Simultaneous Transmission Opportunities for LTE-LAA Smallcells Coexisting with WiFi in Unlicensed Spectrum

Long Li[1], Amir Hossein Jafari[1 2], Xiaoli Chu[1] and Jie Zhang[1]
[1]Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, United Kingdom
[2]Bell Laboratories Alcatel-Lucent, Dublin, Ireland
Email: {lli11, a.jafari, x.chu, jie.zhang}@sheffield.ac.uk

***Abstract*—LTE License-Assisted Access (LTE-LAA) in unlicensed spectrum has drawn a lot of attention due to its appealing data traffic offloading potential. However, the coexistence of LTE and WiFi technologies in the same unlicensed bands needs careful design to avoid severe interference between them. In this paper, we propose a coexistence scheme to create opportunities for LTE-LAA small cells and WiFi devices to transmit simultaneously. We combine Multiple Signal Classification (MUSIC) direction of arrival (DOA) estimation with null steering techniques to avoid collisions between LTE-LAA and WiFi transmissions. We assume that the LTE-LAA small cells are equipped with the latest 802.11 receivers for monitoring WiFi transmissions and for capturing simultaneous transmission timing. The performance of the proposed scheme in terms of collision avoidance and channel occupancy time ratio is evaluated via simulations. The results show that with DOA estimation and null steering, LTE-LAA small cells can transmit simultaneously with nearby WiFi devices without causing significant interference to them. As a result, LTE-LAA small cells can gain much more channel access opportunities and longer channel occupancy time while being "invisible" to coexisting WiFi networks.**

Keywords*—*LTE-LAA, WiFi, coexistence, unlicensed spectrum, MUSIC DOA estimation, beamforming, null steering.

I. Introduction

To alleviate the high data traffic load on conventional cellular networks, which are limited to the licensed cellular spectrum, LTE License-Assisted Access (LTE-LAA), also known as LTE-Unlicensed (LTE-U), has recently been proposed to enable LTE-Advanced systems to use unlicensed spectrum for their downlink transmissions through carrier aggregation [1]. Given the less congested 5 GHz unlicensed bands, LTE-LAA has been mostly considered for small cells. The Integrated Femto-WiFi (IFW) [2] introduced by the Small Cell Forum allows a small cell to simultaneously access the licensed spectrum via LTE interface and access the unlicensed spectrum via WiFi interface. The Dual-Band Femtocell (DBF) [3] can access both the licensed and unlicensed spectrum via LTE interface.

Assisted by the control channels in licensed bands, LTE-LAA small cells are anticipated to provide better quality of service (QoS) to end users in unlicensed bands than WiFi access points (APs) [4]. As the well established WiFi technologies are not going to phase out in the foreseeable future, LTE-LAA small cells need to coexist with WiFi systems in unlicensed bands. Since WiFi transmitters follow the Listen-Before-Talk (LBT) regulation through Carrier Sense Mulitple Access with Collision Avoidance (CSMA/CA), most existing schemes for coexisting LTE-LAA small cells and WiFi devices to share the unlicensed bands are based on time division duplex (TDD) [5]. Qualcomm proposed Carrier-Sensing Adaptive Transmission (CSAT) technology [1], where duty cycles are used to adaptively adjust the LTE-LAA channel access opportunities and LTE-LAA small cells are periodically switched on and off to guarantee fair channel access of WiFi networks. In the framework proposed in [6], DBFs perform channel sensing and can only initiate LTE-LAA transmissions when the channel is sensed free, leading to a lower collision probability as compared to CSAT. In [7], WiFi carrier sensing and decoding procedures are modified to enable WiFi and LTE-LAA to transmit simultaneously. However, to ensure smooth coexistence, the impact of LTE-LAA on and changes made to WiFi systems should be kept to a minimum [8]. In [9], LTE-LAA transmissions are allowed when the nearby WiFi AP is transmitting, as long as the receiving WiFi user is out of the LTE-LAA small cell's coverage. However, none of the above works has exploited multiple antenna technologies that can be deployed at both LTE-LAA small cells and WiFi APs.

In this paper, we refer to both a WiFi AP and a WiFi user equipment (UE) as a WiFi node. In Section II, we first explain the motivation behind finding new simultaneous transmission opportunities for LTE-LAA small cells to harmoniously coexist with WiFi networks and provide preliminaries to prove its feasibility. This is based on the idea to estimate the Direction of Arrival (DOA) of the WiFi receiver at the LTE-LAA small cell. The LTE-LAA small cell will then be able to conduct beamforming to steer one of its null beams towards the WiFi receiver to mitigate interference. In Section III, we propose a new comprehensive coexistence scheme based on this simultaneous transmission strategy for LTE-LAA small cells and WiFi networks in unlicensed spectrum. The advantage of such simultaneous LTE-LAA transmission is that, in a WiFi network, only one WiFi device is transmitting at any time instance due to the contention-based medium access, so that the rest WiFi devices stay either in their backoff frozen phase or NAV countdown phase, and the LTE-LAA transmission within this time period does not affect their current states. This means the simultaneous LTE transmission does not add more impact on the WiFi network than that already caused by the transmitting WiFi device. In Section IV, we evaluate the performance of the proposed coexistence

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scheme via simulations and theoretical analysis in Section IV. In Section V, we draw the conclusions.

II. Motivation

For LTE-LAA small cells to more effectively utilize the unlicensed spectrum in coexistence with WiFi nodes, a question arises: Do LTE-LAA small cells have to mute during WiFi transmissions? The spectrum reuse efficiency would be much higher if there are simultaneous transmission opportunities for LTE-LAA small cells without interfering WiFi transmissions. To answer this question, we first need to look into the WiFi channel access method, namely, CSMA/CA. A collision happens when one WiFi transmission is interrupted by strong interference. The WiFi transmitter detects the collision if there is no successful acknowledgement from the receiver. To avoid collisions, WiFi transmitters perform channel sensing and exponential random backoff procedures. A WiFi node can only proceed with its transmission when the channel is sensed unoccupied, but has to wait for an exponential backoff period, which consists of a random number of time slots, before starting transmission. Each WiFi node has a backoff countdown timer, which decreases by 1 with each elapsed time slot, and is ”frozen” when the channel is sensed busy during the backoff countdown. Once the backoff counter reaches zero, the transmission may start. Collisions not only lead to failed transmissions, but also increase the backoff stage of the WiFi transmitter, which in turn doubles the backoff period next time it initiates a new backoff counter. Given the contention-based channel access behavior of WiFi systems, the sharing of unlicensed spectrum between coexisting LTE-LAA and WiFi systems has mainly been considered in a TDD fashion. The TDD duty cycles can avoid LTE-LAA small cells dominating channel occupancy wile guaranteeing channel access opportunities for WiFi nodes. The LTE-LAA channel occupancy time ratio can be tuned by adjusting the duty cycle [1] or the parameter η in [6].

However, the TDD spectrum sharing by LTE-LAA small cells reduces the total channel access time and channel access opportunities of the WiFi networks, thus decreasing spectral efficiency. Moreover, the existing TDD based spectrum sharing schemes cannot completely avoid collisions between LTE-LAA and WiFi transmissions. For instance, with CSAT [1], if the LTE-LAA small cell is turned on just when the backoff count down timer of a nearby WiFi node reaches zero, or with the method in [6] the LTE-LAA small cell has sensed the channel free for a sensing period and starts to transmit and at the same time the WiFi backoff timer reaches zero, the LTE transmission will collide with the WiFi transmission.

In this paper, instead of dividing channel access opportunities in the time domain, we exploit the spatial domain by using multiple-antenna technology at LTE-LAA small cells and WiFi APs to create simultaneous transmission opportunities between the two systems in coexistence. LTE-LAA and WiFi transmissions can occur simultaneously in the same unlicensed band as long as none of the associated receivers detect the resulting mutual interference as a collision. We propose a coexisting scheme for an LTE-LAA small cell to utilize its beamforming capability (more specifically, through null steering) to avoid causing noticeable interference to nearby WiFi nodes while seeking opportunities for transmitting simultaneously with the WiFi nodes in the same unlicensed band, as illustrated in Fig. 1.

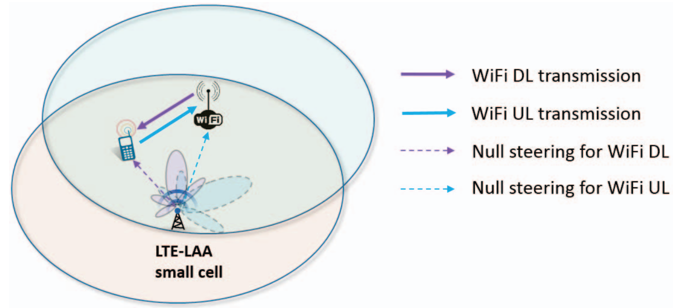

Fig. 1: LTE-LAA small cell null steering for interference mitigation.

III. Proposed Simultaneous Transmission Scheme

A. System Model

We consider one LTE-LAA small cell whose coverage area is overlapped with that of a WiFi AP as depicted in Fig. 1. The LTE-LAA small cell and the WiFi AP are sharing the same 20 MHz unlicensed sub-band within the 5 GHz band. The coverage area of them can be fully overlapped (co-located) or partially overlapped (adjacent but not co-located). There are n WiFi UEs associated with the WiFi AP. We assume the LTE-LAA UEs are uniformly distributed around the small cell. No handover is considered in this paper. We assume that the WiFi AP is equipped with the latest 802.11ac technology, which uses 5 GHz band, and the LTE-LAA small cell is equipped with an 802.11ac receiver.

B. Simultaneous Transmission Timing

The LTE-LAA transmission timing is important since the LTE-LAA small cell needs to decide when to steer its beams and how long it can transmit. The 802.11ac Physical Layer Convergence Protocol (PLCP) defines a PLCP Protocol Data Unit (PPDU) format, as shown in Fig. 2. The Legacy Signal Field (L-SIG) contains the LENGTH field for the current transmission. This LENGTH value forces legacy devices to wait until the transmission of the packet is over, and can be read by any devices within range. Note that the LENGTH field only indicates the transmission length of the current frame. The DURATION field located in the MAC header of the DATA field indicates the duration to complete the whole conversation minus the length of current frame, as shown in Fig. 3. The DURATION filed is also used for other devices to set up their Network Allocation Vector (NAV) timer. A WiFi node sees the channel being reserved and remains idle till the current conversation is finished during the countdown of its NAV timer.

The LTE-LAA small cell can also capture the LENGTH and DURATION information and use it to initiate its simultaneous transmissions. It is worth mentioning that, in 802.11ac, frame aggregation is mandatory, which means all frames are transmitted using the aggregate Mac Protocol Data Unit (A-MPDU) format even for a single frame, as shown in Fig. 4. In 802.11ac, the LENGTH indicator is moved from the

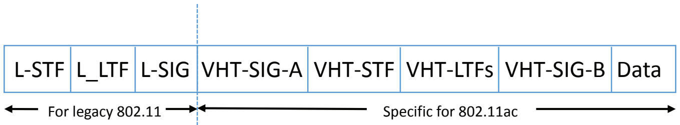

Fig. 2: 802.11ac PPDU format.

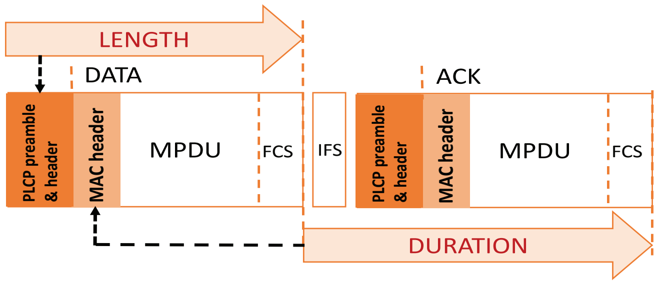

Fig. 3: The LENGTH and DURATION fields in legacy 802.11.

PLCP header, which is transmitted at the lowest possible data rate, to the MPDU delimiter as part of the high data-rate payload [10]. In order for the LTE-LAA small cell to successfully decode the LENGTH and DURATION information, we recommend that it is equipped with an 802.11ac receiver. Once the presence of WiFi signals are detected, the LTE small cell stays mute before it captures the LENGTH information of the current WiFi transmission frame. According to the LENGTH information, it will initiate transmission after the WiFi DATA field transmission (the interference issue will be tackled in the following subsections), and stop transmission when the current WiFi transmission is completed. So that LTE-LAA transmissions will not cause WiFi nodes to go into their backoff frozen phases. For the reverse transmission from the WiFi receiver, the LTE-LAA small cell seeks simultaneous transmission opportunities by using the captured DURATION information.

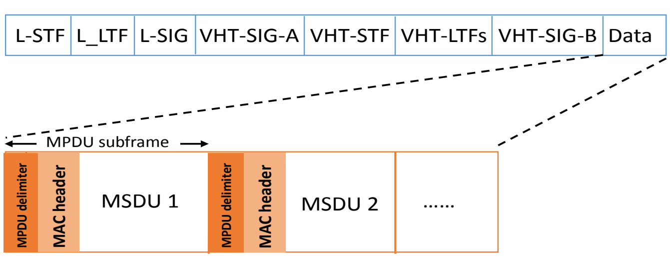

Fig. 4: 802.11ac A-MPDU aggregation.

C. WiFi Beamforming

We propose to exploit the combination of Multiple Signal Classification (MUSIC) based Direction of Arrival (DOA) estimation and null beam steering [11] to mitigate interference from LTE-LAA small cells to WiFi nodes when they have captured the simultaneous transmission timing. We first consider the WiFi uplink, since for WiFi uplink the receiver is the WiFi AP whose location is fixed and can be easily known or estimated by the LTE-LAA small cell. Fig. 5 depicts the 802.11ac VHT-SIG-A1 field which is the first part of the VHT-IG-A field shown in Fig. 2. The 6-bits Group ID field enables a receiver to determine whether the data is for single- or multi-user transmission. More importantly, a Group ID of 63 indicates that the frames are sent to a WiFi UE (downlink), while 0 indicates that the frames are sent to an AP (uplink) [10]. With the assumption that the LTE-LAA small cell is equipped with an 802.11ac receiver, this field can be easily decoded. Thus when the WiFi transmission is uplink, the LTE-LAA small cell can steer its null beams towards the direction of the WiFi AP to avoid strong interference.

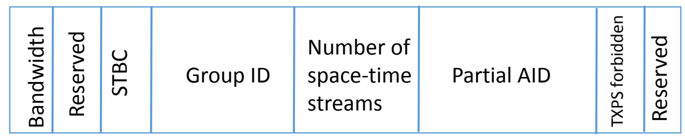

Fig. 5: 802.11ac VHT-SIG-A1 field.

For WiFi downlink transmission, it is more complicated. Although still optional at WiFi APs, beamforming is enhanced in the 802.11ac standard [10]. For beamformed WiFi downlink transmission, we only consider single-user beamforming at this stage as the multi-user MIMO will not be introduced until next wave of deployments. The 802.11ac beamforming process initiates with channel calibration, as shown in Fig. 6. To start with, the WiFi AP sends a Null Data Packet (NDP) Announcement followed by a NDP, which contains frames with known fixed formats. By analysing the received NDP, only the intended receiving UE will reply with a compressed beamforming frame. No beamforming is applied in the channel calibration procedure and hence every node within range (including the LTE-LAA small cell) can hear it. After channel calibration, the WiFi AP sends data packets to the UE. The LTE-LAA small cell can utilize the compressed beamforming reply from the UE to conduct DOA estimation. Once the DOA of the receiving WiFi UE is estimated, the LTE-LAA small cell can conduct null steering towards the direction of the receiving WiFi UE.

For non-beamformed WiFi downlink transmissions, there is a lack of instant signals for the LTE-LAA small cell to conduct DoA estimation. Different from [11], where DOA estimation is based on the cellular UE uplink signals and is updated every subframe, WiFi transmissions have more randomness compared to LTE transmissions. In this case, without instant DOA estimation information, the LTE-LAA small cell cannot simultaneously transmit with nearby WiFi nodes.

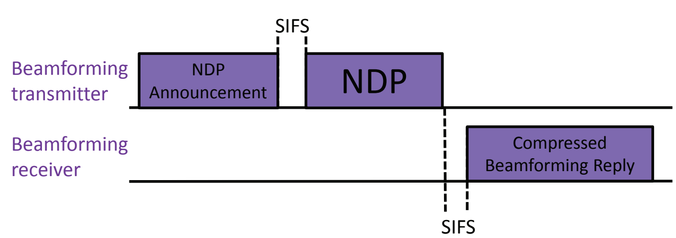

Fig. 6: 802.11ac single-user channel calibration procedure.

D. DOA Estimation

In a linear multiple-antenna system with L elements, the DOA refers to the angle between the array normal vector and the direction vector of the incident plane wave. As the signal arrives at different elements of the array, there will be a wave-way difference which leads to phase difference between array elements. This phase difference can be exploited to estimate the azimuth and elevation angles of the signal and hence DOA. The spatial spectrum explains how signals are distributed in the space from different directions. Considering the Fourier relationship between the beam pattern and the excitation at the array, the DOA estimation can be regarded as spectral estimation. Assuming signals are arriving from M different directions, the signal received at the l^{th} antenna element is given by

$$r_l[n] = \sum_{i=1}^{M} x[n-t_i]\alpha_i e^{j2\pi f_0 \tau_l(\theta_k,\phi_k)} + n_l[n] \tag{1}$$

where $x[n]$ denotes the n^{th} signal sample transmitted by the UE, t_i is the propagation delay of the i^{th} signal and f_0 is the carrier frequency, $n_l[n]$ represents the additive white Gaussian noise (AWGN). The time delay between two consecutive array elements is given by

$$\tau = \frac{d\sin(\theta_k,\phi_k)}{c} \tag{2}$$

where c is the speed of light, d is the spacing between any two adjacent antenna elements and θ and ϕ denote the azimuth and elevation angles, respectively.

The signals arrived at the array elements can be alternatively written in a matrix form as

$$\mathbf{r} = \mathbf{S}\ .\ \mathrm{diag}(\mathbf{h})\ .\ \mathbf{x} + \mathbf{n} \tag{3}$$

where $\mathbf{h} = [\alpha_1, \alpha_2, \cdots, \alpha_M]^T$ consists of the Rayleigh distributed channel coefficients for the M signal paths, and $\mathbf{S} = [\mathbf{s}(\theta_1,\phi_1),\ \mathbf{s}(\theta_2,\phi_2), \cdots, \mathbf{s}(\theta_M,\phi_M)]$ is the steering matrix that includes the steering vectors $\mathbf{s}(\theta_i,\phi_i), i \in [1, M]$. The received signal auto-correlation matrix is defined as

$$\begin{aligned}\mathbf{R_r} &\triangleq E[\mathbf{r}\mathbf{r}^H] \\ &= E[\mathbf{S}\,\mathrm{diag}(\mathbf{h})\ \mathbf{x}\mathbf{x}^{\mathrm{H}}\ \mathrm{diag}(\mathbf{h})^{\mathrm{H}}\ \mathbf{S}^{\mathrm{H}}] + E[\mathbf{n}\mathbf{n}^{\mathrm{H}}] \\ &= \mathbf{S}\,\mathbf{P}\,\mathbf{S}^H + {\sigma_n}^2\mathbf{Id}_L = \mathbf{R}_s + {\sigma_n}^2\mathbf{Id}_L\end{aligned} \tag{4}$$

where $\mathbf{P} = E[\mathrm{diag}(\mathbf{h})\ \mathbf{x}\mathbf{x}^{\mathrm{H}}\ \mathrm{diag}(\mathbf{h})^{\mathrm{H}}]$ and ${\sigma_n}^2$ refers to the noise power. Note that in practice, the auto-correlation matrix is obtained by

$$\mathbf{R_r} = \frac{1}{N}\sum_{n=1}^{N}\mathbf{r}_n\mathbf{r}_n^H \tag{5}$$

with N being the number of data snapshots.

In order to estimate the DOA, we use the MUSIC algorithm, which is based on eigenvalue decomposition of the array output auto-correlation matrix. The MUSIC algorithm estimates the noise subspace and the steering vectors are made orthogonal to the noise subspace. Note that we use MUSIC algorithm to only estimate the azimuth angle. The MUSIC algorithm is detailed as following. First, Eigenvalue decomposition is exploited to determine the eigenvalues of the array output $\mathbf{R_r}$. Note that $\mathbf{R}_r$ is a $L \times L$ matrix which has a rank of M and hence there will be $L - M$ eigenvectors corresponding to zero eigenvalues. This results in two eigenspaces: i) signal subspace which consists of signal eigenvectors contaminated by noise and, ii) the noise subspace which only consists of the noise eigenvectors. Note that the M largest eigenvalues are considered for the signal eigenvectors and the remaining eigenvalues contribute to the noise eigenvectors. Having acquired the signal and noise subsapces, the MUSIC algorithm selects from a range of pre-defined angles to detect the steering vectors that are orthogonal to the noise subspace. The notches of the MUSIC spectrum in (6) give the estimated DOAs.

$$P_{SM}(\theta,\phi) = \frac{1}{\|\ \mathbf{s}^H(\theta,\phi)\mathbf{U}_N\ \|} \tag{6}$$

where $\mathbf{s}^H(\theta,\phi)$ is the steering vector, $\mathbf{U}_N$ denotes noise subspace and is a $L \times L - M$ matrix consisting of the smallest eigenvalues of the correlation matrix and $\|\cdot\|$ represents the norm of the vector. Fig. 7 shows an example obtained from simulation, where the "single path" spectrum corresponds to a Line-of-Sight (LOS) signal with an actual azimuth DOA of 13^o , while the "three paths" spectrum is of a multi-path signal with actual azimuth DOAs of ($17^o, 39^o$ and 78^o). It is also worth noting that the performance of the MUSIC algorithm is highly dependent on the level of the noise that overlaps with the signal as well as the number of paths through which the signal is received. If the number of paths exceeds the number of array elements, the noise subspace has to deal with interference caused by the eigenvectors of weak signals and hence it is impossible to correctly separate the noise subspace.

Due to very large codomain of (6), an alternative approach to estimate the DOAs is to compute its logarithm as in (7). This forms a more compressed shape and by taking second derivatives, the concavities is confirmed and the DOAs can be estimated.

$$P_{SM_{MOD}}(\theta,\phi) = \frac{d^2(\log_{10}P_{SM}(\theta,\phi))}{d\theta^2} \tag{7}$$

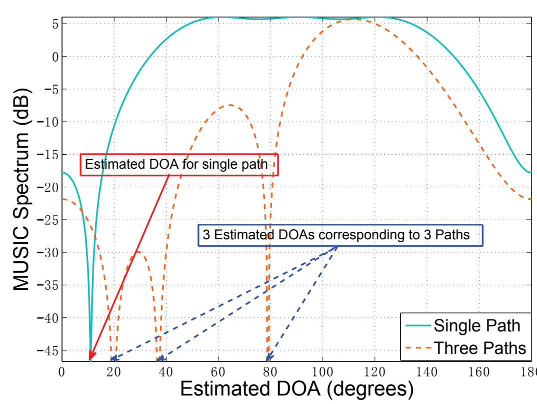

Fig. 7: DOA estimation in single and multipath scenarios.

E. LTE-LAA Small Cell Null Steering

Null steering precoding is a spatial signal processing technique. It modifies the amplitudes and phases of the outputs of array elements to generate a null in the array radiation pattern

[12]. We use null steering to direct the LTE-LAA radiation nulls towards the specific directions where potential WiFi victim receivers are located in order to mitigate interference. Note that the number of null beams is restricted by the number of array elements, i.e., up to $L-1$ null beams can be generated by an array with L elements. The matrix that contains the steering vectors obtained from the DOA estimation stages is specified as

$$\mathbf{A} \triangleq [\mathbf{s}_0, \mathbf{s}_1, ..., \mathbf{s}_k] \tag{8}$$

The vector $\mathbf{e}$ is then defined as $\mathbf{e} = [1, 0, ..., 0]^T$ that has $M+1$ elements. Depending on $\mathbf{A}$ being an square matrix or not, the null steering precoder weighting vector $\mathbf{w}$ is defined as

$$\begin{cases} \mathbf{w}^H = \mathbf{e}^T\mathbf{A}^{-1} & \mathbf{A} \text{ is square matrix} \\ \mathbf{w}^H = \mathbf{e}^T\mathbf{A}^{\mathrm{H}}(\mathbf{A}\mathbf{A}^{\mathrm{H}})^{-1} & \text{Otherwise} \end{cases} \tag{9}$$

Fig. 8 shows the antenna radiation pattern with different settings of null steering obtained from simulation, where the main steering direction is 45^o for all three cases. As we can see from the figure, null steering all three angles causes the peak direction to be shifted to 60^o. This indicates that for optimum LTE-LAA scheduling in terms of maximizing DL signal quality, the UE located at or near the peak radiation direction should be given higher priority. As we assume the LTE-LAA small cell has UEs awaiting for transmissions at all directions, the decision of main steering direction considering null steering angles and corresponding scheduling scheme design are out of the scope of this paper.

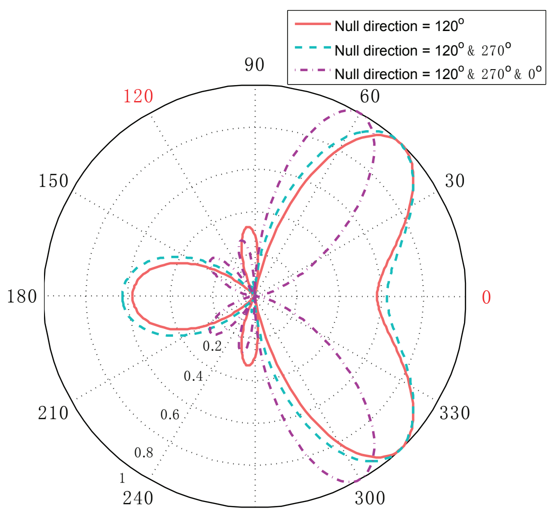

Fig. 8: Null steering antenna radiation patterns (azimuth cut).

IV. Simulation and Performance Evaluation

A. Interference Mitigation and Collision Avoidance

In our simulations, we use 4 element Uniform Linear Array (ULA) operating in the frequency range of 5.1 GHz to 5.2 GHz for the LTE-LAA small cell. The antenna spacing is half wavelength. Fig. 9 shows the transmission power level normalized to that at the peak direction after null steering with the information from DOA estimation. The DOA settings are the same as those in Fig. 7. Fig. 9(a) shows that for the "single path" case, the null steering technique can fully reduce the transmission power to zero. Even with DOA estimation errors, the power level can still be reduced to around 2% of the peak power level. For the "three paths" case as shown in Fig. 9(b), not all the power levels at each direction are reduced to zero. However, even with DOA estimation errors, the summation of the power levels at each angle does not exceed 4% of the peak power level. Therefore, during simultaneous transmissions the interference from the LTE-LAA small cell to the WiFi UE can be well mitigated using the combination of DOA estimation and null steering procedures.

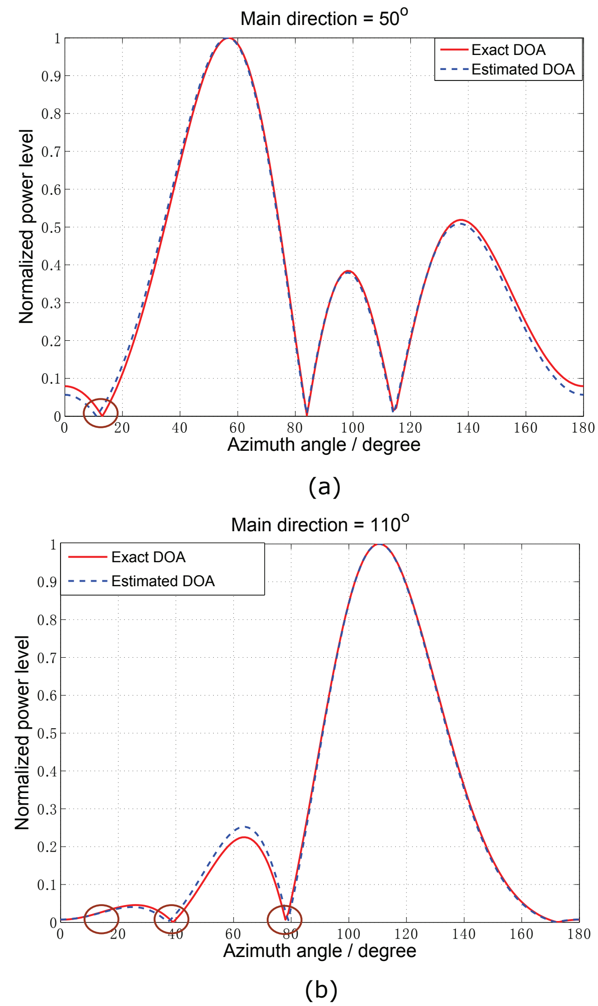

Fig. 9: Normalized power level after null steering for: (a) single path (LOS) DOA, (b) three paths DOA.

In addition to interference mitigation, our simultaneous transmission scheme also aims to avoid triggering collisions so that the LTE-LAA small cell becomes "invisible" to the WiFi networks in unlicensed spectrum. As discussed in Section II, collisions are detected by the absence of successful acknowledgement feedback from the WiFi receiver. The criteria for evaluating collision avoidance capability are Packet Reception Rate (PRR) and Signal-to-Interference-plus-Noise-Ratio (SINR) at the WiFi receiver. From the experimental results in [13], full packet reception ($PRR = 1$) is mapped to SINR in the range of 5.87 dB to 9.93 dB depending on different transmitter power settings. We set the SINR threshold for collision avoidance to 10 dB, which is also used in [14]. In the simulation, we set the WiFi transmission power to 1 Watt which is the 5 GHz Band B legal limit, while the LTE-LAA transmission power is set in the range from 0.2 Watt to 1.5 Watts. Log-normal shadowing is considered, and the distance between the WiFi UE and the WiFi AP is the same as the distance between the WiFi UE and the LTE-LAA small cell for general results. The collision avoidance performance of our proposed scheme is compared to that of a LTE-LAA small cell using omnidirectional antennas for simultaneous transmissions. The results shown in Fig. 10 are averaged over 10 sets of random DOAs (single path and three paths, respectively) and different distance settings. Fig. 10 shows that with interference mitigation, collisions can be safely avoided in the "single path" case, even when the LTE-LAA transmission power is higher than the WiFi transmission power. While for the "three paths" case, the WiFi UE received SINR drops below the SINR threshold when the LTE-LAA transmission power increases beyond the WiFi transmission power. This implies that LTE-LAA small cell has to be equipped with power control mechanisms to assure safe simultaneous transmissions between LTE-LAA small cells and WiFi nodes, especially in multi-path propagation environments.

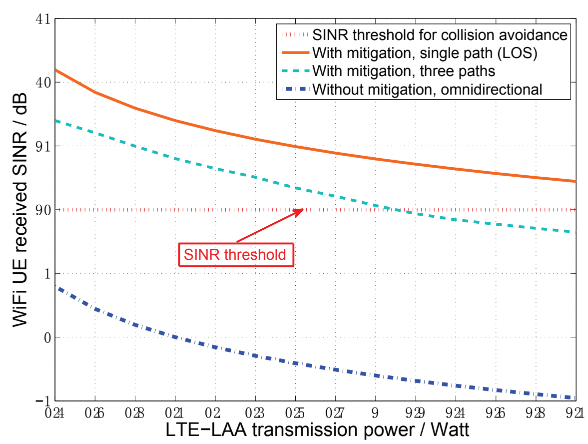

Fig. 10: WiFi UE received SINR compared to the SINR threshold (redoing this figure).

B. Channel Occupancy Time Ratio

In this subsection, we use the Channel Occupancy Time Ratio (COTR), which is also used in [6], [9], as the criterion to evaluate the performance gain of our proposed simultaneous scheme. The time-sharing channel access coexisting scheme proposed in [6] is considered as the benchmark. The simulation settings are listed in Table I. Fig. 11 compares our proposed scheme to the benchmark. The parameter η of the benchmark scheme is used to tune the transmission duration once the LTE-LAA small cell senses the free channel and camp on it. Note that larger η suggests longer transmission duration. Fig. 11 shows that the WiFi COTR decreases with increasing LTE-LAA COTR. However, even with $\eta = 10$, the LTE-LAA COTR of the benchmark scheme is still less than half of the one in our proposed scheme. Further decrease of η to its lowest setting ($\eta = 1$), it is realized that the COTRs of both WiFi DL and UL with the benchmark scheme is still lower than those of our proposed scheme. This is because in our proposed simultaneous transmission scheme, the total channel access time is not divided between the two systems. Indeed, the COTR of the LTE-LAA small cell increases with the WiFi COTR and it is only slightly lower than WiFi COTR due to DOA estimation and null steering delays.

TABLE I: Simulation Settings

Slot Time	9 μs
SIFS	10 μs
DIFS	28 μs
Clear Channel Assignment (CCA) time	4 μs
CW_{min}	32
CW_{max}	1024
NDPA time	9 μs
NDP transmission duration	44 μs
Compressed beamforming transmission duration	9 μs
DOA estimation delay	20 μs
LTE-LAA beamforming delay	10 μs
WiFi DL transmission duration (random each time)	1-10 ms
WiFi UL transmission duration (random each time)	1-5 ms

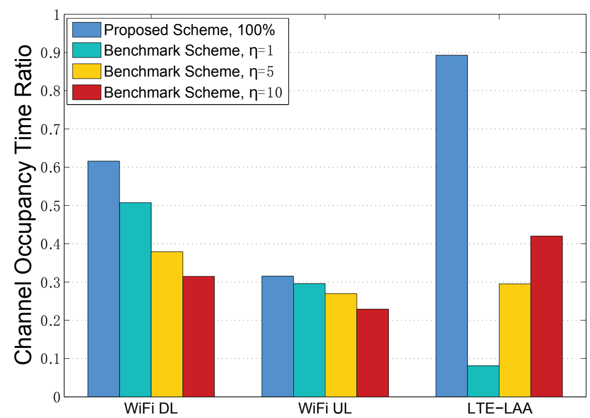

Fig. 11: Comparison of COTR of proposed scheme and benchmark scheme with different η settings.

Fig. 11 shows the LTE-LAA COTR which is obtained based on the assumption that all WiFi transmissions are beamformed and the LTE-LAA small cell can capture the compressed beamforming signal from the WiFi receiver to conduct DOA estimation every time. We label this as the optimal case with 100% safe transmission opportunities. However, in practice not all WiFi transmissions are beamformed and even with beamformed WiFi transmissions, the LTE-LAA may not always be able to conduct DOA estimation or decode the LENGTH and DURATION information. In this case, the LTE-LAA small cell is muted to avoid collisions. Fig. 12 shows the COTR of our proposed scheme with different percentages of safe transmission opportunities. It is realized that even with 30% safe transmission opportunities, the LTE-LAA COTR with our proposed scheme is still higher than that of the benchmark scheme with $\eta = 10$. The WiFi COTR remains the same since the LTE-LAA small cell actions do not affect the WiFi node. Note that, in the simulations we

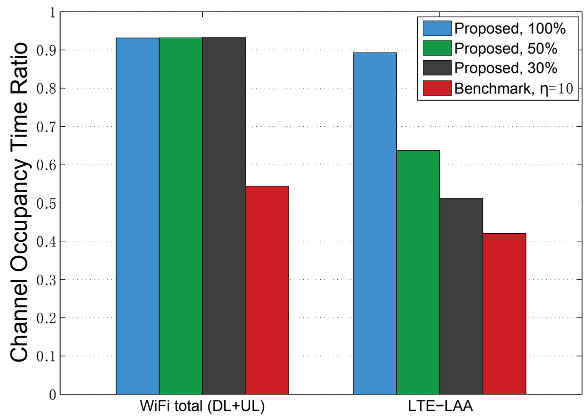

Fig. 12: Comparison of COTR of proposed scheme with different percentages of safe transmission opportunities.

only consider simultaneous LTE-LAA transmissions which are synchronized to WiFi transmissions. Moreover, when sufficient safe simultaneous transmission opportunities are not available, the proposed scheme can be combined with existing TDD based spectrum sharing schemes to achieve even higher LTE-LAA COTR. However, this comes at the cost of lowering the WiFi COTR. One concern brought by dramatically increasing the LTE-LAA small cell's capability of utilizing the unlicensed bands which should not be overlooked is that, the backhaul networks can be the limitation considering noticeably increased traffic volume, especially in dense deployment scenarios [15].

V. Conclusion

In this paper, we proposed a simultaneous transmission scheme for LTE-LAA small cell to coexist with WiFi networks in unlicensed spectrum. The idea is to use MUSIC DOA estimation and null steering techniques to mitigate interferences from the LTE-LAA small cell at the WiFi receiver end to avoid collisions. The simultaneous transmission timing is also crucial which is decided by decoding the LENGTH and DURATION fields information from WiFi signals. For better WiFi signal monitoring capability, we suggest that LTE-LAA small cells to be equipped with the latest 802.11 receivers. Simulation results show that the LTE-LAA interferences can be reduced to almost zero and the proposed simultaneous transmission scheme causes no more collisions. We can safely state that with the combination of DOA estimation and null steering the LTE-LAA small cell is able to simultaneously transmit in coexistence with WiFi transmissions without causing severe damage to the WiFi networks. With simultaneous transmissions only, operations of the LTE-LAA small cell are "invisible" to the WiFi networks. Decisions regarding the main steering direction considering the null steering angles, resource allocation and scheduling designs are left as part of future works.

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