A WiFi SIC Receiver in the Presence of LTE-LAA for Indoor Deployment

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***Abstract*—To fulfill the exponential growth of mobile traffic demands, 3GPP has standardized the use of LTE in the 5 GHz unlicensed band in the Release 13 dedicated to LTE Licensed-Assisted Access (LTE-LAA). Simulations and field trials have shown that incumbent WiFi (802.11ac) in the 5 GHz unlicensed band will be the victim in such co-channel deployment with LTE-LAA. Hence a concern is being raised about fair co-existence. In this work, we investigate the limits of Successive Interference Cancellation (SIC) to recover the WiFi packets corrupted by LTE-LAA in the event of a collision. For an indoor deployment, which is the most probable battleground for WiFi and LTE-LAA, we propose a method to perform SIC by using stored clean channel estimates of stronger signals obtained during an interference-free period. Our approach leverages the slow fading channel and hence high coherence time of the indoor channel. For an experimental proof of this phenomenon, we simulated a scenario with interference between 20 MHz 802.11ac and 20 MHz LTE-LAA at different inter-frame-intervals (IFI) of LTE-LAA frames. Our results show that for an LTE-LAA IFI up to 2 milliseconds, the proposed method of using stored channel estimates to perform SIC can achieve significant transmit power gain (TPG) compared to the conventional way of using instantaneous channel estimates. Our method complements the conventional approach to ensure improved WiFi Frame Detection and Decoding while applying SIC. Moreover, our method does not require any coordination between WiFi and LTE-LAA transceivers and hence can be deployed within existing infrastructure with minimal modifications.**

I. Introduction

With the decision of opening 5 GHz unlicensed bands for LTE, a major concern of incumbent WiFi (802.11ac) operators is fair coexistence with LTE Unlicensed (LTE-U) [1]. To address this issue, 3GPP has decided to make Listen Before Talk (LBT) as a mandatory feature in LTE Licensed-Assisted Access (LTE-LAA) which is a 3GPP standardized version of LTE-U. Apart from LBT, Qualcomm has proposed other methods for allowing co-existence such as Carrier Sense Adaptive Transmission (CSAT) and Absolute Blank Subframes (ABS) [3]. Previous works and field trials have also shown that in the event of interference between WiFi and LTE-LAA, WiFi becomes the primary victim [4], [5]. The scenario with coexistence could be more hostile as there is no provision of exchanging RTS (Request-to-Send)-CTS (Clear-to-Send) [2] packets between WiFi and LTE-LAA. In the absence of RTS-CTS packets, the hidden node scenario − a pervasive problem in contention-based networks [8] − will be another significant factor causing co-channel interference (CCI) between WiFi and LTE-LAA. In the licensed bands, LTE tackles CCI by an appropriate transmit time scheduling and a network-wise coordination [9]. However, in the unlicensed band with LTE-LAA and WiFi competing for the channel, these traditional methods are not available. The well established and operational WiFi is not going to be phased out in the foreseeable future, hence, a framework for a fair coexistence with LTE-LAA needs to be developed.

Knowing that the possibility of interference between WiFi and LTE-LAA cannot be ruled out and LTE-LAA is more robust compared to WiFi, in this work we conduct an experimental study of the application of Successive Interference Cancellation (SIC) to mitigate the interference between 20 MHz LTE-LAA and WiFi. To recover the WiFi frames lost or corrupted due to LTE-LAA interference, we propose to apply SIC technique using the stored channel estimate of the stronger signal well within the channel coherence time of the channel. Exploiting the fact that an indoor deployment is the most probable battleground for WiFi and LTE-LAA, we leverage the slow fading channel characteristic of indoor channels. Stating simply: if the channel coherence time is significantly larger than inter-frame-interval (IFI) – By IFI we mean the time of arrival of the subsequent frame –the channel estimates obtained in the past can be reused in the immediate future, which is the basis of our contribution.

For proof of concept, we have considered LTE-LAA as the stronger signal and apply SIC over the composite WiFi and LTE-LAA signals for different IFI. We observed that for IFI up to $2\,\mathrm{ms}$, our method provides significant transmit power gain (TPG) compared to conventional SIC which uses instantaneous channel estimates. However, for larger IFI, conventional SIC shows better performance. The benefits of our approach are as follows:

- It is suitable for the low mobility indoor users of LTE-LAA and WiFi.
- It requires modifications only on the receiver side

and hence does not depend on coordination between WiFi and LTE-LAA transceivers.

- It is relatively independent of the imperfect channel estimates of the stronger signal obtained during interference caused by, the weaker one.
- It can be used to complement the conventional method of SIC to ensure better performance of SIC at both small and large IFI.

The remainder of this paper is organized as follows: Section II discusses the state-of-the-art interference mitigation techniques between LTE unlicensed and WiFi. Section III provides a background of the physical layer of 802.11ac, LTE-LAA, signal model and SIC technique. Section IV discusses the details of our methods. Section V presents the experimental set-up and concludes with the discussion on the results.

II. Previous Work

Even before 3GPP standardized LTE-LAA for deployment in the unlicensed band, a variety of studies have been conducted, both from a physical and a MAC layer perspective. Among single antenna systems, a majority of the studies focused on modifications in physical or MAC layer architecture of either LTE-LAA or WiFi. For example, a Carrier Sense Adaptive Transmission (CSAT) [7] based LTE-LAA performs carrier sensing similar to WiFi CSMA/CA, but it adapts the transmission time of LTE-LAA to schedule free slots for WiFi transmission. A similar approach where duty-cycle of LTE-LAA is varied based on machine learning is proposed in [12]. In Almost Blank Subframes (ABS) [3] blank LTE-LAA subframes are periodically transmitted so that WiFi enjoys interference-free transmission during that interval. Authors of [10] propose a coordination of WiFi and LTE-LAA transmitters in order to avoid collisions while authors in [11] talk about frequency reassignment. Among multi-antenna systems, beamforming based solutions have been proposed in [13] and [14] however, both of them require co-ordination between WiFi and LTE-LAA transmitters.

III. Background

In the unlicensed 5 GHz band, the minimum bandwidth allocated for WiFi and LTE-LAA is 20 MHz. Nonetheless, both of them are capable of increasing their operational bandwidths up to 160 MHz through carrier aggregation and channel bonding respectively. The physical layer of both LTE-LAA and WiFi is based on OFDM. LTE-LAA uses 2048 point FFT and a sampling rate of 30.72 MHz while WiFi uses 64 point FFT and a sampling rate of 20 MHz. We consider an indoor deployment of single antenna access points of WiFi (W) and LTE-LAA (L) and a single antenna dual-technology (WiFi and LTE-LAA) receiver (RX) as shown in Fig. 1. LTE-LAA access point is connected to an LTE small-cell via an optical link and has overlapping coverage with

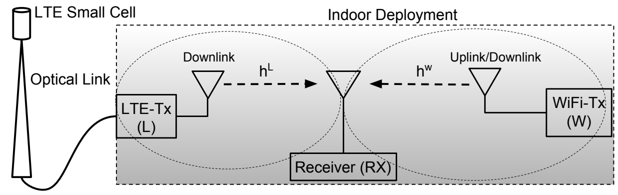

Fig. 1. An indoor deployment scenario of single antenna WiFi Tx (W), single antenna LTE-LAA Tx (L) and single antenna WiFi Plus LTE-LAA dual technology receiver (RX)

WiFi. For simplicity, we consider a downlink transmission of LTE-LAA (because LTE-LAA uplink happens via licensed band as mentioned in 3GPP Release 13) and uplink/downlink transmission of WiFi.

A. Signal Model

Let $s^l[n]$ and $s^w[n]$ be the time domain LTE-LAA and WiFi signals respectively. In the event of collision between WiFi and LTE-LAA, the composite signal $r[n]$ can be written as:

$$r[n] = h^w[n] * s^w[n] + h^l[n] * s^l[n] + v[n] \tag{1}$$

Where h^w and h^l are time domain impulse responses of WiFi and LTE-LAA channels respectively. Term $v[n]$ represents Gaussian distributed thermal noise samples with zero mean and variance σ^2. Note that since the sampling rates of WiFi (20 MHz) and LTE-LAA (30.72 MHz) are different, an appropriate resampling operation needs to be performed before realizing (1). For proof of concept, we have assumed LTE-LAA signal to be stronger than WiFi; nevertheless, all the following work is equally applicable with vice versa assumption. Following (1), Signal to Interference plus Noise Ratio (SINR) of WiFi in the received signal $r[n]$ is

$$\mathrm{SINR}_{\mathrm{WiFi}}[n] = \frac{\mathbb{E}\left\{|h^w[n] * s^w[n]|^2\right\}}{\mathbb{E}\left\{|h^l[n] * s^l[n]|^2\right\} + \sigma^2}. \tag{2}$$

With this $\mathrm{SINR}_{\mathrm{WiFi}}$, the detection and decoding of a WiFi frame depends on the strength of the LTE-LAA interference. In order to increase $\mathrm{SINR}_{\mathrm{WiFi}}$, SIC can be used as discussed in the next section.

B. Successive Interference Cancellation

Successive Interference Cancellation is a well known physical layer technique to recover a weaker signal corrupted by a stronger signal [6]. SIC is possible when the receiver can decode the stronger signal and cancel its effect from the composite signal. In this way the effective post-processing SINR of the weaker signal is likely to exceed the required receiver sensitivity [6] of the weaker signal, and thus could be decoded. In our case, if the LTE-LAA frame is detected, it undergoes a channel estimation and demodulation process. During this process, the channel estimates are stored, and once the decoded bits are available, the channel estimates are used to regenerate LTE-LAA back. After the frame detection and N point ($N = 2048$ for LTE) FFT of received samples, the frequency domain complex sample $R^l[k]$ on k^{th} subcarrier of LTE-LAA is:

$$R^l[k] = H^l[k]X^l[k] + H^w[k]I^w[k] + N[k], \quad (3)$$

where $X^l[k]$, $I^w[k]$ are frequency domain LTE symbols and WiFi interference respectively. Note that since WiFi uses 64 point FFT, performing 2048 point FFT does not orthogonalize WiFi subcarriers, hence recovering WiFi from $I^w[k]$ is not possible. The elements of $R^l[k]$ corresponding to the pilot subcarriers are used to compute estimates $\hat{H}^l$ of the actual channel H^l. Assuming that SINR of LTE-LAA is strong enough to allow the frame to pass the Cyclic Redundancy Check (CRC), the next step is to regenerate the LTE-LAA frame for its subsequent cancellation from the received signal $r[n]$. The regenerated frequency domain received baseband LTE-LAA signal $Y^l_{\text{Reg}}[k]$ can be written as:

$$Y^l_{\text{Reg}}[k] = X^l[k]\hat{H}^l[k]. \quad (4)$$

We use X^l and not the estimates because we regenerate only those LTE frames which have passed CRC. We then convert $Y^l_{\text{Reg}}[k]$ into the time domain $y^l_{\text{Reg}}[n]$ by performing 2048 point IFFT which results in:

$$y^l_{\text{Reg}}[n] = \hat{h}^l[n] * s^l[n]. \quad (5)$$

Here $\hat{h}^l[n]$ represents the time domain estimate of the LTE-LAA channel. After SIC of estimated LTE-LAA interference the residue signal is now:

$$\begin{aligned} r^{\text{SIC}}[n] &= r[n] - y^l_{\text{Reg}}[n] \quad (6)\\ &= h^w[n] * s^w[n] + (h^l[n]-\hat{h}^l[n]) * s^l[n] + v[n]. \end{aligned}$$

After SIC the effective SINR of weaker WiFi becomes

$$\text{SINR}^{\text{SIC}}_{\text{WiFi}}[n] = \frac{\mathbb{E}\left\{|h^w[n] * s^w[n]|^2\right\}}{\mathbb{E}\left\{|(h^l[n]-\hat{h}^l[n]) * s^l[n]|^2\right\} + \sigma^2}. \quad (7)$$

From (7), it can be observed that the more accurate the channel estimate $\hat{h}^l$, the smaller is the noise term $\mathbb{E}\{|(h^l-\hat{h}^l) * s^l|^2\} + \hat{\sigma}^2$ in the denominator and the higher is post processing SINR of WiFi, i.e., $\text{SINR}^{\text{SIC}}_{\text{WiFi}}$. Thus, it is vital to accurately estimate the channel of the stronger signal to increase the post-processing SINR of the weaker one.

Obtaining an accurate estimate of h^l is difficult as LTE-LAA pilots get corrupted by WiFi interference. We want to emphasize that up to a certain degree of the imperfect channel estimation; the LTE-LAA receiver is capable of accurate detection the data bits using Turbo decoders (likely at the price of an increased number of turbo iterations). Nevertheless, the accuracy of channel estimates is significant for regeneration of LTE-LAA interference to perform SIC. The residue signal $r^{\text{SIC}}[n]$ is further downsampled from 30.72 MHz to 20 MHz and fed to WiFi frame detection module, and if any frame is detected, the remaining steps of demodulation are performed to recover the WiFi payload.

IV. Proposed Method

Let t_1 be the time when there is no interference between WiFi and LTE-LAA frames and t_2 be the time of interference ($t_2 > t_1$). Also the LTE-LAA channel estimates at time t_1 and t_2 be $\hat{h}^l_{t_1}$, $\hat{h}^l_{t_2}$ respectively. We propose to regenerate the LTE-LAA interference occured at time t_2 using the interference-free LTE-LAA channel estimates $\hat{h}^l_{t_1}$ obtained at time t_1 in the following two phases:

*A. **Phase-1**: Obtain clean LTE-LAA channel estimates when WiFi frame is not being transmitted*

Since WiFi uses CSMA/CA and LTE-LAA uses LBT, simultaneous transmission from both of them is already minimized (except the hidden node case). Thus, there will be ample opportunities for the dual technology receiver RX for listening and decoding the ongoing LTE-LAA transmissions and estimating the channel between LTE-LAA transmitter L and RX. Nonetheless, an obvious question is how to confirm that the received LTE-LAA frame is interference free?

As discussed before, up to a certain degree of the imperfect channel estimation an LTE-LAA frame can still pass CRC, thanks to the Turbo decoders. In contrast, in the low SNR and no interference scenario, the decoding might fail even if the receiver is provided with perfect channel estimates. Hence, CRC cannot serve as a reliable indicator of the presence or absence of the interferer.

Instead, to register interference, we evaluate RMS of Error Vector Magnitude (R-EVM) between received LTE-LAA samples $R^l[k]$ and regenerated samples $X^l[k]$ after decoding of the LTE-LAA frames. For a fixed LTE-LAA transmit power (TxP) of -80 dBm and modulation scheme QPSK, we performed simulations to monitor the R-EVM of LTE-LAA in the presence and absence of WiFi frames. We observed that a WiFi signal (MCS-0) with TxP almost near to WiFi receiver sensitivity, i.e., -90 dBm increases the R-EVM of LTE-LAA received signal almost 4 times compared to the R-EVM in the absence of WiFi. Hence, RX can be trained to monitor sudden jumps in R-EVM of LTE-LAA signal to reliably find the presence of WiFi interference on those LTE-LAA packets which have passed CRC.

*B. **Phase-2**: Regenerate LTE-LAA interference at t_2 using $\hat{h}^l_{t_1}$ instead of $\hat{h}^l_{t_2}$ if $(t_2 - t_1) << T$, where T is the LTE-LAA channel coherence time*

For LTE-LAA, Extended Pedestrian Model-A (EPA) channel model [15] can be considered as a very close approximation of the indoor channel model in terms of Doppler shift. The maximum Doppler shift specified in EPA channel model is 5 Hz which corresponds to a coherence time of approximately $80\,\text{ms}$. This is eight times the duration of a typical LTE-LAA frame duration, i.e., $10\,\text{ms}$ (Coherence time = 0.423/Doppler frequency). Here the term (t_2-t_1) represents the inter-frame interval

(IFI). We propose that if IFI is significantly below LTE-LAA channel coherence time T, then $\hat{h}^l_{t_1}$ can be reliably used instead of $\hat{h}^l_{t_2}$ to regenerate the LTE-LAA interference for a collision which has happened at t_2.

C. Proposed Receiver Operation

An illustration of our scheme is shown in Fig. 2.

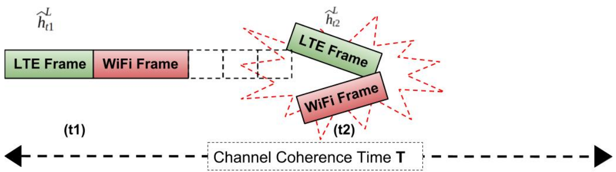

Fig. 2. Proposed Scheme to Capture LTE-LAA Channel

Given the knowledge of t_2^{max} over which the operation discussed in **Phase-2** is valid, we explain the proposed receiver operation as follows:

1) RX detects an LTE-LAA frame at t_1. It estimates the channel $\hat{h}^l_{t_1}$ and decodes the frame.
2) If the decoded frame passes the CRC and the R-EVM does not exceeds the threshold, the frame is considered interference-free and $\hat{h}^l_{t_1}$ is stored with time stamp t_1.
3) A new LTE-LAA frame is detected at t_2. Its channel is estimated which is $\hat{h}^l_{t_2}$ and the frame is decoded using $\hat{h}^l_{t_2}$.
4) If the frame fails CRC, it is altogether discarded. However, if frame passes CRC and the R-EVM also exceeds the threshold, the presence of a WiFi frame is identified[1].
5) If t_2 does not exceed t_2^{max}, $\hat{h}^l_{t_1}$ is used to regenerate the LTE-LAA signal instead of $\hat{h}^l_{t_2}$, otherwise $\hat{h}^l_{t_2}$ is used to regenerate the LTE-LAA signal.
6) Further the regenerated LTE-LAA interference is canceled from the composite signal and the residue signal is downsampled to 20 MHz and sent for WiFi packet synchronization and decoding.

In Section V, we make an attempt to empirically find t_2^{max} and hence Maximum IFI inside an indoor deployment.

V. Performance Evaluation

A. Simulation Setup

To validate our method, we perform simulations using the standard compliant IEEE 802.11ac and LTE libraries available in MATLAB Release 2018a. In our experiments, we use 20 MHz LTE bandwidth for the downlink and 20 MHz of 802.11ac bandwidth. For proof of concept, we chose a fixed LTE TxP of -80 dBm and varied the WiFi TxP. For each WiFi TxP, 100 frames weer transmitted. The worst case scenario was considered, as if there is no CSMA and there is 100% chance of collision between WiFi and LTE-LAA packets. The simulation parameters are summarized in Table I.

[1]If the frame passes CRC and R-EVM has not crossed the threshold, clean channel estimates are updated.

TABLE I: Simulation Parameters

	802.11ac	**LTE-LAA**
Center Freq	5 GHz	5 GHz
Bandwidth	20 MHz	20 MHz
Channel	TGac Model-B	EPA
Sampling Rate	20 MHz	30.72 MHz
Payload	500 Bytes	500 Bytes
Modulation and Coding	MCS $0, 2, 4$	QPSK
Noise Power	-100 dBm	-100 dBm

B. Experimental Methodology

Step-1: In the first step, the LTE-LAA packets do not interfere with WiFi packets. The LTE-LAA channel is estimated from the received frame and stored along with the timestamp t_1.

Step-2: As a second step, we simulate the scenario with LTE-LAA packets colliding with WiFi at time t_2 ($t_2 > t_1$). To realize the effects of the same channel at t_2, we regenerate the channel as in Step-1 but with a timing offset of t_2 set using **lteFadingChannel.InitTime** parameter in MATLAB. Here $t_2 - t_1$ is the inter-frame interval (IFI). The composite signal is further processed as discussed in Section IV-C. For comparison, we also perform conventional SIC using instantaneous channel estimates of interfered LTE-LAA frames. In all our experiments, a moderate Doppler shift of 3 Hz was applied for the LTE-LAA channel which corresponds to a coherence time of $141\,\text{ms}$ and IFI of 2, 10 and $20\,\text{ms}$ were chosen. As performance metrics we used *WiFi synchronization error* and *WiFi frame error*, which are further explained.

Synchronization, i.e., frame detection is the very first and vital step in frame-based communication (WiFi and LTE). Without synchronization, no interference cancellation technique can be applied at the first place. In 802.11ac, frame synchronization is based on the Legacy Short Training Sequence (L-STS) and Legacy Long Training Sequence (L-LTS) [2]. Both L-STS and L-LTS are BPSK modulated (regardless of the MCS) and hence very robust to fading and interference. In this paper, the WiFi synchronization error is registered when a WiFi frame is transmitted and not detected.

Once a WiFi frame has been detected after canceling of the LTE-LAA signal from the composite signal, it is decoded, and the CRC is performed to check its sanity. The WiFi frame error is registered when the CRC of the frame fails. Besides, we logged WiFi frame error and WiFi synchronization error without LTE interference as a benchmark (plotted with the red squares in Fig.3 - Fig.6.).

C. Results & Discussions

WiFi frame error for MCS $\in \{0, 2, 4\}$ are plotted from Fig. 3 to Fig. 5. From observations, the amount of WiFi frame errors significantly increases in the presence of LTE-LAA interference for all MCS. Additionally, for all WiFI MCS, SIC – whether it is conventional or proposed – only works when WiFi TxP is at least 5

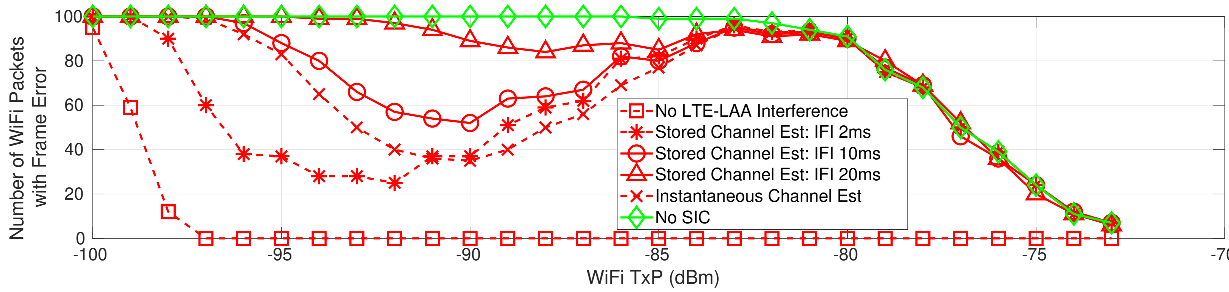

Fig. 3. WiFi MCS 0 requires lesser TxP when IFI $< 2\,\mathrm{ms}$ compared to the conventional SIC. For IFI $> 2\,\mathrm{ms}$, the conventional method performs better.

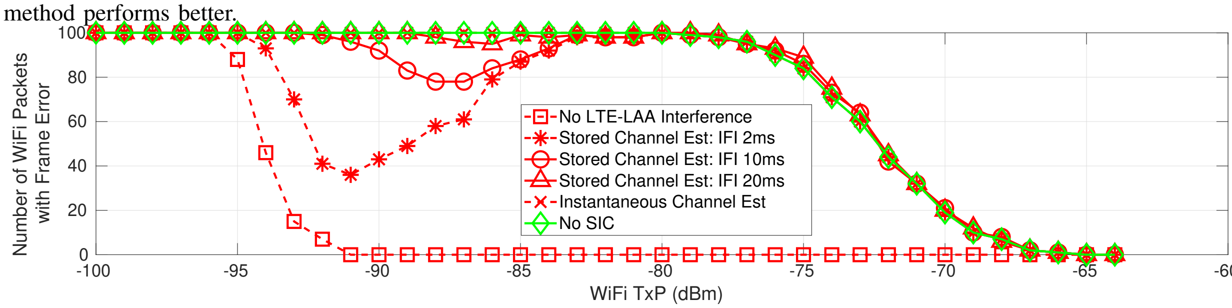

Fig. 4. For WiFi MCS-2, the conventional SIC ceases to recover any corrupted packet however, our method provide significant TPG for IFI $< 2\,\mathrm{ms}$.

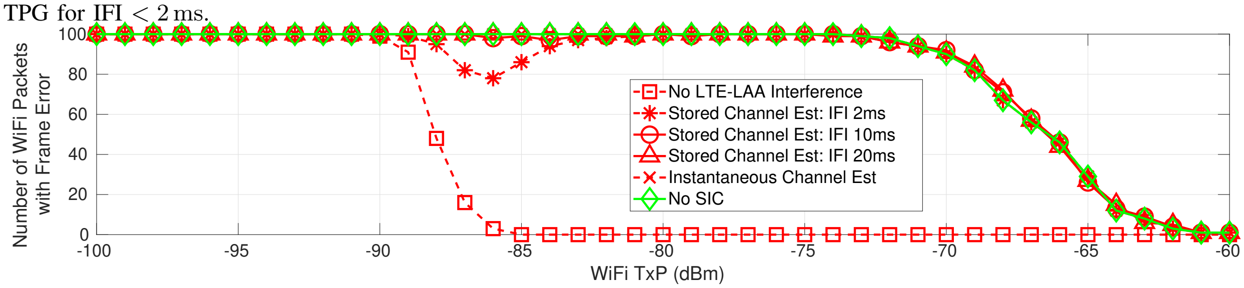

Fig. 5. For WiFi MCS 4, our method provides marginal performance at IFI $< 2\,\mathrm{ms}$. Conventional SIC fails to recover any corrupted WiFi packet.

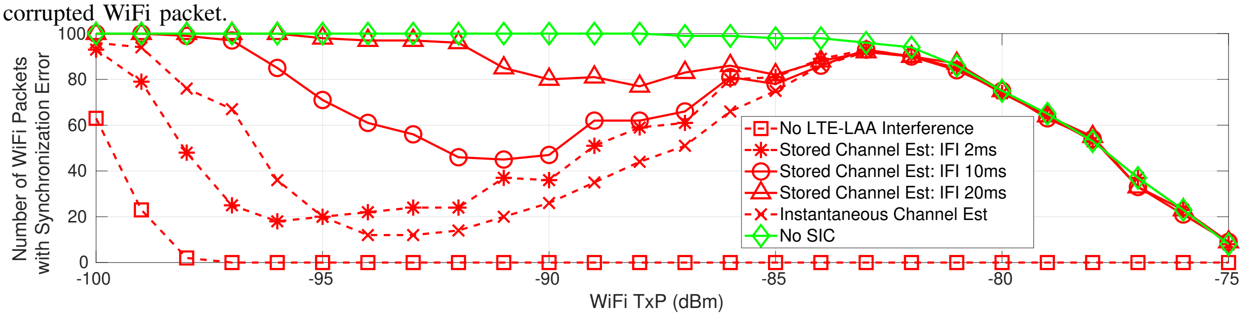

Fig. 6. For WiFi MCS-0, proposed method of SIC provides significant TPG compared to the conventional SIC during WiFi packet synchronization at IFI $< 2\,\mathrm{ms}$. For IFI $> 2\,\mathrm{ms}$, the conventional method performs better. The performance curve remain the same for all the WiFi MCS.

dB less than LTE-LAA TxP. Beyond that, SIC ceases to work because LTE-LAA frame starts experiencing CRC errors. In our simulations, only the LTE-LAA frames that pass the CRC check are used for regeneration. With further increase of the WiFi TxP beyond the TxP of LTE-LAA, the WiFi signal becomes dominant, and as a result, the number of erroneous WiFi frames starts decreasing. However, this performance comes at the cost of the increase in LTE-LAA frame error.

When bringing frame error count to approx 20% for MCS-0 (Fig. 3), our method has approximately 5 dB of Transmit Power Gain (TPG) compared to SIC using instantaneous channel estimates if IFI $\leq 2\,\mathrm{ms}$. However, TPG of our method gradually reduces with the increase of IFI. This happens because even though the statistics of the channel remains the same during the coherence time, the samples of the channel are not. From the curves for MCS-2 in Fig. 4, our method performs significantly superior to conventional way of using instantaneous channel estimates for SIC if IFI $\leq 2\,\mathrm{ms}$. Although the

TPG is not as prominent as was observed for MCS-0, nevertheless, it is far better than SIC using instantaneous channel estimates which is incapable of recovering any WiFi packet. The reason for this is that the SINR requirement for MCS-2 is higher compared to the one for MCS-0. Hence, the post-processing noise becomes more significant in MCS-2 compared to MCS-1 due to LTE-LAA channel estimation inaccuracy caused by WiFi interference. For MCS-4, the performance of SIC – both proposed and conventional methods – degrades significantly. Nonetheless, at IFI $\leq 2\,\mathrm{ms}$, our method shows marginal performance. The performance degradation is solely due to higher SINR requirement for WiFi MCS-4 which none of the SIC methods are capable of providing.

Since WiFi synchronization is based on WiFi preambles (identical for all WiFi MCS), we have plotted the WiFi synchronization error count only for WiFi MCS0 (Fig. 6). Performance for other WiFi MCS remains equivocally the same. We observe that without using any interference cancellation scheme, WiFi synchronization significantly degrades in the presence of LTE-LAA interference. To achieve WiFi frame synchronization error approximately 20%, our SIC method provides TPG of 1–2 dB compared to conventional SIC if IFI $< 2\,\mathrm{ms}$. Here also the TPG gradually decreases with the rise of IFI.

In summary, our simulation results suggest the use of stored channels estimates when LTE-LAA frames are arriving continuously which is a practical situation in burst based communications which follow CSMA/CA or LBT. Usage of instantaneous channel estimates should be reserved for the scenarios when the LTE-LAA frames arrive after a long gap for example start of the burst.

VI. Conclusion

Even with LBT as a compulsory feature in LTE-LAA, the interference between WiFi and LTE-LAA cannot be ruled out. The experimental evidence shows WiFi as the primary victim motivated us to investigate the capability of SIC to recover WiFi packets under LTE-LAA interference. Recognizing that indoor deployment is the most probable battleground between WiFi and LTE-LAA, we leverage the fact that indoor channel experiences slow fading. We thus propose to use stored channel estimates instead of instantaneous channel estimates for applying SIC. Simulations support our assumptions and show that for small inter-frame intervals, our method of performing SIC provides significant transmit power gain compared to the conventional method of SIC which uses instantaneous channel estimates. Our method along with the conventional method can provide efficient coexistence for WiFi and LTE-LAA. Although our study is conducted for the single antenna transceivers, it can be extended to the multi-antenna terminals with minimal modifications. Finally, our method requires physical layer signal processing at the receiver side only and operates without any coordination between WiFi and LTE-LAA transmitters. Hence, it can be integrated with existing infrastructure with minimal modifications.

Acknowledgment

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