separately [21]. When the preamble from the WiFi transmitter j overlaps with LTE signals, the resulting signal is as follows:

$$\begin{aligned} Y_1^w[k] &= H_1^l[k]I^l[k] + H_{1j}^w[k]X_p^w[k] \\ Y_2^w[k] &= H_2^l[k]I^l[k] + H_{2j}^w[k]X_p^w[k] \\ Y_3^w[k] &= H_3^l[k]I^l[k] + H_{3j}^w[k]X_p^w[k]. \end{aligned} \tag{6}$$

It has four unknowns: $I^l[k]$ and $H_{ij}^w[k]$. By using the channel ratios α_k^j and β_k^j, we reduce the number of unknowns to 2 and solve the linear system (with rank 2) to get H_{ij}^w.

Iterative decoding: In Section IV-A3, we improved the channel estimation accuracy by re-modulation and iteration. It can be also extended to WiFi MIMO with the following modification. Based on the initially measured WiFi channel using the above method, we can also demodulate, decode, and re-modulate WiFi data symbols. But unlike the preamble that each transmitter separately transmits, the WiFi data symbols are transmitted together, which yields:

$$\begin{aligned} Y_1^w[k] &= H_1^l[k]I^l[k] + H_{11}^w[k]X_1^w[k] + H_{12}^w[k]X_2^w[k] \\ Y_2^w[k] &= H_2^l[k]I^l[k] + H_{21}^w[k]X_1^w[k] + H_{22}^w[k]X_2^w[k] \\ Y_3^w[k] &= H_3^l[k]I^l[k] + H_{31}^w[k]X_1^w[k] + H_{32}^w[k]X_2^w[k], \end{aligned}$$

where $X_j^w[k]$ is the data symbol from transmitter j. Even if we already know $X_j^w[k]$ by re-modulation and LTE channels, it still has 7 unknowns (*i.e.*, six $H_{ij}^w[k]$ and one $I^l[k]$). So we cannot solve it. Using α_k^j and β_k^j, we can transform the equations to

$$\begin{aligned} Y_1^w[k] &= H_1^l[k]I^l[k] + H_{11}^w[k]X_1^w[k] + H_{12}^w[k]X_2^w[k] \\ Y_2^w[k] &= H_2^l[k]I^l[k] + \alpha_k^1 H_{21}^w[k]X_1^w[k] + \alpha_k^2 H_{22}^w[k]X_2^w[k] \\ Y_3^w[k] &= H_3^l[k]I^l[k] + \beta_k^1 H_{31}^w[k]X_1^w[k] + \beta_k^2 H_{32}^w[k]X_2^w[k], \end{aligned} \tag{7}$$

which has three unknowns (*i.e.*, $I^l[k]$, H_{11}^w and H_{12}^w). Therefore, we can solve it, get the WiFi channels, and use them to improve the accuracy.

Extending to more WiFi MIMO streams: When there are more than 2 MIMO streams, we can use the same methodology: have one WiFi antenna transmit during LTE reference time to get the channel ratios and incorporate these ratios into the linear system resulting from interfering WiFi preamble and LTE signals similar to Equation 6 to solve for the WiFi channel. Similarly, we apply the ratios to the linear system derived under interfering WiFi data and LTE signals, similar to Equation 7 during iterative decoding.

Practical issues: Disabling spatial multiplexing during LTE reference time can be achieved as follow. Section IV-D shows we can synchronize with LTE base station and determine the transmission time of the next LTE reference. Then the WiFi transmitter modulates the data as usual, but now inserts null signals at the expected LTE reference time for one antenna. WiFi symbol duration is 4 us, whereas an LTE reference signal lasts 71 us, which is around 18 WiFi symbol durations ($18 * 4 = 72 \approx 71$). So we insert 18 null WiFi symbols at the LTE reference time to facilitate channel estimation. The two antennas can take turns to send the null signal so that they finish transmission around the same time.

The cost of disabling spatial multiplexing during LTE reference is low. The theoretical gain are 81%, 71%, and 66% over isolation for 2, 3, 4 WiFi streams, respectively. We can further increase the gain for larger WiFi frames by disabling spatial multiplexing during two LTE reference symbols and enabling spatial multiplexing during all the remaining time (including the remaining LTE reference symbol time).

C. WiFi Carrier Sensing under LTE Interference

Given the capability of decoding WiFi and LTE even when they overlap, we need to design a new carrier sense so that a WiFi transmitter can send in the presence of LTE interfering signals. The traditional energy based carrier sense no longer works since LTE interference can be high and WiFi will sense the carrier and defer to LTE transmissions.

Motivated by [14], to avoid carrier sensing LTE transmissions, we carrier sense by projecting the received signal orthogonal to the LTE channel to remove their impacts. The main issue remains is how to estimate LTE channel under possible WiFi interference. We develop the following procedure:

- Estimate the boundary LTE channel using LTE reference signals.
- Extrapolate the M LTE channels closest to the boundary LTE channel. $M = 12$ in our implementation.
- Project the received signals on these M LTE channel orthogonal to their channel estimates. Let R_k denote the received signal on the k-th LTE channel, H_k^l denote its channel estimate. We compute $R_k \cdot w_k$, where w_k denotes two vectors in a subspace orthogonal to H_k^l.
- If the projected signal exceeds a threshold (*i.e.*, $|R_k \cdot w_k| > thresh$), the channel is considered busy. Our evaluation uses $thresh = 0.1|R_k|$.

Note that if there is no other interference on the boundary LTE channel, the channel estimate of the boundary channel should be accurate. Since M channels are adjacent to the boundary LTE channel, extrapolation accuracy should be high and the projection based carrier sense should work well. If there is interference on the boundary channel, the channel estimation is off and the projected signal does not completely eliminate LTE signals and carrier will be sensed. Interestingly, this is the right decision since there are indeed additional interference (*e.g.*, due to WiFi transmissions on a wider band that overlaps with the LTE boundary channel or other interferers).

D. Discussion

Synchronization: LTE cell synchronization is the first step involved in establishing LTE communication. The device extracts the physical ID and cell ID of an LTE base station from PSS and SSS. Since PSS and SSS are transmitted frequently (once every 5 ms) and WiFi transmission is intermittent, a device can easily receive the IDs when WiFi is silent. Once the ID is known, the device synchronizes with the LTE base station by running cross correlation between the received signal with the PN sequence corresponding to the ID. A natural question arises is whether such correlation still works under strong WiFi interference. Interestingly, we observe that PSS resides on the center of a 20MHz channel, spanning 960 KHz bandwidth. One third of PSS overlaps with WiFi DC subcarrier with no WiFi transmission. This means that one third of PSS experiences little interference from WiFi. As shown in Figure 7, owing to the robustness of Zadoff Chu sequence used in PSS and the low interference in one third of PSS, the correlation accuracy is almost perfect even when two thirds of the PSS may experience as low as -10 dB SNR due to strong WiFi interference. This result indicates that synchronization is feasible in presence of WiFi interference.

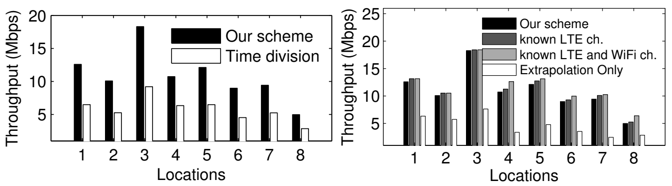
Wider channel: So far, we focus on 20MHz channels, the most widely used channel widths in WiFi today. IEEE 802.11n and 802.11ac support wider channels. When WiFi uses a wider channel than LTE, LTE may not have uninterfered boundary channel. In this case, we can add a few null WiFi subcarriers so that we can accurately estimate LTE channel on these WiFi subcarriers. As shown in Section V, using the guardband of 0.875 MHz width, we can accurately estimate the channel coefficients of the half of the interfered channel spanning 8.12MHz. With 3 empty subcarriers every 10 MHz, we get 0.94MHz uninterfered channel and it should be sufficient to apply the same technique without guardband.

Carrier Frequency Offset (CFO) Estimation: The carrier frequency offset (CFO) is incurred due to the slight frequency difference between the transmitter and the receiver, which causes inter carrier interference (ICI) in OFDM. One of the widely used CFO estimation technique is schmidl & cox algorithm that exploits two identical symbols transmitted in different time [26]. As CFO is a linear function time, we can estimate it by dividing the two identical symbols assuming that the channel is constant during the symbol interval. In our coexistence design, CFO of the LTE sender can be easily estimated using the boundary channel. Estimating WiFi CFO is more challenging, but we can estimate it using known WiFi pilot symbols and LTE reference symbols. WiFi has 4 pilot subcarriers dedicated to transmit pilot symbols. When the pilot symbols are collided by known LTE reference symbols, LTE symbols can be subtracted to estimate WiFi CFO by dividing it by the other pilot symbol sent at different time.

WiFi ACK frames: ACK frames are short and can be sent as a PN sequence to tolerate LTE interference instead of going through the above full fledged decoding. A nice feature of the PN sequence is that it works under high interference. This is achieved by correlating the received signal with a PN sequence, and detecting the correlation spikes if and only if the signal contains the PN sequence. As shown in several previous works (*e.g.*, [11], [15], [16], [27]) correlation based detection is reliable even under -6 dB SNR. Increasing PN sequence duration can further improve its reliability. A similar approach can be used to send other short WiFi control frames, such as RTS and CTS.

Computation time: The additional complexity in our decoder mainly comes from channel estimation. It involves (i) extrapolation, (ii) getting channel ratios by cancelling out the interference from the other signal, and (iii) solving small linear systems (2 constraints with 2 unknowns in the case of 1 WiFi interfering with 1 LTE signal). Since channel estimation is performed once every frame, the channel estimation cost is amortized by decoding multiple data symbols in a frame.

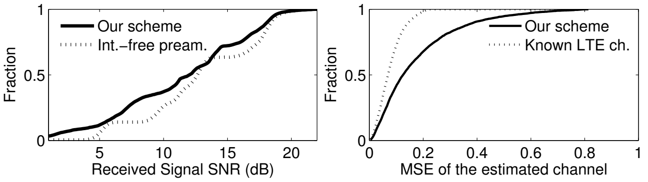
Processing LTE and WiFi signals together: Our system assumes that both LTE and WiFi signals are handled in the



(a) Comparison with time-division

(b) Comparison with different channel estimation

Fig. 4. Total WiFi and LTE throughput comparison



(a) CDF of received WiFi signal SNR

(b) CDF of MSE of WiFi estimated channel

Fig. 5. Comparison between our scheme using interfered references vs. using interference-free WiFi and LTE references.

same processor. This is feasible considering that most recent application processors (AP) implements all of the functionalities required for smartphone in one hardware chipset, such as CPU, RAM, LTE and WiFi processors. For example, both Qualcomm snapdragon 615 and Apple A8 processor have LTE and 802.11ac modem in them. Therefore, it is not difficult to support our decoding on top of recent processors. Moreover, Picasso [13] and SVL [29] have shown that it is possible to process multiple PHY techniques simultaneously in one radio. This makes it possible to enable the proposed scheme on smartphones in practice.

Antenna separation: To guarantee independence between WiFi and LTE spatial streams, these antennas should be separated by at least half of the wavelength (*e.g.*, 6.25 cm in 2.4GHz and 3 cm in 5GHz) [22]. Most of smartphones sold in market these days have at least 4-inch display, which is possible to separate LTE and WiFi antennas so that they get independent channels. Moreover, when 5GHz unlicensed band is used (as considered by Qualcomm and Huawei), it is possible to put multiple WiFi antennas along with an LTE antenna on a few popular smartphones (*e.g.*, iPhone 6 is 6.7 cm x 13.8 cm, iPhone 6 Plus is 7.8 cm x 15.8 cm, and Samsung Galaxy S5 is 7.2 cm x 14.2 cm).

V. PERFORMANCE EVALUATION

We evaluate WiFi and LTE co-existence using our GNU-Radio USRP N200 testbed. We set the channel bandwidth to 10 MHz due to limited processing speed of USRP, and use one of the channels in 2.4GHz that has minimum interference from external networks. We generate IEEE 802.11a WLAN and LTE signal according to the standard, and send and receive them through USRP to capture the real channel characteristics. For WiFi, we fix the channel coding to 1/2 rate convolutional coding, and use three different modulations: BPSK, QPSK and 16-QAM, which give 3, 6 and 12Mbps transmission rates in a 10 MHz bandwidth channel, respectively. For LTE, we use QPSK and 16-QAM modulations and 3/4 rate Turbo coding. We let one USRP device send LTE signal and another send WiFi signal on the same frequency band with a timing offset.

During the experiments, we place USRPs at various locations with different channel conditions. In particular, locations from 5 to 8 experienced more fading due to non-line-of-sight path as well as low received SNR. The average standard deviation for the magnitude of CSIs of locations 1 to 4 and 5 to 8 are 0.43 and 0.61, respectively.

Comparison with time-domain sharing: We first compare our approach with time-domain sharing, where half of time is allocated to WiFi transmissions and the remaining half is used for LTE transmissions. At each location, WiFi and LTE transmitters each send 1000 frames, and we compute the throughput based on the time of delivering these frames. In the time-division approach, LTE and WiFi frames are transmitted separately to avoid interference. In our approach, we store the received signals at two receivers to trace files and feed the resulting trace to our decoder, which implements channel estimation and decoding based on the interfered signals. Our approach estimates the channel using 200 WiFi data symbols, 3 LTE reference symbols, and 2 iterations. For both our approach and time-domain approach, the modulation is selected as the one that gives the maximum throughput at each location. WiFi frame size is selected so that the frame duration is 2 ms. Figure 4(a) compares the total throughput of LTE and WiFi at 8 different locations with different fading and SNR. As we would expect, our scheme almost doubles throughput in all channel conditions. The average throughput gain is 87%, and the maximum and the minimum gains are 92% and 72%, respectively. The gains are slightly below 2 due to imperfect channel estimation. Since our approach is much better than isolation, below we focus on decoding interfering signals.

Comparison of decoding interfered signals: The main challenge of the LTE-WiFi coexistence idea is the channel estimation. We compare the following schemes that decode interfered signals, where all of them use the same decoding algorithm described in Section IV-A1 but differ in channel estimation:

1. Our final scheme: joint channel estimation based on interfered WiFi preambles and LTE reference signals, as described in Section IV-A3.
2. LTE channel is estimated based on interference-free LTE reference signals, and WiFi channel is estimated using interfered signals as described in Section IV-A2.
3. WiFi and LTE channels are estimated using interference-free WiFi preambles and LTE reference signals.
4. LTE channel is estimated by first estimating the LTE boundary channel and then using extrapolation alone to estimate the remaining overlapping portion. WiFi channel is estimated as described in Section IV-A2.

Schemes 2 and 3 are not realistic, but provide useful baselines on the upperbound of our scheme. For fair comparison, we use the same received signal traces for evaluation.

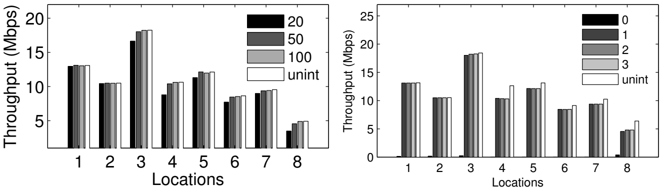
Figure 4(b) compares throughput at 8 locations using different channel estimation schemes. We make several observations. First, our scheme is comparable to the estimation that relies on interference-free references. The average throughput of our channel estimation is 93% of the scheme that has uninterfered WiFi and LTE reference signals, and 96% of the scheme that has uninterfered LTE reference signals. Since our approach does not need a complicated synchronization technique to guarantee interference-free reference signals, this small reduction is acceptable. Second, the channel estimation based on the extrapolation alone yields significantly lower throughput. This is expected since channel is usually frequency selective and relying on extrapolation alone is inaccurate.

Figure 5(a) shows the cumulative distribution function (CDF) of the SNR of the received WiFi signals for all frames received in 8 links. Given the same received signal, the accuracy of the channel estimation affects the quality of the decoded signal, which is another metric of the channel estimation performance. We compute SNR of the received signal by calculating the Euclidean distance between transmitted and the decoded signals (*i.e.*, EVM). As shown in Figure 5(a), the estimation accuracy of our scheme is comparable to the estimations using interference-free WiFi preambles. The median SNR of our scheme is 12 dB, which is only 0.6 dB lower than the scheme using interference-free preamble. As SNR decreases, the channel ratio estimation has a higher error, which in turn increases channel estimation error. This reduction accounts for the throughput reduction in Figure 4(b).

Figure 5(b) shows the cumulative distribution function (CDF) of the channel estimation error. We quantify the error using Minimum Squared Error (MSE), defined as $E[(x_{est} - x_{true})^2]$, where x_{est} and x_{actual} are the estimated and actual channel, respectively. We consider the channel estimation using interference-free references as the ground-truth though the ground truth itself has error, which increases as SNR decreases. We compare MSE of our scheme against the ground truth. The result shows that the median MSEs in our scheme and scheme 2 are 0.12 and 0.065, respectively. For largest 20%, MSEs are 0.39 and 0.14, respectively. In terms of the median MSE, both schemes have small MSEs, but the difference in large MSEs is non-negligible. This is partly because the ground truth itself is inaccurate and the actual error of our scheme may be lower. The signal quality reduction by the channel estimation error depends on the channel SNR. For example, when the channels are 12 dB and 6dB, the signal SNR reductions are 2 dB and 1.5 dB, respectively. This result is consistent with the received signal quality in Figure 5.

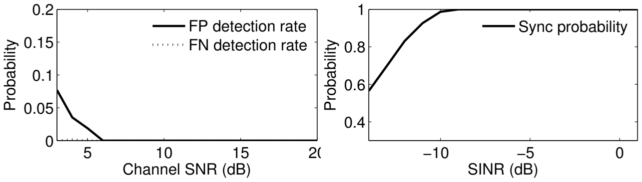
To understand the tradeoff between complexity and accuracy, we vary the number of data symbols and iterations. Figure 6(a) shows the throughput when 20, 50, 100, 150 and 200 WiFi data symbols are used for the channel estimation. Here the number of iterations is fixed to 1. For comparison purpose, we also include the throughput using uninterfered WiFi and LTE references for channel estimation. As we can see, our decoding under interference achieves close to the performance with uninterfered preambles. Moreover, comparing different number of data symbols, we observe that the throughput is similarly high as long as at least 50 data symbols are used for channel estimation. For example, the throughput using 50 data symbols is 99.5% of the throughput using 200 data symbols in all cases. The throughput of using 20 data symbols is noticeably lower at a few locations.

To improve the channel estimation accuracy, we use iterative channel estimation described in Section IV-A3, which decodes and re-modulates WiFi data symbols and repeats the channel estimation process. Figure 6(b) compares throughput under varying numbers of iterations, where the number of data symbols for re-modulation is fixed to 50. When the number of iterations is zero, data symbol re-modulation is not used and the receivers estimate the channel only using the interfered preamble. As we can see, without any iteration, the throughput is close to zero. This is because channel estimation that relies on the LTE boundary channel and extrapolation is susceptible to noise. Therefore the iterative channel estimation is critical to achieving acceptable channel estimation accuracy. However, iterating just once is sufficient, and the improvement from more iterations is negligible. All schemes with at least one iteration perform close to the scheme that estimates channel using uninterfered WiFi and LTE references. Therefore we conclude that 50 data symbols and one iteration are sufficient to achieve high accuracy and low computational cost.



(a) Different # WiFi data symbols for channel estimation (b) Different # iterations

Fig. 6. Total WiFi and LTE throughput comparison under different scenarios.



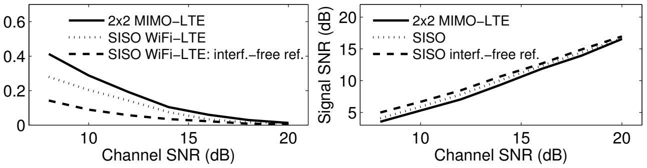
(a) Carrier sense false positive/negative rates (b) Synchronization accuracy

Fig. 7. Carrier sensing and synchronization accuracy.

Carrier sense: We use the False Positive (FP) and False Negative (FN) ratios to quantify the performance of carrier sense at various SNR. We perform experiments at different locations, and classify them based on the SNRs of the received WiFi signals. Figure 7 shows that our carrier sensing is accurate in all SNR range when the communication is possible. When SNR is higher than 6 dB, both FP and FN rate are 0. The average FP detection rate in SNR 3 - 5 dB is 4%. The impact of the false positive carrier sensing is negligible since it just wastes one slot time, which is acceptable. On the other hand, the false negative carrier sensing is more serious since it may result in more hidden terminals. Our evaluation shows that FN rate is 0.2% for 4 dB SNR and 0 for higher SNR.

Synchronization: We evaluate the synchronization of LTE PSS under WiFi interference using MATLAB simulation since the channel is more precisely controlled in simulation. We generate PSS using MATLAB LTE toolbox and send it through channel along with WiFi signal. To make sure its robustness against random phase error, the received signals are multiplied by random complex channel coefficients (*i.e.*, Rayleigh fading). The channel SNR is fixed to 5 dB, and WiFi signal strength is varied so that the received signal SINR is between 2 dB and -14 dB. We send PSS at a random time, and see if the receiver can accurately detect the starting sample of PSS using cross-correlation.

As shown in Figure 7, the PSS is accurately synchronized even under very low SINR such as -10 dB. The main reason is due to the robustness of Zadoff Chu sequence in PSS and the uninterfered portion at the WiFi DC subcarrier. When WiFi and LTE signal strength differ by more than 10dB, we can nullify 2 additional subcarriers close to the center frequency as well as the DC subcarriers. This allows the whole sequence of PSS are transmitted with minimal interference from WiFi, thereby achieving high synchronization accuracy. The cost of nullifying 2 WiFi subcarriers is 4% given 48 data subcarriers in IEEE 802.11a, and is even lower in IEEE 802.11n, which have more data subcarriers. Without WiFi interference, PSS



(a) Channel estimation error (b) Decoded signal quality evaluation

Fig. 8. Compare SISO and MIMO WiFi-LTE coexistence: WiFi Performance.

is robust enough to have over 99% synchronization accuracy when SNR is as low as -5 dB.

Decoding multiple WiFi signals: To evaluate the performance of LTE and WiFi 2×2 MIMO co-existence, we perform simulation. We estimate the channel and decode WiFi MIMO signal interfered by LTE signal using the method in Section IV-B. We compare with the SISO WiFi-LTE co-existence results in terms of the channel estimation error (quantified using MSE) and decoding accuracy (quantified using decoded signals SNR). For realistic fading modeling, we used Clarke's model [25] and set the root mean square (rms) of the delay spread to 20 ns, which generates frequency-selective fading channel. As shown in Figure 8 (a), the WiFi channel estimation MSE under MIMO is slightly higher than that under SISO, because the former involves a larger linear system with more variables, each of which contains error. The gap decreases with an increasing channel SNR. Figure 8 shows signal SNR as the channel SNR varies from 8 to 20 dB. The signal SNR in MIMO is similar to SISO using interference-free WiFi and LTE references when the channel SNR is 12 dB or higher, and 1.4 dB lower for a lower channel SNR. So our decoding algorithm is effective in supporting WiFi MIMO and LTE co-existence.

VI. CONCLUSION

We develop a novel system to support co-existence between WiFi and LTE. It offers four distinct advantages over existing MIMO work: (i) it decodes all the interfering signals under cross technology interference even when the interfering signals have similar power and occupy similar frequency, (ii) it does not need clean reference signals from either transmission, (iii) it can decode WiFi MIMO transmissions even under strong LTE interference, and (iv) it has a simple yet effective carrier sense to avoid other WiFi transmissions while co-existing with LTE. Our implementation shows it out-performs time division approach by 87%, and performs comparably to using interference-free reference signals for channel estimation. The decoded WiFi MIMO signal using interfered reference signals is comparable to SISO using interference-free WiFi and LTE reference signals. The carrier sense is accurate: 0 false positive and false negative under higher than 6 dB SNR, and 4% and 0.2%, respectively, under 3 – 5 dB SNR.

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