Simultaneous Transmission Opportunities for LTE-LAA Co-existing with WiFi in Unlicensed Spectrum from Exploiting Spatial Domain

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Abstract

In this thesis, we first give an intensive review on the background of LTE-LAA technology, the research status of LTE-LAA and WiFi co-existence mechanisms and 3GPP Rel. 13 standardization on LTE-LAA. The existing co-existence designs focus on the time-domain, frequency-domain and power-domain to achieve fairness between two systems. Simultaneous transmissions are avoided to reduce collision probability. However, by exploiting the spatial domain, we discover the possibility of simultaneous LTE-LAA/WiFi transmission opportunities as long as the interference received at the WiFi receiver is well managed. We first show the feasibility of such simultaneous transmission opportunities considering AP/UE location diversity and various coverage overlap situations between LTE-LAA small cell and WiFi AP. Then, by utilizing multi-antenna beamforming capability, we propose a more practical co-existence scheme combing DoA estimation and null steering technologies. As the lack of direct communication link between LTE-LAA and WiFi systems, we also give our design of information exchange that requires minimal modifications on current WiFi standards and with little to none extra overhead. From the discussions and simulation results, we prove the existence of such simultaneous transmission opportunities that do not bring extra impact on WiFi networks. The channel occupancy time of LTE-LAA can be greatly improved. However, problems and challenges are also identified that require future investigations.

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List of Abbreviations

AP Access Point

ABS Almost Blank Subframe

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

CA Carrier Aggregation

CCA Clear Channel Assessment

CCA-CS CCA Carrier Sense

CCA-ED CCA Energy Detection

CHS Channel Selection

COTR Channel Occupancy Time Ratio

CW Contention Window

DBF Dual Band Femtocell

DoA Direction of Arrival

IFW Integrated Femto-WiFi

LBT Listen-Before-Talk

LTE Long Term Evolution

LTE-A LTE Advanced

LTE-U LTE in Unlicensed spectrum

LAA License Assisted Access

MIMO Multiple Input Multiple Output

MuSiC Multiple Signal Classfication

NAV Network Allocation Vector

RTS/CTS Request-To-Send/Clear-To-Send

SDL Supplemental Downlink

SP Schelkunoff Polynomial

STA Station

UE User Equipment

Chapter 1

Introduction

1.1 Background of LTE in Unlicensed Spectrum

1.1.1 What is LTE in Unlicensed Spectrum?

To accommodate the explosive growth of traffic load and capacity demand, the severely scarce and expensive license spectrum has shown its limitation of addressing the 1000X mobile data increment challenge. Starting from 2013, major companies in the Communications industry started to push forward the idea of extending LTE/LTE-A technologies into the readily available unlicensed spectrum, which is currently dominated by WiFi technologies, in order to break through the limitation. The concept of LTE in the unlicensed spectrum (LTE-U) was first proposed by Qualcomm [8] based on 3rd Generation Partnership Project (3GPP) Release 10/11/12, in 2013. In 2014, Verizon created the LTE-U Forum, together with Qualcomm, Ericsson, Alcatel-Lucent and Samsung. In the same year, Huawei also declared their move into this area by giving their U-LTE solutions [9], which is essentially identical to LTE-U. Later in 2015, Ericsson firstly deployed LTE small cells in the unlicensed spectrum to boost indoor user experiences[10]. And the term LTE License-Assisted-Access (LTE-LAA) used by Ericsson to represent the LTE in unlicensed spectrum technology was later adopted by 3GPP in the standardization of Release 13 [11] and introduced as part of LTE Advanced Pro [12].

Other than LTE-U and LTE-LAA, which are the two widely known terminologies, there are other terms representing certain types of LTE in unlicensed spectrum technologies. These terminologies are closely related, however inherently differentiated. To avoid confusion, these terms are distinguished below and illustrated in Figure 1.1. And we refer to a collective term **LTE Unlicensed technologies** in the following content to include all these individual terms.

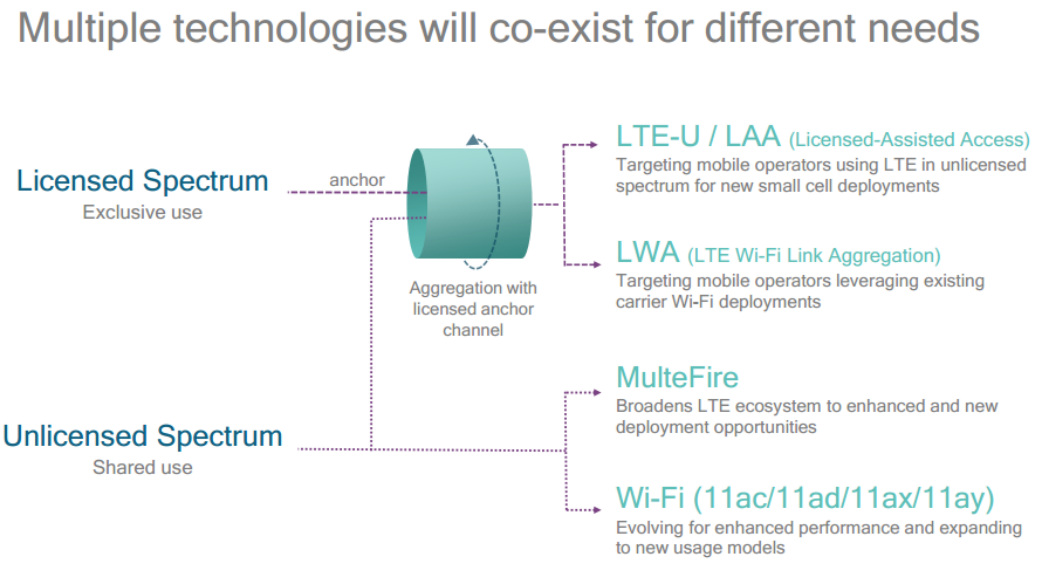


Figure 1.1: Multiple LTE-U technologies.

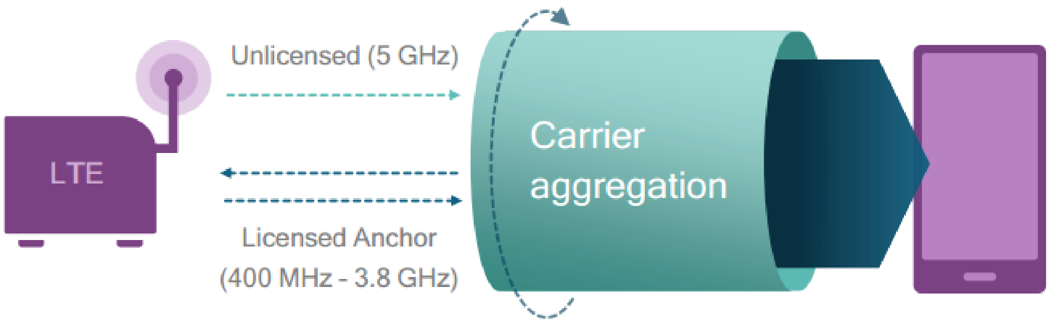


Figure 1.2: Carrier aggregation for LTE in unlicensed spectrum.

- **LTE-U**: It is defined by LTE-U Forum based on 3GPP Rel. 10/11/12 for early time deployments in certain markets, such as USA, Korea, India, etc., where Listen-Before-Talk regulations are not mandatory. It utilizes a small fraction of the licensed spectrum as the anchor to convey control signals, and variable bandwidth of the unlicensed spectrum as the Supplemental Downlink (SDL) to boost downlink data transmission. The licensed anchor and the unlicensed SDL are combined via Carrier Aggregation (CA), as shown in Figure 1.2. The fairness in coexistence with WiFi is achieved by Dynamic Channel Selection (DCS) and Carrier-Sensing Adaptive Transmission (CSAT) [8]. It is the initial phase of the evolution of licensed & unlicensed CA, and provides support for migration towards LTE-LAA.

- **LTE-LAA**: It is part of 3GPP Rel. 13. It also combines licensed anchor and unlicensed SDL via CA. DCS is applied for the LTE-LAA smallcell to monitor the traffic and noise level across the available unlicensed spectrum, and select the unoccupied bands to transmit, so that interferences introduced to the WiFi devices that are currently operating is avoided. To coexist with WiFi devices on the same band, it includes contention-based LBT, which is mandated in European countries, to comply with global regulations [12]. With LBT requirements, LTE-LAA as the second phase of licensed & unlicensed CA, is ready for global deployments.

- **LTE-LWA**: LTE-WLAN Aggregation (LWA) is also included as part of 3GPP Rel. 13 specifications. LWA leverages existing carrier WiFi hotspots, which are deployed by the operators to complement their cellular networks, and configures multi-homed handsets that support both LTE and WLAN access to simultaneously utilize both LTE and WiFi links. Unlike LTE-U/LAA, LTE-LWA does not require hardware changes to the mobile devices and network infrastructure while still providing similar performance to that of LTE-U/LAA. The aggregation involved in LWA is referred to PDCP aggregation [13], which combines LTE and WiFi data packets at the Layer2 Packet Data Convergence Protocol (PDCP). And it requires a standardized interface X_W to connect links from non-collocated LTE and WiFi devices [14].

- **LTE-eLAA/eLWA**: The terms eLAA and eLWA stand for enhanced-LAA and enhanced-LWA, respectively. On the basis of LAA and LWA, uplink aggregation is added as part of 3GPP Rel. 14 and beyond to boost uplink capacity and data rates [12]. And the aggregation of unlicensed uplink and downlink is possible with either licensed TDD or FDD [12]. Additionally, link aggregation across different non-collocated small cells is also an added feature, which is referred as Dual Connectivity. The complexity and cost are expected to be reduced. An demo of eLAA is going to be showed at the Mobile World Congress (MWC) by Qualcomm in 2017.
- **MulteFire**^{TM}: Unlike the other LTE in unlicensed technologies, MulteFire is soly operated in the unlicensed spectrum without an licensed spectrum anchor. It is proposed by Qualcomm [12] based on 3GPP standards. New deployment opportunities is opened up by combining WiFi-like deployment simplicity in unlicensed spectrum and LTE-like enhanced performance, which broadens the whole LTE ecosystem. Formed in December 2015, MulteFire Alliance is an international association dedicated to developing global technical specifications, product certifications as well as a global ecosystem for MulteFire.

1.1.2 Benefits of LTE Unlicensed Technologies

Licensed spectrum is without question scarce and costly, while at the same time there is a vast amount of free unlicensed spectrum in 5 GHz bands. The “1000X data increase” goal has been driven by the exponential growth of connected devices and the demand of faster and richer content delivery. As the consumer hunger for data traffic rapidly outpaces the current utilization of available spectrum, on one hand the government and the wireless industry are working together to facilitate more usable spectrum for mobile communications, on the other hand leading companies and organizations in the wireless industry are persistently pursuing more effective utilization of current available spectrum. Given the fact that today’s mobile device users rely more and more heavily on WiFi networks for their communication demands, bringing new innovations into the utilization of unlicensed spectrum seems to be an effective way to reach this remarkable goal. LTE

Unlicensed technologies take advantages of all kinds of maturely developed 4G LTE/LTE-A features such as advanced interference mitigation techniques, better spectral efficiency and more effective resource management and user scheduling techniques, and for the first time brings these techniques into the unlicensed spectrum realm.

In cases of LTE-U/(e)LAA/(e)LWA, assisted by the control channels in licensed bands, LTE Unlicensed enabled small cells are anticipated to provide better quality of service (QoS) to end users in unlicensed bands than WiFi access points (APs) [15]. While in the case of MulteFire, even though there is no anchor in licensed bands, the unlicensed bands are still be able to be better utilized with enhanced range and capacity, improved QoS and mobility, and mature interference mitigation techniques which enable hyper-dense deployments that are also self-organized. Meanwhile, compared to conventional WiFi utilization of unlicensed spectrum that consists of separate spectrum sub-bans and user deployments, MulteFire uses common spectrum and deployment to provide neutral host services [12]. These advantages of MulteFire pave its way to all enterprises, venues, malls, campus and homes, etc. as a better option.

LTE Unlicensed enabled small cells are controllable by mobile operators, which means the unlicensed spectrum that they are deployed in is utilized in a more regulable manner. Thus, time and frequency resources can be more managed and scheduled towards higher spectrum efficiency and capacity gain.

Unlike 802.11 devices that use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) techniques, LTE Unlicensed technologies utilize Listen-Before-Talk (LBT) to access unlicensed channels. CSMA/CA is composed of Clear Channel Assessment (CCA) which determines whether the medium is idle or busy for the current frame, and Network Allocation Vector (NAV) which reserves the medium as busy for future frames transmitted right after the current frame. Moreover, upon detecting the medium for current frame is idle, every 802.11 device starts a random back-off before it can actually transmit. On the other hand, LBT in LTE Unlicensed technologies can be classified into various categories, wherein Load Based Equipment (LBE) Category 4 defined in [11] is the most relevant and similar to the random channel access procedure used in WiFi as it is defined with random back-off procedure and adaptive contention window size. The significant advantage of implementing LBT-LBE with similar random channel access procedure to WiFi in acquisition of transmission opportunities in LTE Unlicensed technologies is that, fair coexistence with WiFi technologies can be better guaranteed as LTE Unlicensed small cell does not act as a bandit that forcibly occupy the unlicensed resources. Moreover, coexistence of multiple LTE Unlicensed networks within the same unlicensed band can also be adjusted in a more controllable manner.

The benefits of LTE Unlicensed technologies over WiFi do not stay on theoretical analysis, but also verified via test trial. Through an outdoor test case conducted by Qualcomm in 2016 [12], LTE-LAA small cells achieve up to 2.5 times outdoor coverage improvement over to WiFi APs, especially in high downlink throughput portion of the test results. More importantly, LTE-LAA outperforms WiFi in challenging radio conditions during mobility, with more challenging radio conditions LTE-LAA small cells have higher downlink throughput gain over WiFi APs, and remain consistent over a larger area. From the test, results also show that LTE-LAA benefits everyone playing in the same 5 GHz channel. Switching from baseline scenario with 4 pairs of WiFi to 2 pairs of LTE-LAA and 2 pairs of WiFi, around extra 50% downlink throughput gain is achieved for neighbouring WiFi APs, which indicates that LTE-LAA is a better neighbour to WiFi than WiFi itself. Moreover, from the same comparison setup, everyone playing in the same unlicensed spectrum gains around the same share of channel occupancy, which indicates LTE-LAA helps to promote fairer sharing of the unlicensed spectrum. Last but not least, LTE-LAA also fairly shares the unlicensed channel in corner cases, which makes LTE-LAA a better neighbour to hidden WiFi nodes than WiFi itself. Detailed LTE-LAA performance benefits over WiFi are further explained in the next chapter.

1.1.3 Challenges of LTE in Unlicensed Spectrum Deployment

According to the estimated wired WiFi and mobile growth by Cisco [1], data traffic conveyed via WiFi will continue to increase for years. In the foreseeable future, WiFi will continue to play an important role in providing wireless data services to end users. However, transmissions of LTE-LAA enabled small cells in the unlicensed bands may cause problems to the operation and performance of WiFi systems. WiFi transmitters access the channels in the unlicensed bands in a contention-based manner, i.e., with CSMA/CA. More specifically, a WiFi transmitter needs to sense the channels in the unlicensed bands and can only start a transmission when it finds a free channel. Frequent transmissions from LAA small cells in the unlicensed bands may dramatically reduce the transmission opportunities of WiFi APs, thus degrading their performance. But with the temptation of benefits provided by deploying LTE in unlicensed spectrum, operators have already and will continue to share the cake of unlicensed spectrum. This situation highlights the importance of carefully designing fair LTE/WiFi co-existence mechanisms. The co-existence problem in unlicensed spectrum has drawn attention from both industry [8, 16] and academia [17, 18, 19, 20].

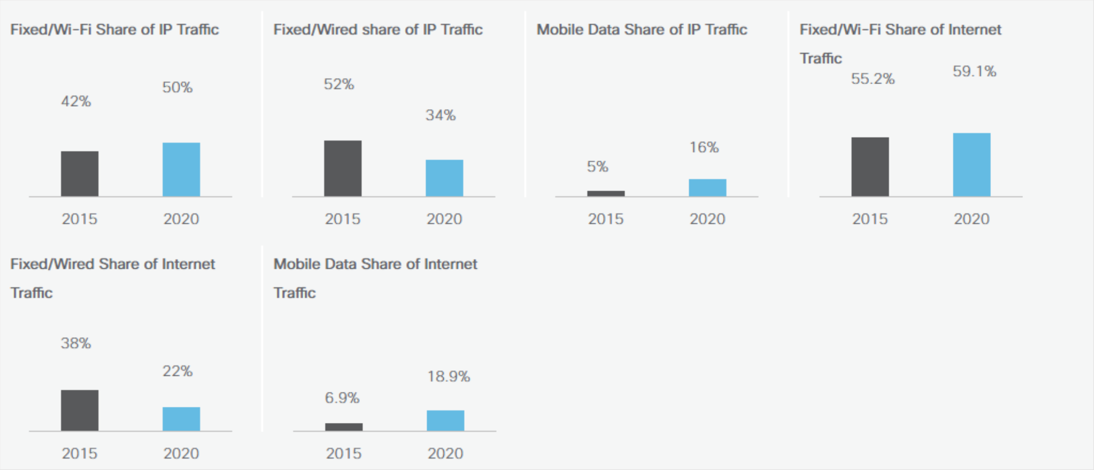


Figure 1.3: Estimated Wired WiFi and mobile growth from 2015 to 2020 [1].

1.2 Motivation of Our Co-existence Approach and Contributions

In existing LTE-LAA/WiFi co-channel co-existence mechanism designs, the shared unlicensed channel is accessed by both technologies in a time sharing manner, *i.e.* simultaneous transmissions are avoided for the purpose of collision avoidance. This is due to the contending nature of WiFi CSMA/CA medium access mechanism. However, in future ultra dense deployment scenarios, sharing the channel access time cannot be regarded as optimum as the spectral efficiency will soon reach a bottleneck. The main objective of this thesis is to identify the possibility of simultaneous transmission opportunities by looking at the spatial domain diversity.

1.3 Contributions of the Thesis

In Chapter 3, we first conduct derivations of the probability of coverage overlap between LTE-LAA small cells and WiFi APs by modelling the network nodes with a spatial bivariate Poisson point process. Then we propose a coexistence scheme for LTE-LAA small cell and WiFi AP in the unlicensed spectrum with the consideration of various possibilities of coverage overlap between them. The theoretical analysis is conducted in simple scenario where an LTE-LAA small cell overlaps with one WiFi AP within a WiFi network. Backoff frozen state of the WiFi AP due to transmissions from other WiFi APs in the WiFi network is considered. The analysis can be extended to a more general scenario where an LTE-LAA small cell overlaps with multiple WiFi APs with little effort.

In Chapter 4, following the first attempt made in Chapter 3, we continue to exploit such simultaneous transmission opportunities in a more practical way. 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. We then 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 back-off 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.

1.4 Thesis Outline

The structure of this thesis is organized as follows. Chapter 2 summarizes a comprehensive review of the background, standardizations of LTE-LAA and the research status of the co-existence problem. In Chapter 3 and Chapter 4 we make our attempts to exploit simultaneous transmission opportunities. In Chapter 5, we state the ongoing works and the future research orientations to modify our co-existence mechanism design. And Chapter 6 concludes the thesis.

1.5 List of Contributing Publications

1. L. Li, X. Chu, and J. Zhang, "A novel framework for dual-band femtocells coexisting with wifi in unlicensed spectrum," in 2015 IEEE Global Communications Conference (GLOBECOM), Dec 2015, pp. 16.
   Contributes the main content of Chapter 3.

2. L. Li, A. H. Jafari, X. Chu, and J. Zhang, "Simultaneous transmission opportunities for lte-laa smallcells coexisting with wifi in unlicensed spectrum," in 2016 IEEE International Conference on Communications (ICC), May 2016, pp. 17.
   Contributes the main content of Chapter 4.

Chapter 2

Research Status Reviews on LTE-LAA

LTE in Unlicensed technologies have chosen their playground within the 5 GHz unlicensed spectrum, where the major resident is WiFi. By introducing a new competitor for the limited spectrum resources, co-existence between LTE-LAA and WiFi is inevitably the main issue. For the purpose of better understanding various existing co-existing mechanisms, in this chapter we first briefly summarize several key features related to the co-existing issue, and shed some light on the co-existence challenges. Then, we review representative researches on coexisting mechanisms between LTE in unlicensed spectrum technologies and WiFi conducted so far. Academical investigations and industrial tests are included. And as LBT is one of the key technologies to guarantee fair co-existence and has been standardized in 3GPP Rel. 13, researches on LBT enhancements for LTE-LAA are also reviewed. Later, with the insights gained from the research status review, we then give recommendations on future research directions on the co-existence issue, and emphasis on the novelty of our approach of exploiting simultaneous transmission opportunities for LTE-LAA small cells.

2.1 Co-existing-related Features and Insights

The mobile networks are now experiencing a blossom of capacity and data demands. Seeking solutions to achieve higher network capacity has always been the major task throughout the evolution of mobile communications. However, due to the Shannon capacity limit and the scarcity of the expensive licensed spectrum resources, gaining more capacity out of the limited licensed bands is like squeezing the last few drops of water from a sponge, which is going to be harder and harder. According to Cisco's global mobile data traffic forecast, by 2021, the average mobile device will generate a fourfold growth in monthly data traffic, from 1.6 GB in 2016 to 6.8 GB per month [21]. Not only that, one noticeable fact of current mobile communications is that, a great portion of the data traffic occurs indoor. It is anticipated that, by 2020, the indoor mobile data traffic will grow by more than 600% worldwide [22]. Most of the indoor data traffic has been handled by low cost WiFi networks and small cells. To better cope with the capacity demand and the fast increasing indoor data traffic, deploying the mature LTE technologies into the free unlicensed bands is considered by the industry, and the benefits from the fair coexistence LTE and WiFi networks in unlicensed spectrum is promising and have attracted interests industrial and academical communities [23]. An LTE-LAA small cell has been proved to be a better neighbour to a WiFi system than another WiFi AP, as the adjacent channel interference caused by LTE-LAA is less [24], hence better adjacent channel coexistence is achievable.

However, these benefits from co-deployed LTE-LAA and WiFi systems within the 5 GHZ unlicensed spectrum does not come with no limitations. It is obvious that, the traffic load on the unlicensed band increases after introducing LTE-LAA [25]. And if the co-existence between the two contending technologies cannot be reasonably scheduled, the rat race for spectrum resources contention and yielded channel congestion not only weaken the benefits of LTE-LAA, but also impact the performance of WiFi system [26].

On the contrary, with finely tuned co-existence, there can be mutual benefits between LTE-LAA and WiFi networks. For an instance, there is a lack of central coordination in WiFi networks, which lead to dramatically decreased individual throughput when a large number of user competing for the same amount of resources. While for LTE-LAA networks, co-tier and cross-tier interferences in high load condition can also degrade the perceived throughput and QoS. In either cases, offloading a certain amount of traffic to the other network results in better and even utilization of the spectrum resources, which not only reduce interferences in LTE-LAA networks but also alleviate congestion in WiFi networks [3]. Together, with fairly tuned co-existence and efficient integration, the capacity and spectral efficiency of the 5 GHz unlicensed bands are envisioned to be boosted.

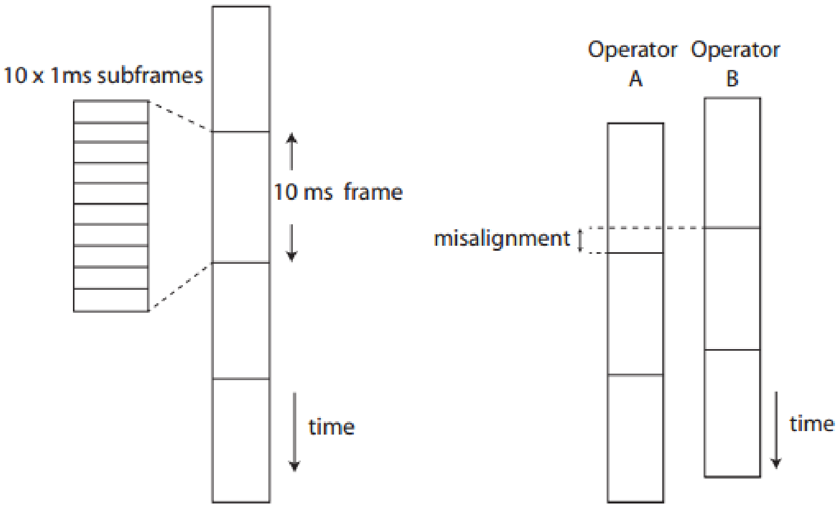
2.1.1 Comparison of LTE and WiFi MAC Protocols

LTE and WiFi systems implement different MAC protocols. Understanding the differences between them is essential for designing fair co-existence schemes. Hence, we first briefly review the two different MAC layer mechanisms, and then highlight the co-existence challenges arising from their differences in Section 2.1.5 below.

- **Frame-based LTE MAC Protocol:** LTE systems are enabled by Orthogonal Frequency-Division Multiple Access (OFDMA) technology, in which multiple access is achieved by subsets of multiple sub-carriers to different users. In an LTE communication system, time is partitioned into 10 ms duration units, each unit is referred to a frame, and LTE transmissions are structured from continuous streams of these frames [27, 28, 29]. An LTE frame consists of 10 subframes with 1 ms duration, which is further divided into 2 slots with 0.5 ms duration, as shown in Figure 2.1(a). One can refer to [30, 31, 32, 33] for detailed LTE frame structure.

  There is a certain amount of time-frequency resources associated with each subframe. Scheduling in LTE systems are carried out by the scheduler in LTE base station in a centralised manner within each cell. All LTE transmissions from either the base station or the UEs within one cell are assigned with some time-frequency resources by the LTE scheduler, and all UEs must be tightly synchronised with its master base station time and frequency wise. What's more, neighbouring cells in LTE systems are also tightly synchronized in time with each other, for the favour of interference management, so that time-frequency reuse is enabled among neighbouring cells to fully utilize empty subframes without causing severe interferences to adjacent subframes [34].

The centralized MAC protocol of LTE was originally designed for operating in licensed bands only. The dynamic scheduler within each cell acts as the main brain for arranging physical resources, considering the data traffic load, radio link condition, UE ACK feedback and QoS requirements, *etc.*. For detailed LTE Radio Resource Management, refer to [35]. Need to mention that, as the licensed spectrum is not free and not shared commonly, different network operators may use different licensed bands for their network establishment, and there exists inter-network misalignments of frame boundaries, as shown in Figure 2.1(b). And these misalignments can be an issue for carrier aggregation, which will be discussed later in detail.



(a) Frames and subframes (b) Frame misalignment

Figure 2.1: Illustration of Frames and Subframes in LTE Scheduling.

- **Load-based WiFi MAC Protocol:** On the contrary, WiFi systems implement decentralized transmission scheduling protocol. The WiFi MAC protocol is based on the mechanism called Carrier Sense Multiple Access with Collision Avoidance (CSAM/CA), with which a WiFi device senses the shared transmission medium and only initiate its own transmission upon detecting absence of other ongoing detectable transmissions [36, 37]. To be more detailed, a WiFi device (an AP or a station), performs idle medium check referred to as Clear Channel Assessment (CCA) every time it wants to initiate a transmission. It is when the shared medium is sensed idle for a certain period of time, namely Distributed Inter-Frame Space (DIFS), the transmission is ready. Once the shared medium is free, all WiFi devices within detection range are contending for the transmission opportunity. In order to avoid collisions among them, a random back-off mechanism is applied, which is relying on a count down timer in each WiFi device. This timer is given with a initial number randomly chosen within a range, and starts to count down after the CCA procedure completes and pauses (frozen state) when the medium is occupied by other transmissions [36, 37, 38, 39]. Once the timer reaches 0 and the medium is still sensed idle, the transmission proceeds.

The CSMA/CA mechanism implemented in the WLAN 802.11 MAC layer is also known as Distributed Coordination Function (DCF), which allows time-division multiple access from different WiFi devices based on their channel sensing states [40]. This mechanism is fairly effective when the shared medium is not heavily loaded, as the CCA procedure within all WiFi devices generate less delay and the average back-off frozen time is less. Collision only happens when there are more than one WiFi devices reaching their transmission starting point simultaneously. To avoid collisions with the maximum effort, there are some other mechanisms besides setting individual random back-off count down timers. The first one is using Acknowledgement Packet (ACK) from the receiving WiFi device to check if the transmission is collided, and if yes, retransmits [36, 37]. Another one is so called Virtual Carrier Sense (VCS) defined in IEEE 802.11 standards [36, 38], with which the transmitting WiFi device first send a short Request-to-Send (RTS) packet. And upon receiving the RTS packet, the receiving WiFi device will reply with another short packet called Clear-to-Send (CTS). Both RTS and CTS packets contain indicators of the transmission duration, and all the other WiFi devices receiving the RTS/CTS message

> will set their VCS counter based on the duration information [36, 37, 39]. As compared to the VCS mechanism, the channel sensing procedure is called Physical Carrier Sense (PCS), and they are used together to minimize collisions.

The conflict of centralised and decentralised natures of LTE and WiFi MAC mechanisms is the main obstacle of their co-existence [41]. And compared to LTE transmissions, WiFi transmissions are not restricted to deterministic frames, and not synchronised with LTE transmissions generally. With the fact that LTE transmissions are more dominant, for the accomplishment of co-existence fairness, there is a need for extra means to add on conventional LTE channel access mechanism for LTE-LAA to share the unlicensed medium with WiFi, such as LBT. Note that, the notion of fairness is still discussable. It can be equal throughput, equal transmission opportunities, equal air-time, or proportional fairness according to other considerations such as QoS [42].

2.1.2 Co-channel Interference between LTE-LAA and WiFi

Another angle to look at the LTE-LAA and WiFi issue comes down to the interference management problem between them. When an LTE-LAA small cell is deployed around the interfering range of a WiFi AP, and they are sharing the same unlicensed spectrum resources, there are two sources of co-channel interference caused by the LTE-LAA network to the WiFi network [43], as depicted in Figure 2.2. One of them is the interference from LTE-LAA small cell downlink to the WiFi devices, including control signalling and data transmissions. The other source is from the LTE-LAA UEs to the WiFi devices.

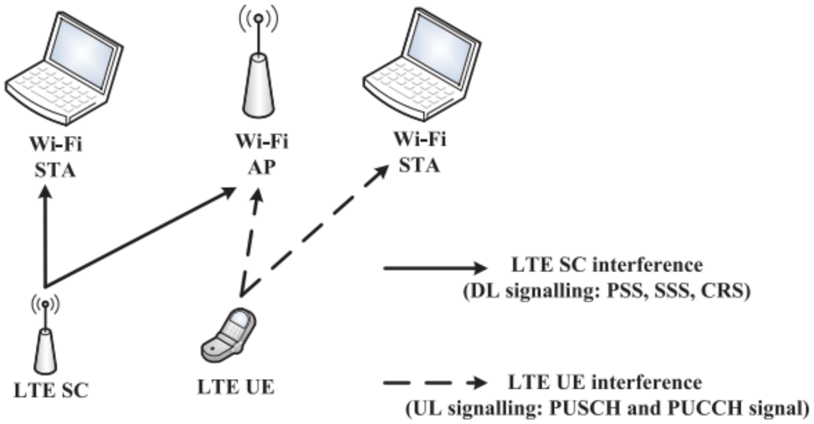


Figure 2.2: Co-channel Interference between LTE-LAA and WiFi.

The interference management problem of LTE-LAA co-existing with WiFi includes interference detection, interference measurement, interference mitigation or avoidance, *etc.* [3, 24]. One example method for improving interference management between LTE-LAA and WiFi systems provided in [44] is comparing the monitored signal energy by WiFi devices to a pre-defined waveform signature simulating LTE-LAA signals. By comparison, it can be indicated whether there exists an LTE-LAA interferer on the unlicensed sub-band. The interference pattern matching is carried out periodically for reliable interference identification, and after the LTE-LAA interference is identified, the WiFi AP is able to perform further matching process on the signal energy pattern to categorize the type of the identified interference [43].

2.1.3 LTE Carrier Aggregation Enabling Supplemental Downlink

LTE carrier aggregation (CA) is the key technology enabling LTE-LAA operating in 5 GHz unlicensed bands, particularly SDL. CA is a technology that enables the LTE-LAA small cell to schedule time-frequency spectrum resources from disjoint bands, such as licensed bands and unlicensed bands [34]. Applying CA in the LTE-LAA small cell requires the licensed interface to be always available and ready to be bundled with the selected unlicensed sub-bands [42].

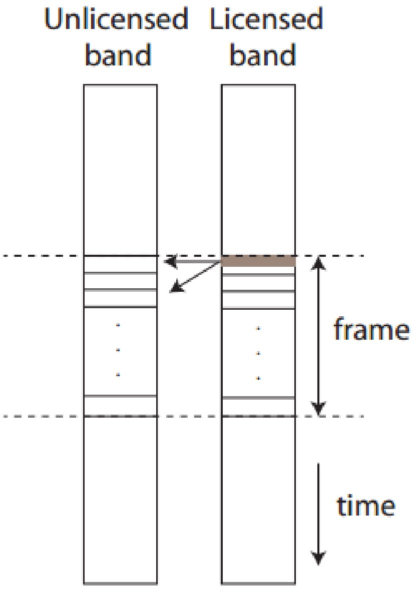


Figure 2.3: Illustration of Cross-scheduling LTE Carrier Aggregation.

With cross-scheduling depicted in Figure 2.3, the control plane in the licensed band specifying information regarding assignment of time-frequency resources for transmissions and Modulation and Coding Scheme (MCS) in each subframe, while the unlicensed band is combined to simultaneously transmit the user plane information [42]. In Figure 2.3, the shaded area represents the control plane in the licensed band, and the arrows pointing at the unlicensed band indicate a scheduling grant of user plane transmission, *i.e.* SDL transmission, in the selected unlicensed sub-band. The availability of 5 GHz unlicensed spectrum and corresponding regulations differ themselves in different regions, more details on regional 5 GHz unlicensed spectrum availability refer to Section 2.4.1.

Based on the conventional LTE CA protocol, the CA implemented in LTE-LAA in unlicensed spectrum is an extension [45, 46, 47, 48]. The conventional LTE CA protocol allows flexible aggregation of two or more disjoint sub-carriers, while in LTE-LAA CA, the unlicensed sub-carrier is always combined with licensed sub-carrier to convey control signalling and control signalling only. This is how the terminology "Licensed-Assisted-Access" is given, and what differs the first stage LTE-U technology which is a natural extension of the conventional LTE CA using the unlicensed bands as secondary carriers to complement primary licensed carriers [49]. For more details on LTE-LAA CA, refer to Section 2.4 summarizing what has been standardized by 3GPP in Rel. 13 [24, 50, 51].

2.1.4 LTE-LAA Performance Differences Compared to WiFi

As briefly stated in the Introduction, there are several LTE-LAA performance benefits as compared to WiFi. Before giving the comparison of them, we must give the statement beforehand that, WiFi technology is not going to fade out in a foreseeable future due to multiple reasons such as massive deployments, easy to self-install and use, reliable and cheap for data offloading, and wide acceptance for residential users, *etc.*. It is rather a matter of choice when it comes to LTE-LAA or WiFi, and a better choice can be made when the following key differences between them are clearly considered.

1. **Stability:** The first obvious benefit of LTE-LAA over WiFi comes from the integration of licensed carriers and unlicensed carriers for each transmission. As mentioned in the carrier aggregation discussion, assisted by the licensed anchor, control messages are reliably exchanged between LTE-LAA base stations (macrocell base station or small cells depending on the deployment scenarios detailed in Section 2.4.2) and their users. According to the QoS class identification in LTE systems, the control signalling carried on the licensed carrier is granted with the highest priority [30]. Medium accesses in unlicensed spectrum are opportunistic, the licensed-assisted-access feature allow LTE-LAA small cells to better facilitate the medium access. On the other hand in WiFi systems, the randomness in CSMA and the contending behaviour among all WiFi devices make the medium access not as efficient, and the connection is highly affected by the system load [52, 29, 53].

2. **Spectral Efficiency:** The utilization of 5 GHz unlicensed spectrum before the participant of LTE-LAA was not very effective, due to the contending medium access nature of WiFi, especially in high load condition, as already discussed. From the following aspects, LTE-LAA performs better as compared to WiFi in terms of spectral efficiency.

(a) ***Multi-user Diversity Gain:*** As detailed before, WiFi applies contention-based random medium access, while LTE-LAA implements scheduling-based medium access scheme.The robust centralized MAC adopted by LTE-LAA enables multi-user transmission scheduling based on user acknowledgement feedback (ACK) information, Channel State Information (CSI), *etc.*, which brings frequency-selective multi-user diversity gain [27, 32]. On the other hand , WiFi transmissions are more often to be assumed one-to-one, that is from the WiFi AP to one user. Even though with the help of Multiple-Input-Multiple-Output (MIMO), split transmissions are supported in 802.11 ac which supports up to four radio links towards more than one user devices[37], it still does not show multi-user diversity from the coordinated-scheduling point of view.

(b) ***Mobility Support:*** The unified structure in an LTE-LAA system features a centralized core network, within which there is a mobility management functionality that is in charge of managing integrated authentication, security control and handover procedure. Also, synchronization in LTE-LAA network makes it easier to handle interference burst and handover between LTE-LAA small cells. More importantly, the networks deployed in unlicensed spectrum are usually in conjunction with the overlaid macrocell cellular network. That reveals the benefit of LTE-LAA over WiFi, as handover across different Radio Access Network (RAN) is classified as Vertical Handover (VHO), while that between the same RAN is Horizontal Handover (HHO) [54, 55]. Handling VHO is more complicated than HHO, and inevitably causes longer delay, for more details on VHO and HHO, refer to [56]. Thus, from one user's view point, connecting to LTE-LAA network can provide itself with ubiquitous coverage and better mobility management, as there is only HHO between LTE-LAA small cell and LTE macrocell, which makes the LTE-LAA network an extension of the cellular network. Thus, the concept of being "Always Best Connected" [57] is better achieved. And by extending the cellular network into the resource-rich unlicensed bands, a larger cellular network combining both types of spectrum resources with ultimate mobile coverage is formed [58].

(c) ***HARQ versus ARQ:*** When encountering a failed transmission, retransmission attempts need to be made in order to eliminate random channel failures. The retransmission mechanisms adopted in LTE and WiFi are different, and obviously LTE-LAA inherits the retransmission mechanism from LTE. LTE implements Hybrid Automatic Repeat Request (HARQ) while WiFi adopts Automatic Repeat Request (ARQ) at MAC layer [30, 36]. The detailed differences between them are not the point here. To be brief, HARQ helps LTE systems make fuller use of diversity in time-domain, which yields higher time efficiency than ARQ, which is a single loop mechanism with immediate ACK and has more overhead [59]. In WiFi systems with ARQ, the received data packets are discarded once they are detected with an error, and then a retransmission is requested. And if the retransmission is again detected with error, the received packets are discarded again and another retransmission is requested. The maximum number of retransmissions before deciding transmission failure is six in newer WLAN standards, such as 802.11 ac [37]. However with HARQ in LTE, the receiver buffers the data packets with detected error and a retransmission request is made at the same time. Upon receiving the retransmitted data packets, the receive will compare and cross-check the series of retransmitted data with the buffered data and try to decode [30]. If the decoding is still not successful, another retransmission request is sent out. With cumulated information, the lost packets can be fast put together like a puzzle, and then an ACK is sent back to the transmitter [29]. Clearly, LTE-LAA inheriting HARQ is more effective in terms of retransmission mechanism as compared to WiFi with ARQ, as each retransmission made by the WiFi transmitter may contain different random errors and there is no cumulated information to help the decoding. This also implies that LTE-LAA has better capability of handling poor radio link quality situations than WiFi.

   (d) ***Interference Management:*** Dealing with interferences since the beginning, LTE system has developed various interference management techniques such as enhanced Inter-cell Interference Coordination (eICIC) and Coordinated Multi-point (CoMP). These interference mitigation techniques help to increase spectral efficiency by reducing or mitigating interferences. Especially with CoMP, which requires coordination among two or more adjacent site base stations, joint transmissions, scheduling and signal processing are enabled. Cell edge users, which originally suffer from poor quality connections, can now be jointly served by two or more adjacent base stations, thus their perceived signal quality and throughput are improved [60, 31, 61]. While for WiFi coverage edge users, due to authentication procedure they are tied to the serving WiFi AP and only served by one WiFi AP, transmission failures are more likely when radio link quality is poor.

   Better spectral efficiency of LTE-LAA networks does not just come from the listed aspects above, but also other ones such as carrier aggregation discussed before. Without repeating what has been discussed, CA also brings trunking gains from dynamic traffic scheduling across the whole available spectrum by aggregating multiple radio carriers [3]. As a result, the network capacity and efficiency are increased, which bring better user experiences. More importantly, CA also contributes to optimum spectrum resource utilization for the operators. As for most mobile operators, it is often impossible for them to purchase a big trunk of pricey spectrum resources. Their fragmented spectrum resources cover different bands with various bandwidths. With CA, traffic load can be well distributed across these bands in order to make full use of them [35, 33, 62].

3. **Link Adaption:** The open-loop link adaption adopted by WiFi does not require feedback of Channel Quality Indicator (CQI), hence the fast varied channel condition is not updated before WiFi transmissions. Differently, LTE adopts close-loop dynamic link adaption method taking into account the instantaneous CQI feedback information, based on which the LTE-LAA small cell is able to determine resource block assignment accord-

ingly [9]. Additionally, adopting dynamic instantaneous-CQI-based link adaption also helps LTE-LAA achieve higher Power Spectral Density (PSD) than WiFi under the same consumed power condition [3]. PSD is an important terminology which indicates the distribution of signal power or time series over frequency [63]. Higher PSD under the same power condition implies that, to achieve the same level of PSD, the power consumption of a LTE-LAA small cell is lower than that of a WiFi AP. Thus, LTE-LAA is a "greener" option than WiFi.

4. **Throughput:** Unlike the other aspects, the throughput comparison of LTE-LAA and WiFi is not as clear. It can be affected by many factors including the ones we have already discussed. But the importance of throughput comparison is obvious, as it is a straight forward performance indicator that everyone is interested in when considering LTE-LAA roll-out. Despite the MAC difference, LTE-LAA and WiFi adopt mainly the same physical layer (PHY) technologies, such as OFDM, MIMO and Quadrature Amplitude Modulation (QAM), especially in newer IEEE 802.11 standards. According to [64, 65], with respectively centralized and decentralized random access scheduling schemes used in LTE-LAA and WiFi, the achievable throughput capacities are the same. However, collisions are inevitable in WiFi systems when there are more than one devices and tend to increase with the number of active devices due to the contending random access behaviour. When the number of collisions increases, the network throughput decreases. On the other hand, LTE-LAA network throughput also falls as the number of UEs increases, as with increased transmission scheduling the overhead in the control plane increases. From the examples in [66, 67], with increased number of UEs, the quantity of Downlink Control Information (DCI) signalling increases, which in turn increases the Control Format Indicator (CFI) value. This decrement of network throughput can be lightened via appropriate scheduling, however cannot be easily quantified. Another difficulty of quantifying the comparison of LTE-LAA and WiFi throughput is the flexibility of co-existing mechanisms used by LTE-LAA. Different co-existing mechanisms result in different LTE-LAA channel idle time, which

affects overall averaged throughput.

In [42], the authors conducted simulations to compare LTE-LAA and WiFi throughput under the same conditions, *i.e.*, same bandwidth, Modulation and Coding Scheme (MCS) for a high SNR channel and MIMO configuration, while ignored co-existing requirement for LTE-LAA channel idle time. From the simulation results, the peak throughput of the LTE-LAA small cell has a 27 % increment over the 802.ac WiFi AP when the CFI is set to 1, and the increment drops to 7% when the CFI is 3. With the assistance of LTE licensed bands to convey downlink control plane, the CFI overhead in unlicensed bands equals to 0, then the unlicensed band throughput of LTE-LAA increases and is 57.6% higher than that WiFi offers. Obviously, the simulation settings are rather idealistic and what have been neglected in the simulation such as co-existence requirement for LTE-LAA channel idle time and LTE licensed band control plane overheads, can hold back the throughput benefits of LTE-LAA over WiFi. Additionally, WiFi allows for a larger amount of channel bandwidths to be aggregated to yield a higher peak throughput [42]. With all being said, whether the throughput provided by LTE-LAA is substantially higher than WiFi and is enough to justify that LTE-LAA is more worth deploying compared to WiFi remain discussable.

LTE-LAA no doubt offers higher spectral efficiency, better performance stability and link adaption mechanism than WiFi. It is anticipated that with the assistance of well-managed control channels in licensed bands, LTE-LAA enabled small cells would provide better quality of service (QoS) to mobile users than WiFi in unlicensed bands [15]. However, making the choice of LTE-LAA or WiFi really need to assess the deployment scenarios and all the aforementioned factors. And also importantly, the choice can be subjective. The public acceptance of WiFi is currently a lot higher than LTE-LAA due to cumulated customer loyalty, but will the situation alter in the near future?

2.2 Research on LTE-LAA and WiFi Co-existence Mechanisms

As the newcomer in the 5 GHz unlicensed spectrum, the main challenge identified for LTE-LAA is how to harmoniously co-exist with native technologies that have been residing in this spectrum region since their births. And the core challenge of the co-existence issue occurs in the situation where LTE-LAA and WiFi are operating on the same unlicensed sub-band. The performance of WiFi can be easily and significantly impacted while the performance of LTE-LAA is hardly affected, if there is a lack of proper co-existing protocols. This is due to the difference of medium access method adopted in their MAC layers, as stated in previous section. Inheriting from conventional LTE which is designed under the basic assumption that the operator has full exclusive control of the given spectrum, LTE-LAA in nature is nothing less dominant. The almost continuous data transmission protocol with minimum gap period and the periodical transmission protocol for control and reference signals fully occupies the channel. As a result, WiFi perceives the medium to be busy nearly all the time, and will be forced to remain silence.

In order to achieve a relatively “fair” co-existence between the two technologies, enhancements must be made. The core design concept of all existing enhancements is to put limits to LTE-LAA so that it can behave similarly to WiFi in unlicensed spectrum by actively giving up some transmission air time to guarantee sufficient WiFi transmission opportunities. That is, LTE-LAA holds back for WiFi to attain a “fair” share of the medium access in time-domain. Representative mechanisms of such co-existing enhancements are Carrier Sense Adaptive Transmission (CSAT), Almost Blank Sub-frame (ABS) and Listen-Before-Talk (LBT). CSAT, also referred as duty cycling, is such a mechanism with which the LTE-LAA small cell adaptively mutes itself according to the medium access frequency, and is the dominant technology in the market where LBT is not mandatory. ABS is in nature similar to CSAT, which force the LTE-LAA small cell to mute every n of 5 sub-frames to allow WiFi to access the channel. While the LBT mechanism, as a simplified version of Distributed Coordination Function (DCF) [68, 69], is enforced on LTE-LAA transmissions in unlicensed spectrum in those regions where LBT is mandatory to enable fair co-existence [41]. In this section, we first give an overview of recent investigations on LTE in unlicensed spectrum, and then look into details of the representative works on the LTE-LAA and WiFi co-existence problem based on the two main categories, *i.e.*, with and without LBT requirements. At the end of this section, we also give an summary of recent testing results to complete the review.

2.2.1 Overview of Related Works on LTE in Unlicensed Spectrum

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. The problem of co-existence of LTE in unlicensed spectrum and WiFi had attracted the community's interest since the very beginning. Several investigations were conducted and the results of which shows that without well designed co-existence mechanism applied, the performance of WiFi is severely degraded. In [70], co-existence of LTE and WiFi in TV white space is investigated, and the simulation results show that the WiFi throughput is significantly decreased due to LTE interference when LTE and WiFi nodes are randomly deployed in a certain region. In [71], performance of LTE and WiFi when co-existing with each other is evaluated, and the results show that the unlicensed channel sharing between them is absolutely unfair to WiFi as LTE transmissions dominate the shared medium and WiFi stays idle during LTE transmissions. It is clear that without enhancements and limitations applied to LTE for its unlicensed spectrum deployment, the large number of existing WiFi stations are in vulnerable position. Thus, quite a few WiFi operators and the WiFi Alliance community have approached the regulatory government bodies to express their concern that LTE in unlicensed spectrum deployments may be a disaster to the existing technologies in unlicensed spectrum [42].

Then, investigations were conducted around the thought that how to explore the benefits of LTE in unlicensed spectrum without harming the WiFi performance, that is, fair co-existence. As discussed before, the main co-existence issue comes from the difference of medium access schemes of both technologies. So, studies on LTE MAC protocol adjustments to enable fair co-existence of LTE-LAA and WiFi are proposed. Since WiFi transmitters follow the CSMA/CA medium access scheme, most existing schemes for coexisting LTE-LAA small cells and WiFi devices to share the unlicensed bands are based on time division duplex (TDD) [72]. Authors of [2] filed a patent on mathematically modelling the LTE-LAA behaviour with added muted period. The probability of WiFi back-off delay is calculated to be less than the LTE-LAA muted period. However, from the point of pure statistical analysis, the authors neglect the PHY layer effects and hidden and exposed node problem. The authors of [73] identify technical and business challenges regarding expanding LTE into unlicensed spectrum, and suggestions are given in terms of frequency-domain, time-domain and power-domain adaptive scheduling. In [68], under the assumption of accurate simulation of interferences between LTE-LAA and WiFi systems, with the proposed MAC scheme, the author has drawn the conclusion that LTE-LAA is able to achieve high throughput without impacting the performance of co-existing WiFi networks. However, the assumption is rather idealistic. There are methods for simulating LTE interferences in unlicensed spectrum, as stated in the previous interference management subsection. That is pre-defining a waveform signature simulating LTE-LAA signals, and compare it with the monitored signal energy at WiFi devices [44]. The interference pattern matching is then conducted periodically according to reliable interference identification, and the WiFi AP can further match the signal energy pattern to categorize the type of interference after the LTE-LAA interference is identified [43]. Besides the precise interference recognition assumption, there are some other assumptions seem idealistic and challenging to facilitate in real transmission environment, such as in [74], the authors recommend to divide the LTE-LAA transmission burst time into segments, which requires the exact number of LTE-LAA small cells and WiFi nodes to be known.

For the system modelling of co-existing LTE-LAA and WiFi networks, authors of [75, 73] leverage stochastic geometry to analyse the impact of LTE-LAA on WiFi in unlicensed spectrum. From the simulation results in [73], the LTE-LAA energy detection threshold plays an important role in altering the balance of throughputs of LTE-LAA and WiFi. Generally, the LTE-LAA throughput increases while the WiFi throughput decreases with higher LTE-LAA energy detection threshold. That is because with higher threshold setting, the LTE-LAA small cell is more aggressive when contending for the shared unlicensed medium. The conclusion drawn from the study is that, in order to achieve a fair co-existence between LTE-LAA and WiFi in terms of balanced network throughput, the LTE-LAA energy detection threshold needs to be adjusted so that the minimum throughputs of both LTE-LAA and WiFi are maximized. And through the stochastically analysis in [75], it is shown that the Density of Successful Transmission (DST) of LTE-LAA and the rate coverage probability of WiFi can be improved while maintaining reasonable data rate performance for both technologies when one or more co-existence mechanisms are applied on LTE-LAA, including lower channel access priority, shorter transmission duty cycle, and more sensitive CCA thresholds.

Apart from academic investigations on the co-existing problems, the community of industrial participants and IEEE standardization bodies also put a lot of their efforts in to this realm. Companies like Qualcomm, Ericsson, Nokia and Huawei, *etc.*, have set their feet into this playground, and later become big participants for commercial and standardization development of LTE-LAA [76, 10, 12, 9, 16]. Qualcomm proposed Carrier-Sensing Adaptive Transmission (CSAT) technology [8, 2], 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. The proposition of CSAT is also a supplement to the Channel Selection (CHS) mechanism proposed in [77, 78]. The drawback of CHS is that, when there is no available clear channel, the LTE-LAA small cell has to hold its transmission till the channel becomes unoccupied again. The details of works related to CSAT is reviewed in the following section together with ABS. On the other hand, co-existence mechanisms utilizing contention-based LBT-like schemes with additional collision avoidance algorithms are also introduced by papers like [79, 59, 80, 68]. For regions where LBT requirements are mandatory, LBT enhancements for LTE-LAA and WiFi co-existence are studied intensely. These related works are reviewed in the section below in details. 3GPP has included enhanced LBT in Release 13 and beyond as a global mandatory requirement, detailed in Section 2.3. CSAT and LBT both have TDD-like behaviours that force LTE-LAA to mute for WiFi transmission opportunities, while CHS explore the FDD possibility for managing the co-existence problem. As stated in [73], another angle to solve this challenging problem is looking into the power domain. In [81], a scheme applying power control to the LTE-LAA uplink is proposed. The simulation results show that for low density deployment scenario, the proposed power control approach is able to improve the performance of both LTE-LAA and WiFi networks. However, for high density deployment scenarios, this approach does not show its advantages.

For realization forms of LTE in unlicensed spectrum, various technologies have been proposed apart from LTE-LAA small cells, such as dual-band femtocells (DBFs), which can access both the licensed and unlicensed bands simultaneously with LTE interface [17], or the Small Cell Forum introduced Integrated Femto-WiFi (IFW) [82] that is able to simultaneously access the unlicensed band via WiFi interface and the licensed band via LTE interface. In the framework proposed in [19], 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. A few attempts on exploiting simultaneous transmission opportunities have been made. In [83], 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 minimum [16]. In [84], 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 these works has exploited multiple antenna technologies that can be deployed at both LTE-LAA small cells and WiFi APs. In [85], a co-existence scheme based on multi-antenna beamforming and Direction of Arrival (DoA) estimation combined with null steering is proposed to exploit simultaneous transmission opportunities for LTE-LAA with adjacently WiFi devices without causing significant interferences. One of the key factor that enables this approach is to capture the LTE-LAA transmission timing, which avoids collision with WiFi transmissions. From the simulation results, the channel access opportunities and channel occupancy time of LTE-LAA small cells are greatly improved, while being “invisible” to co-existing WiFi networks. The problem of this approach is that, DoA estimation and null steering operations may cause delay in LTE-LAA transmissions and thus affect the captured transmission timing, and also, for indoor environments where signals are scattered to be multi-path, the precision of DoA estimation really depends on the size of the antenna matrix equipped on the LTE-LAA small cell. In the following subsections, we give detailed reviews on co-existence mechanisms designed without LBT and with LBT regulation requirements.

2.2.2 Co-existence Mechanisms without LBT Requirement

For those regions where there is no LBT regulation requirement, first wave of LTE in unlicensed spectrum is able to be deployed in the form of LTE-U, as modifications on legacy 3GPP Rel. 10/11 LTE MAC and PHY layers are not needed for fairly managing the resource sharing between LTE and WiFi systems in unlicensed bands. In order for WiFi to regain transmission opportunities from dominating LTE-LAA transmissions, LTE-LAA small cells have to periodically give up control of the shared medium by actively muting themselves. The periodical on-and-off behaviour of LTE-LAA is called duty cycling, and is for releasing spectrum resources to the WiFi networks in time domain. Carrier-Sensing Adaptive Transmission (CSAT) is a typical realization of duty cycling. Co-existence mechanisms based on CSAT are practical for the purpose of achieving fair co-existence between LTE-LAA and WiFi networks, related works on CSAT include [4, 8, 12], *etc.*. Besides CSAT, another representative category of co-existence mechanisms are the ones based on the assistance of Almost Blank Subframe (ABS) [70, 71, 86]. These two main categories are widely studied particularly for the regions without LBT regulation requirements.

1. ***CSAT-based Co-existence Mechanisms:*** Originally proposed by Qualcomm [8], CSAT is an adjustment put on LTE-LAA MAC layer for configured scheduling. The basic idea of CSAT is to adaptively define a Time-Division Multiplexing (TDM) cycle that consists of discontinuous short time windows for LTE-LAA transmissions. During the operation of CSAT, as long as the traffic level is above a certain threshold, the LTE-LAA small cell stays in the CSAT-configured mode, and when traffic is light the LTE-LAA small cell de-configure itself to go back to normal transmission mode [3]. During the ON periods of CSAT, the LTE-LAA small cell is allowed

to transmit at the regular power level, while during the OFF periods the transmit power of the LTE-LAA small cell is tuned to a very low level or even reduced down to zero to allow the co-existing WiFi nodes to access the shared medium without being strongly interfered [49].

(a) *Duty Cycle Adaptivity*

As the name Carrier-Sensing Adaptive Transmission suggests, the ON and OFF periods of CSAT can be adaptively adjusted according to the channel utilization condition. The adjustment is done based on measurements taken by UEs and base stations of both networks, to which the CSAT ON and OFF related parameters adapt [8, 87]. In [2], an example of message exchange flow between LTE-LAA and WiFi systems are given, as depicted in Figure 2.4. As illustrated, there are three steps that consist the message exchange flow. During the first step, illustrated in continuous arrows, the LTE-LAA Self-organizing Network (SON) informs the LTE-LAA stack with a notification message stating that there is an upcoming measurement time gap on the shared unlicensed sub-band. At the same time, the LTE-LAA radio, which is the engaging LTE-LAA small cell, receives a message commanding itself to temporarily its transmission on the shared unlicensed band, to allow the measurements to be taken without being interfered. Then continuing to step 2, the LTE-LAA SON send a message to the WiFi SON to request measurements taken on the shared unlicensed band regarding the channel utilization condition. Upon receiving the measurement request, the WiFi SON command its subordinate WiFi AP or WiFi user device to conduct the measurements. And after that, in step 3, the WiFi device send the measurement report directly to the LTE-LAA SON entity, which then analyses the measurement report to make the decision whether to give permission to the LTE-LAA small cell for turning on its transmission mode, and send a message to the LTE-LAA stack for communication modification according to the measured channel occupation status.

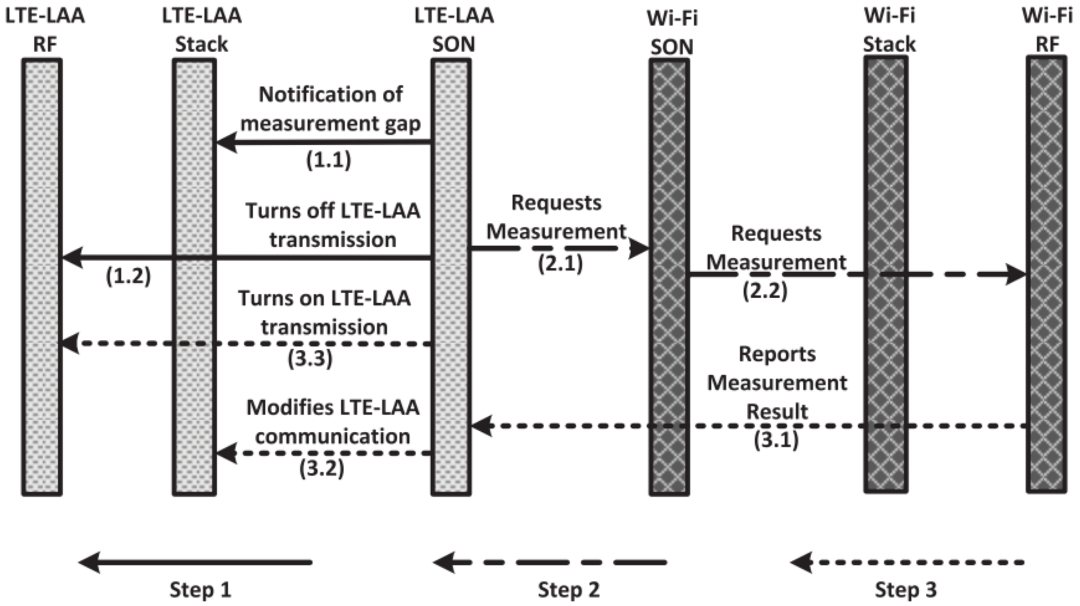


Figure 2.4: Information Communication between Co-existing LTE-LAA and WiFi Systems [2].

(b) *Duration and Ratio of ON/OFF Periods:*

The durations of CSAT ON and OFF periods are key parameters in this adaptive transmission scheme, and vary in different situations. Note that, during the CSAT OFF period, the LTE-LAA small cell does not necessarily turns itself off, but rather lowers its transmission power to keep background communications and control signalling exchange with its attached UEs. Data transmission is muted during the OFF period, and the power level is lowered as appropriate. The summation of one ON and OFF periods is the duration of one CSAT cycle. The longer the CSAT cycle is, the higher capacity can be achieved by the LTE-LAA system, as there is less carrier activation overhead [4]. On the other hand, the shorter the CSAT cycle is, the less impact caused by LTE-LAA to WiFi delay sensitive traffic in terms of latency [3]. There are inconsistent opinions on the duration of CSAT ON and OFF periods. As stated in the co-existence specification reports from LTE-U Forum [88, 89], the duration length of CSAT ON and OFF periods cannot exceed 50 ms. While in some other papers including

[2], the overall length of one CSAT cycle is longer than 200 ms in order to assure the user equipments to get at least one opportunity to measure the shared channel condition. There is a lack of authoritative specifications apart from LTE-U Forum that set mandatory limits to the duration of CSAT ON and OFF periods so far. Hence, there is a room for design flexibility to deal with various requirements.

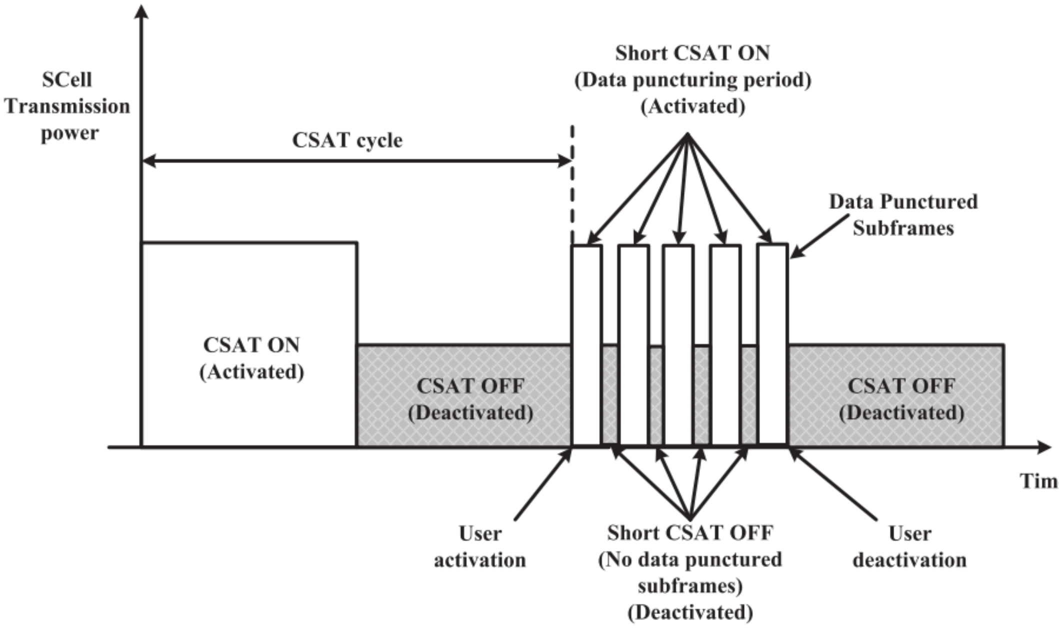


Figure 2.5: CSAT On and Off Periods [3].

Within one CSAT cycle, or looking at an observation time window, the duration ratio of ON and OFF period is an key adjustable parameter for balancing the medium access resource sharing between LTE-LAA and WiFi networks. Through solving the optimization of CSAT ON and OFF duration ratio subjects to the traffic condition on the shared channel and specific requirements, the medium access resource sharing between LTE-LAA and WiFi networks can be optimized, which in turn provides a better co-existence environment for both types of RANs. Figure 2.5 illustrates a representative CSAT ON and OFF transmission management [3]. The basic medium access tuning strategy is rather straightforward. For an instance, as shown in Figure 2.5, when there is a need to release some resources to the WiFi networks to increase WiFi channel utilization, the LTE-LAA channel access is reduced by tuning down the CSAT ON and OFF ratio. By pulling down the LTE-LAA small cell transmission power during its CSAT ON period as compared to its normal transmission power can also reduce the LTE-LAA channel utilization.

(c) *Integration with Other Mechanisms:*

CSAT, as a time-domain mechanism, can also be integrated with other mechanisms such as CHS stated before. Figure 2.6 shows an integrated co-existence framework consists of three technologies: *Channel Selection (CHS)*,*Opportunistic SDL (OSDL)*, and *CSAT*. CHS, as stated before is a mechanism in frequency-domain that performed by the LTE-LAA SON entity to scan and classify different available unlicensed channels in the first stage of the framework flow. Upon identifying an unoccupied unlicensed channel, a LTE-LAA small cell is allowed to conduct transmissions on this channel without causing co-channel interferences to co-located WiFi networks. CHS procedures are originally defined in 3GPP Rel. 10 to switch the LTE transmission towards a less interfered cleaner channel if the currently operating channel affected by various sources interferences. For triggering CHS, the interference level is more of concern than the source and type of it, and it can be measured via energy detection, which is also being done in [87]. CHS is also a practical method to avoid interfering with radar signals, as there is a certain amount of unlicensed spectrum reserved for radar and satellite communications in the 5 GHz band, as shown later in Section 2.3.1. In low traffic density situations, solely applying CHS is sufficient for a relatively fair co-existence between LTE-LAA and WiFi networks [8, 12]. However, as the traffic volume exponentially expands, it is almost unlikely to identify a clean channel in dense deployment areas. To complement for this, OSDL is integrated into the framework to alleviate the impact on co-channel transmissions. According to the CHS negative output and corresponding measurements, OSDL makes the decision whether to turn off the LTE-LAA small cell (acting as the

SDL) based on the traffic scheduling condition. If there is not enough traffic that demands a secondary SDL carrier, the LTE-LAA small cell is turned off, *i.e.*, data traffic is conveyed on the licensed band. CSAT, as the final process in the framework flow, is adopted to improve the co-existence fairness following the afore-mentioned CSAT principles.

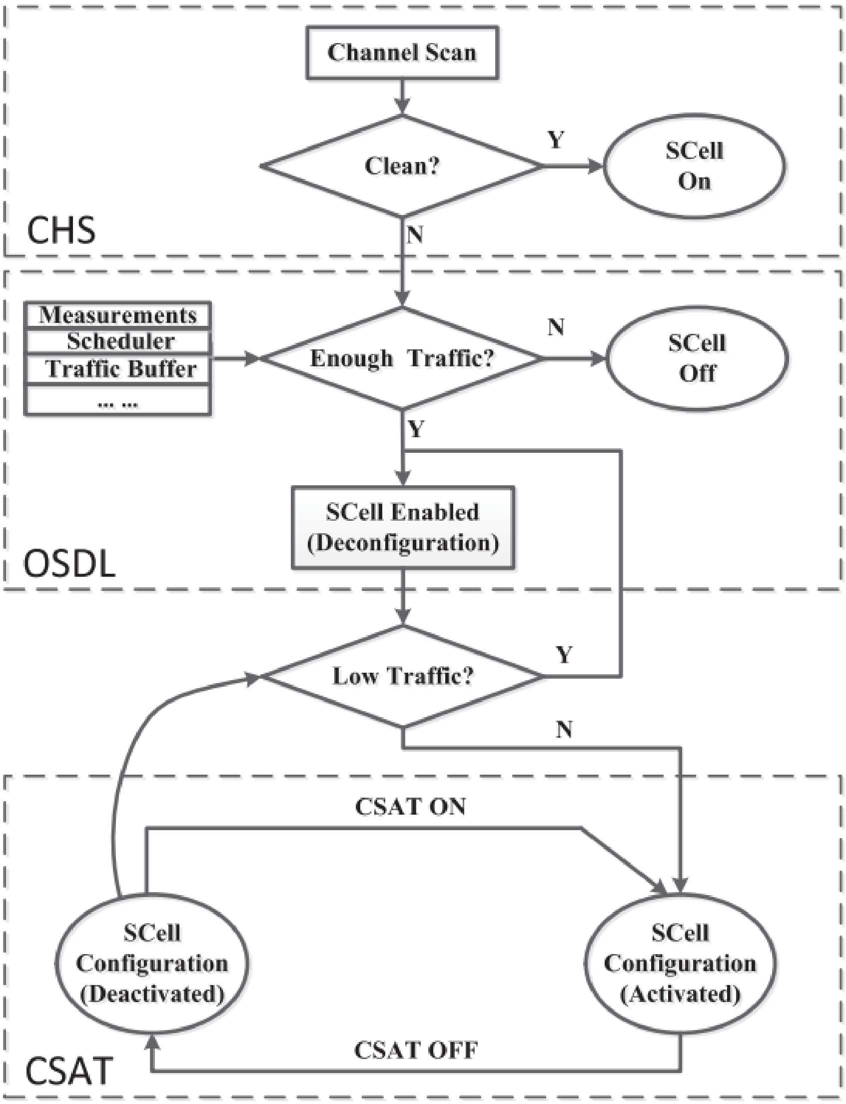


Figure 2.6: Work Flow of CSAT-centralized Co-existence Mechanism [4].

(d) *Advantages and Weaknesses of CSAT:*

The advantages of CSAT are not only presented by its effectiveness in balancing the resource sharing between LTE-LAA and WiFi networks, but also compatible with other schemes, as shown in the previous subsection. And more importantly, CSAT operation does not require modifications for the underlying LTE Rel. 10/11 MAC protocols, which makes it one of the best tool enabling the first wave of LTE deployments in unlicensed spectrum in regions without LBT regulatory requirements [4, 8, 2]. The weakness of CSAT is that, comparing to CSMA used in WiFi systems, it has longer latency. To reduce the latency impact, one method is to prevent primary sub-channel of the unlicensed channel being occupied by WiFi [8]. And also depicted in Figure 2.5, the short CSAT ON and short CSAT OFF periods are divided from one regular length CSAT ON period by introducing data punctured subframes which can help reduce latency.

2. ***ABS-assisted Co-existence Mechanisms:***

   Almost Blank Subframe (ABS), is another periodically muting strategy for that is similar to CSAT for LTE-LAA to actively give up some channel occupancy time to avoid medium access collisions. To be specific, ABSs are LTE subframes in LTE-LAA transmissions with reduced transmission power or activity. Originally proposed as one of the LTE eICIC mechanisms in 3GPP Rel. 10, the concept of ABS is to mute the transmission of the macrocell eNB during these certain blank subframes to allow the small cell or picocell edge users that suffer from strong interferences from the macrocell eNB to be served better [30, 70]. Adopted in LTE-LAA and WiFi co-existence situation, the LTE-LAA needs to mute its transmissions for certain amount of subframes, for example every 5 subframes, during which period WiFi devices take the chance to transmit on the shared unlicensed channel [49]. Compared to CSAT, which is adaptive to channel access conditions, ABS is simpler to implement but rather not that adaptive. CSAT requires coordination among technologies that facilitate CSAT adaptivity. This kind of coordination may not always be guaranteed if involved devices belong to different network operators. To achieve different types of fairness between LTE-LAA and WiFi networks, such as allocating equal amount of channel time to each active nodes within the combined co-existing network, the technology coordination in CSAT is not required and ABS comes in handy [74, 90]. ABS could also be used to exploit LTE-LAA transmission opportunities when WiFi devices are in back-off state, which might be quite long if the channel competition is intense. The probability of LTE-LAA attaining such transmission opportunities are derived in works like [19, 91, 92]. Similar to CSAT ON and OFF periods ratio, the number of blank subframes is the tuning parameter in ABS, which can strike a balance between the performances of LTE-LAA and WiFi. Additionally, the ABS positioning also makes an impact. Performance degradation can be observed if the selected blank subframes are not adjacent [70], as WiFi transmissions may not be confined within the LTE-LAA blank subframe boundaries and scattering blank subframes does not have enough trunking effect thus increases collision probabilities. This issue can be addressed by reporting the duration and timing of occurring blank subframes to WiFi at the beginning, and WiFi devices are able to confine their transmissions within LTE-LAA blank subframe boundaries to avoid collision and interference with LTE-LAA [3].

2.2.3 Co-existence Mechanisms with LBT Requirement

In those regions where LBT is a mandatory requirement, such as Europe and Japan, modifications on LBT need to be made to fit the specific goal of harmoniously deploying LTE in unlicensed spectrum. The key functionality in LBT for determining whether a unlicensed channel is feasible for LTE-LAA downlink data transmissions is called Clear Channel Assessment (CCA). CCA, as one of the two WLAN carrier sense mechanisms, is originally defined as part of the Physical Layer Convergence Protocol (PLCP) and Physical Medium Dependant (PMD) layer in the IEEE 802.11-2007 standards [93]. CCA consists of two main functions, namely *CCA Carrier Sense (CCA-CS)* and *CCA Energy Detection (CCA-ED)*.

- *WLAN CCA-CS:* For detecting and decoding a WiFi preamble. The decoded information includes but is not limited to the PLCP header, transmission packet length and duration (in μs) information, *etc.*. When successfully detecting and decoding the WiFi preamble, CCA indicates the channel being reserved for data transmission according to the length and duration information. The CCA-CS detection threshold is set to be the minimum receiver sensitivity of PHY, which is typically -82 dBm in 20 MHz band [37, 93].

- *WLAN CCA-ED:* For detecting a non-WiFi energy. As the non-WiFi signal cannot be decoded at the WiFi receiver, when the in-band signal energy is detected across the CCA-ED threshold, which is typically 20 dBm higher than the CCA-CS threshold, *i.e.* -62 dBm, the data transmission will back off, and the operating channel is marked as busy till the medium energy is detected below the CCA-ED threshold [37, 93]. Higher ED threshold allows the WiFi system to be more resilient to non-wifi signals. The setting of ED threshold in LTE-LAA CCA is an important parameter for alternating co-existence performance in terms of throughput, as discussed in previous Section 2.2.1.

Before starting a transmission, the LTE-LAA small cell needs to perform CCA to examine whether the target unlicensed channel is clean. If it is, the CCA procedure contends for occupying this channel. During Discontinuous Transmission (DTX) period after the successful CCA, one or more following CCA procedures will be conducted to keep checking if the operating unlicensed channel is still available [59, 6]. In Figure 2.7, one example CCA subframe placement within a downlink frame structure is illustrated [5]. In this figure, Subframe D (Subframe 0 through 8) represents downlink data subframes, and Subframe S (Subframe 9) represents CCA operation subframes. Within the structure of a Subframe S, there are a Guard Period (GP) to guarantee enough idle time before activating CCA, several DL CCA (DCCA) slots conducting the CCA operation, and one slot for the Channel Usage Beacon Signal (CUBS) that reserves the channel after CCA. Putting the CUBS slot at the end of Subframe S is to notify nearby small cells which may be also performing CCA that the CCA procedure in this small cell has already finished and the channel is no longer available. The number of

DCCA slots plus the CUBS slot is referred to as CCA reuse factor, which varies from 2 (one DCCA slot plus the CUBS slot) [78] to 3, 4, 7, 9 or 12 [5]. After a successful CCA, the channel is held by the LTE-LAA small cell till the next CCA procedure, *i.e.* the next Subframe S. As the illustrated example in Figure 2.8, if the first DCCA procedure fails, the LTE-LAA small cell stay silence for the whole transmission period, *i.e.* the fixed LBT frame period as shown in Figure 2.7. If the first DCCA procedure succeeds, there may be one or more following DCCA procedures in between data transmission subframes to check if the channel is still available. And once one DCCA after the first successful DCCA reports that detected signal level in this channel is beyond the threshold, the transmission is stopped until the next successful DCCA within this transmission period [6].

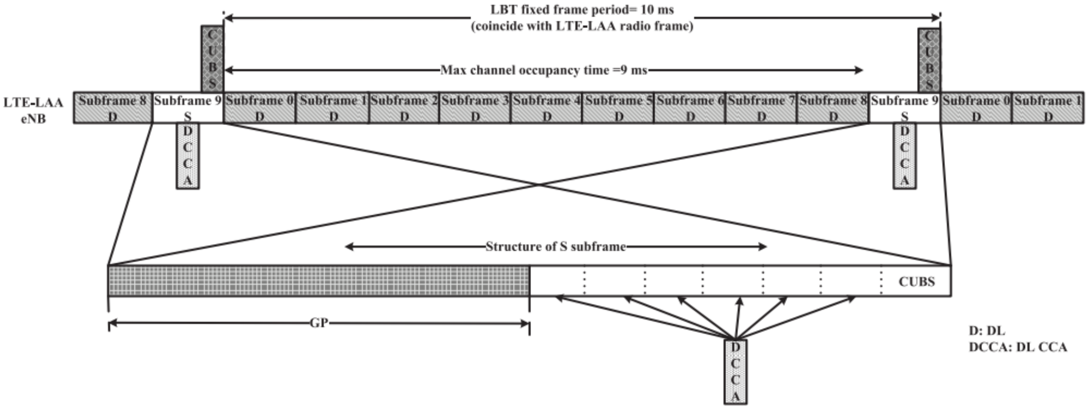


Figure 2.7: Clear Channel Assessment Subframe Placement [5].

The CCA threshold needs to be set properly to ensure fair medium access opportunities for LTE-LAA small cell and WiFi devices. With higher CCA threshold, the effectiveness of LBT for protecting WiFi transmissions are reduced, as ongoing WiFi transmission with lower detected power (in a relatively far distance with the LTE-LAA small cell or due to strong fading) will not be sensed by CCA, thus permitted LTE-LAA transmission will interfere with WiFi transmission and may cause collision. However, with low CCA threshold, the LTE-LAA LBT may be too sensitive to attain enough transmission opportunities [59]. The two types of CCA thresholds, *i.e.*, *CCA-CS* threshold and *CCA-ED* threshold designed for WLAN can both be adopted into the LTE-LAA LBT procedure, and the threshold values must be carefully set to adapt different deployment scenarios and traffic offloading requirements [94].

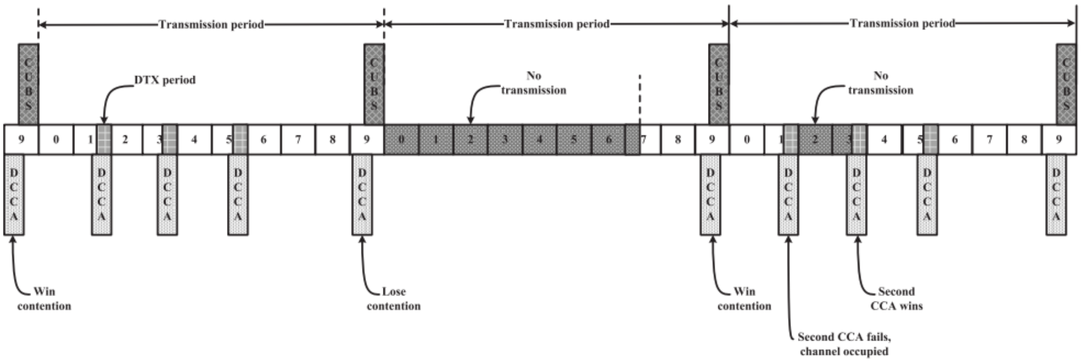


Figure 2.8: Example of DTX Periods with Downlink CCA (DCCA) Intervals [6].

2.2.4 Comparison of Duty Cycling and LBT

Generally speaking, the primary LTE-LAA and WiFi co-existence mechanisms for markets without LBT requirement can be concluded as ON and OFF duty cycling. And the primary co-existence mechanisms for markets with LBT requirement, are obviously LBT-based ones.

The major advantage of duty cycling lies in its easy operability and availability. Fewer modifications are needed for LTE to deploy in unlicensed spectrum with duty cycling-based mechanisms, and there is no need to wait for standardized regulations before deployments. This is particularly attractive for operators that need to rapidly increase their short-term network capacity with available unlicensed channels. And in fact, duty cycling method drives the first wave early commercial LTE-U deployments. However, the convenience comes with some natural weaknesses. The main one is that, even though the LTE-LAA ON and OFF periods can be adaptively adjusted to fit various conditions and requirements, the fairness of LTE-LAA and WiFi networks is still in the hand of LTE-LAA. That is, the LTE-LAA small cell controls the ON and OFF periods, and the performance of WiFi networks can be severely degraded if the ON and OFF settings are not chosen or updated properly [95]. Compared to LBT, duty cycling is generally more aggressive and relatively less fair, as it does not have the similar channel sensing-based opportunistic medium access behaviour as WiFi.

With LBT, WiFi throughput is better protected at the cost of degrading LTE-LAA performance benefit over WiFi [96]. This intuitively makes sense as duty cycling and LBT both aim for striking a balance between LTE-LAA and WiFi networks in terms of medium access opportunities and channel holding time. One additional advantage brought by LBT is that a distribution of unlicensed spectrum resources is allowed considering traffic load condition of each co-existing network [3]. The weakness of LBT is its complication in terms of implementation and modifications that need to be made on existing LTE MAC and PHY layers, as compared to duty cycling. Moreover, according to the 3GPP Rel. 13 standardization which has just been completed in 2016 [24], the impact on WiFi performance from LTE-LAA depends on the different implementations of LBT, as will be elaborated in Section 2.3.3 below.

2.3 Lessons Learnt from Literatures and Future Research Directions

From the intense review of LTE-LAA and WiFi co-existence mechanisms, the main goal of them and future investigations is to achieve *fairness* in unlicensed spectrum sharing among contending nodes and devices. However, the definition of *fairness* is not commonly recognizable nor standardized. One commonly accepted blurry description of *fairness*, as stated in white papers such as [8, 88, 76, 96, 97], is that the impact from a newly deployed LTE-LAA small cell should not be more than that from another WiFi AP in the same location spot. The impact can be in terms of interference, throughput degradation, collision probability and caused latency, *etc.*. Besides the co-existence between LTE-LAA and WiFi networks, *fairness* also refers to, as defined by 3GPP [24], the fair co-existence among multiple co-located LTE-LAA networks deployed by different operators to allow comparable performances for all participating players. Establishing common understanding of fairness is critical for considering feasible co-existence mechanism designs. What's more, 3GPP as the regulatory body represents the benefits of mobile operators and users, which only stands on one side of the LTE-LAA/WiFi co-existence scale. Hence, whether the 3GPP-defined *fairness* can be accepted by the WiFi Alliance remains to be seen in the future with more and more planned LTE-LAA deployments. With that being said, to achieve the “true fairness”, the effort may need to go beyond unilateral regulatory specifications and include negotiations among all contending players in this 5 GHz unlicensed spectrum playground. In later Chapter 3 and Chapter 4, we make the efforts to exploit simultaneous transmission opportunities for LTE-LAA small cells while co-existing with nearby WiFi networks. Our proposals are compatible and can be seamlessly combined with the LBT-based medium access standard defined by 3GPP. That means, with the same LBT parameter settings, our approach can provide LTE-LAA small cells with more channel access opportunities without further squeezing WiFi channel access time. And also importantly, our apporoach creates the possibility to achieve an “*even fairer*” co-existence environment for WiFi. To be specific, in order to get the similar channell access opportunities, our approach enables LTE-LAA small cells to utilize feasible simultaneous transmission opportunities to compensate for the concession on cutting down LBT-based channel access time. As a result, co-existing WiFi networks benefit from less impact coming from LTE-LAA small cells.

For future investigations on the co-existence problem, a few directions may be worth the effort. As mentioned in previous sections, optimizations regarding fair spectrum allocation between LTE-LAA and WiFi networks and among different LTE-LAA networks need more attention. The objective functions for the fairness optimization in regions with and without LBT requirements need to be carefully designed, and there is a lack of sufficient works on this. Additionally, more comprehensive tests in real deployment scenarios need to be carried out. In simulations done by LTE-U Forum and 3GPP, only limited types of traffic types are considered, and the co-existence mechanism design may be adjusted depending on test results for various types of traffic.

Another important aspect that future studies can focus on is to exploit spatial diversity and spacial duplexing benefiting from MIMO technology when designing co-existence schemes. Existing co-existence schemes designed for LTE and WiFi systems operating on the same unlicensed band are based on the guiding idea of sharing medium access air time. The idea of exploiting simultaneous transmission opportunities has rarely been attempted enslaved to the CSMA/CA medium access nature of WiFi systems, as discussed in early content . This is appropriate at the early stage of LTE-LAA deployment. However, with increasing deployment of LTE-LAA technologies, the availability of unlicensed spectrum will eventually become insufficient. Following the footprint of licensed spectrum utilization, sharing the same unlicensed bands simultaneously between LTE-LAA and WiFi systems with careffully designed interference mitigation techniques is the future trend, which is the focus point of our approach, as introduced in later chapters. In Chapter 3 we first exploit such simulataneous transmission opportunities considering different UE locations. And then in Chapter 4, we refine our approach by adopting beamforming technologies to further exploit the benefits of spatial diversity.

2.4 Summary

In this chapter we first introduce several key features related to the co-existing problem, and highlight the main co-existence challenges between LTE-LAA and WiFi networks sharing the same unlicensed band. Then, we review representative studies on LTE in unlicensed spectrum technologies and WiFi co-existence mechanismsr. Academical investigations and industrial tests are included. Later, with the insights gained from the research status review, we then give recommendations on future research directions on the co-existence issue, and emphasis on the novelty of our approach of exploiting simultaneous transmission opportunities for LTE-LAA small cells.

Chapter 3

Simultaneous LTE-LAA/WiFi Transmission Opportunities by Exploiting AP/UE Location Diversity

From intense literature reviews in the last chapter, we can see that the mainstream designs for solving the co-channel co-existence problem between LTE-LAA and WiFi are based on the concept of sharing the medium in the time domain. This is mainly because of the WiFi CSMA/CA medium access characteristic which does not allow simultaneous transmissions on the shared channel to avoid collisions. Countless works have been done based on this mindset. The advantage of this kind of time sharing co-existence designs is that it is easy to regulate in early state standardizations, and is able to meet the demand of fast commercial roll-out. More importantly, as a newly-developed technology, LTE-LAA deployments are not going to be ultra dense for now, and the 5 GHz unlicensed spectrum "*cake*" is big enough for multiple technologies to share for a few years. However, as we can learn from the communications history, all spectrum resources will eventually reach their limits for supporting exponentially growing data traffic demand. Throughout the technology evolutions in the licensed spectrum, enhancements such as interference management, spatial reuse and MIMO *etc.* have been made to improve the channel utilization. From exclusively conveying one link to simultaneously and harmoniously supporting multiple links, the potential of each licensed carrier has been squeezed out as much as possible.

We believe, with the premise that WiFi technology will not phase out in the foreseeable future, the increasingly dense deployments of LTE-LAA with time sharing co-existence mechanisms will eventually leave WiFi networks few leftover medium access opportunities. Note that, by introducing one LTE-LAA small cell, not only one WiFi AP but also a WiFi network that can hear this LTE-LAA small cell is impacted. And with increased overall channel sensing overhead in LTE-LAA systems and longer average back-off time in WiFi systems in future dense deployment scenarios, the overall spectral efficiency will stop to increase if not degraded. Hence, with this concern, we intend to exploit more simultaneous transmission opportunities for LTE-LAA without causing more impact than the time sharing methods. This is done by looking at the spatial domain, inspired by the spatial reuse concept in licensed spectrum cellular networks. The ignition of our exploitation is that, in both LTE-LAA and WiFi systems, transmission failure or collisions are determined at the receiver end due to strongly interfered received signals but not at the channel sensing entities (LTE-LAA small cell or WiFi transmitter). As long as the received signals at the receiver end are not or only lightly interfered, even though the channel sensing outcome is negative, the transmission can still be performed as the received data packets are going to be successfully decoded.

In this chapter, and as it is in our paper [84], we first state the motivation of our research, and then we derive the probability of coverage overlap between LTE-LAA small cell and WiFi APs by modelling the network nodes using a spatial bivariate Poisson point process. After that, we propose a novel framework for LTE-LAA small cells to effectively coexist with WiFi APs in the unlicensed spectrum considering the small cell (AP)/UE location diversity and various possibilities of coverage overlap between them. The theoretical analysis is conducted in simple scenario where an LTE-LAA small cell overlaps with one WiFi AP within a WiFi network. Back-off frozen state of the WiFi AP due to transmissions from other WiFi APs in the WiFi network is considered. The analysis can be extended to a more general scenario where an LTE-LAA small cell overlaps with multiple WiFi APs with little effort. The performance of the proposed framework in terms of LTE-LAA small cell channel occupancy in the unlicensed band is evaluated through both theoretical analysis and simulations.

3.1 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 back-off procedures. A WiFi node can only proceed with its transmission when the channel is sensed unoccupied, but has to wait for an exponential back-off period, which consists of a random number of time slots, before starting transmission. Each WiFi node has a back-off countdown timer, which decreases by 1 with each elapsed time slot, and is "frozen" when the channel is sensed busy during the back-off countdown. Once the back-off counter reaches zero, the transmission may start. Collisions not only lead to failed transmissions, but also increase the back-off stage of the WiFi transmitter, which in turn doubles the back-off period next time it initiates a new back-off counter. Given the contention-based channel access behaviour 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 [8] or the parameter η in [19].

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 their spectral efficiency. Moreover, the existing TDD based spectrum sharing schemes cannot completely avoid collisions between LTE-LAA and WiFi transmissions. For instance, with CSAT [8], if the LTE-LAA small cell is turned on just when the back-off count down timer of a nearby WiFi node reaches zero, or with the method in [19] 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 back-off timer reaches zero, the LTE transmission will collide with the WiFi transmission.

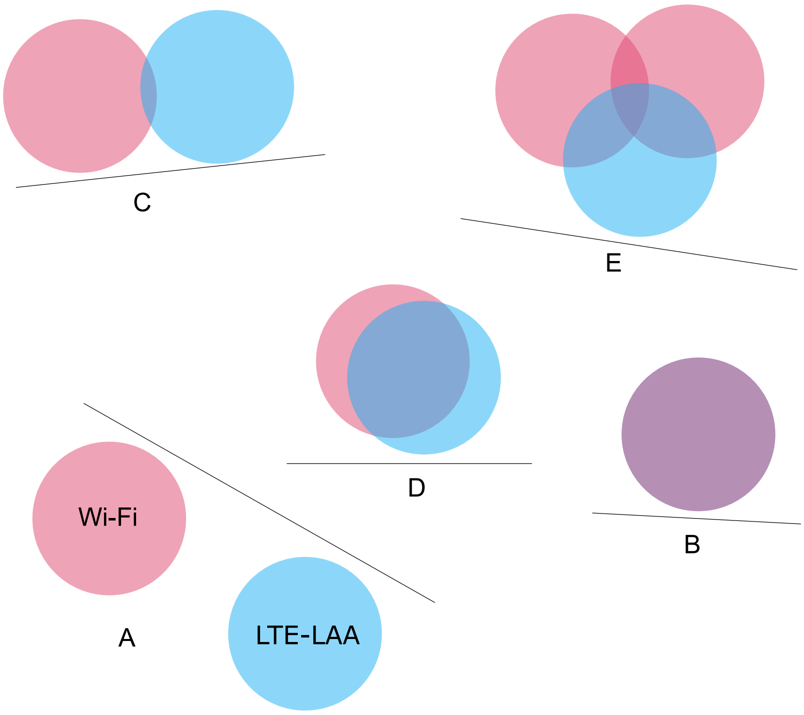


Figure 3.1: Deployment example

As shown in Figure 3.1, the positioning of an LTE-LAA small cell and a Wi-fi AP has several possibilities in terms of their coverage overlap. They can be absolutely not overlapping with each other (A) so that there is no coexisting problem, co-located at the same spatial point (B), lightly overlapped (C), heavily overlapped but not co-located (D), and overlapped with more than one opponent cells (E). Case B is the scenario modelled in [18, 19, 17], based on which the authors have developed a time-sharing access mechanism based on channel-sensing for the coexisting problem. However, this case B is an idealized ”worst case” and somewhat of a limited interest in practical scenarios [98]. We can first discuss case A, C, D, and then further extend to case E.

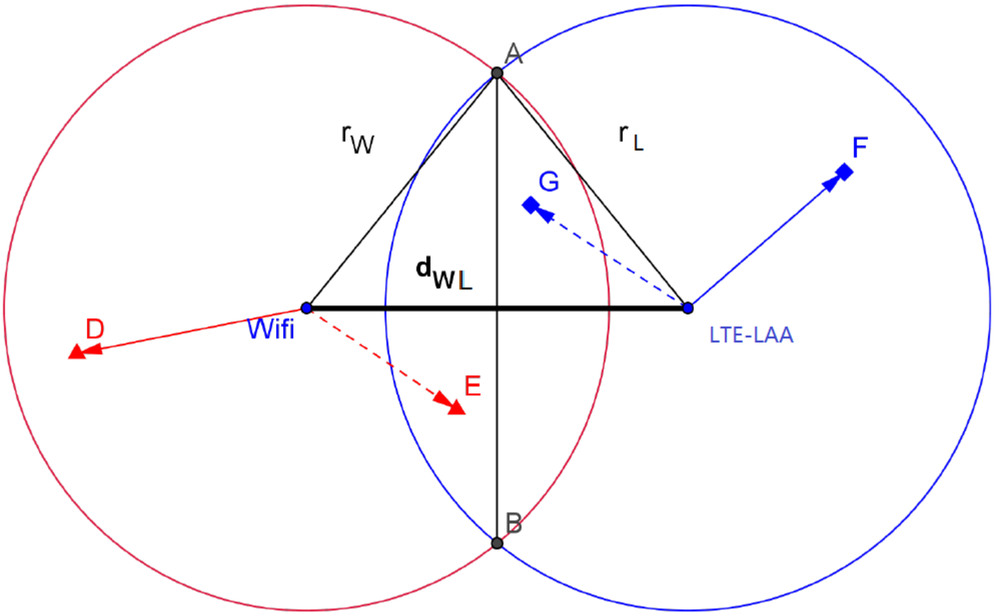


Figure 3.2: LTE-LAA small cell overlapping with its adjacent Wi-fi

Without loss of generality, we show Figure 3.2 to illustrate overlapping situations of case C and D in Figure 3.1. When a WiFi AP is transmitting to a user outside of the coverage overlap area (WiFi user D), even though that the LTE-LAA small cell senses the channel busy it can still transmits since it does not cause severe interference to the WiFi user. When the WiFi AP is transmitting to the WiFi UE D, there are two options for the LTE-LAA transmission. The better option is that the LTE-LAA small cell initiate a DL transmission towards its user that is outside of the coverage overlap, *i.e.* the LTE-LAA UE F. The second option is that the LTE-LAA small cell can try to transmit to the UE G locating in the coverage overlapping area. But as we assume the WiFi AP is equipped with omni-directional antenna, UE G suffers from WiFi interference. So, only if there is UE F type of users available for transmission due to scheduling problems and the interference that UE G is manageable, the transmission is initiated. Otherwise, the LTE-LAA small cell gives up this simultaneous transmission opportunity. And when WiFi is transmitting to its UE E locating within the coverage overlapping area, the LTE-LAA can only chose to transmit to UE

F or give up this opportunity.

Due to the contention-based WiFi CSMA/CA channel access mechanism, there would be at most one WiFi transmission in an unlicensed channel at any time instant in a WiFi network in which each WiFi AP can sense the transmissions from the others. Therefore, the complicated scenarios of an LTE-LAA small cell overlapping with more than one WiFi APs (case E) can always be decomposed into a series of events of the LTE-LAA small cell overlapping with each individual WiFi AP in time domain. That is, the case E overlapping situation can be decomposed into a series of case C or/and case D situations along the time line.

3.2 Probability of Overlap

For a network consisting of randomly deployed WiFi APs and LTE-LAA small cells, there could be various possibilities of coverage overlap between LTE-LAA small cell and WiFi AP. If an LTE-LAA small cell does not have coverage overlap with any nearby WiFi APs, then it can fully utilize the unlicensed spectrum without causing significant interference to WiFi users. Hence, in order to analyse the spectrum utilization opportunities and performance of LTE-LAA small cells in the unlicensed bands, it is necessary to first derive the probability of coverage overlap between LTE-LAA small cell and WiFi AP. Possible overlaps between LTE-LAA small cells and between WiFi APs are ignored for simplicity.

For analytical tractability, we model the random locations of LTE-LAA small cells and WiFi APs as a spatial bivariate Poisson point process, defined on the Euclidean plane, $\mathbb{R}^2$. Bivariate Poisson distribution can be used to model heterogeneous random networks consisting of two types of nodes, however there has been limited work applying it [98]. There are two types of nodes in our system model: type-W nodes representing WiFi APs, and type-L nodes representing LTE-LAA small cells. There are three possible events:

- Event-L: occurrence of a single type-L (LTE-LAA) node with intensity of λ.
- Event-W: occurrence of a single type-W (WiFi) node with intensity of μ.

- Event-LW: occurrence of a pair of type-L and type-W nodes with intensity of ν.

There might be some confusion about how to define the Event-LW, as the spatial positions of the LTE-LAA small cell and WiFi AP in any pair are totally distinguishable independent and identical distributed (i.i.d.) points. Claiming that Event-LW equals to coverage overlap seems subjective. To explain that, let us first define a distance threshold term D_T. Any two points of each type that are closer than D_T can be treated as a pair. According to [98], the probability of Event-LW depends only on the relative distance between the two points in a pair. For example, if we set D_T equals to the minimum distance between any two points from each type in this bivariate point process, then the probability of Event-LW is zero ($\nu = 0$). So if we set $D_T = r_L + r_W$, where r_L and r_W are the coverage radius of LTE-LAA small cell and WiFi AP, respectively, then an occurrence of Event-LW means coverage overlap between them.

Given an occurrence of an event of this process at point x, with probability $\frac{\lambda}{\lambda+\mu+\nu}$ there is a single LTE-LAA small cell without overlapping with any WiFi AP, with probability $\frac{\mu}{\lambda+\mu+\nu}$ there is a single WiFi AP, and with probability $\frac{\nu}{\lambda+\mu+\nu}$ there is a pair of LTE-LAA small cell and WiFi AP with the LTE-LAA small cell at point x_1,the WiFi AP at point x_2 , and the distances $\|x_1 - x\|$ and $\|x_2 - x\|$ being independent random variables following probability density functions $f(\|x_1 - x\|)$ and $g(\|x_2 - x\|)$, respectively. We can model $f(x)$ and $g(x)$ as isotropic zero-mean Gaussian distribution with variances σ_f^2 and σ_g^2 , respectively [98].

A point can be classified as a single point (corresponding to Event-L and Event-W) or paired (corresponding to Event-LW). Considering a differential area dx at point x, the probability that a type-L (type-W) single node exists at x is λdx (μdx). Given that a paired points (Event-LW) occurs with its reference point at x (with probability νdx), the probability that type-L node at dx_1 and type-W node at dx_2 is $f(\|x_1 - x\|)g(\|x_2 - x\|)dx_1 dx_2$. To find the probability of paired points with type-L node at dx_1 and type-W node at dx_2, we integrate over all points in the Euclidean plane:

$$P_{paired} = \nu h(x_1, x_2) dx_1 dx_2 \tag{3.1}$$

in which

$$h(x_1, x_2) = \int_x f(\|x_1 - x\|) g(\|x_2 - x\|) dx. \tag{3.2}$$

Let us denote the distance between a type-L (type-W) point to its nth nearest type-W (type-L) neighbor point as $D_{LW,n}$ ($D_{WL,n}$). And then we define the event that a type-L point at dx_1 and a type-W point at dx_2 as E_1 and E_2, repectively. The occurance of E_1 and E_2 can be the following situations:

- single type-L and type-W points with probability $\lambda dx_1 \mu dx_2$
- together as a pair with probability $\nu h(x_1, x_2) dx_1 dx_2$
- single type-L with paired type-W points with probability $\lambda dx_1 \nu dx_2$
- single type-W with paired type-L points with probability $\nu dx_1 \mu dx_2$

Given a type-L node at point x_1, the conditional probability of a type-W node at x_2 can be calculated as [98]

$$\begin{aligned} P_{E_2|E_1} &= \frac{\lambda dx_1 \mu dx_2 + \nu h(x_1, x_2) dx_1 dx_2 + \lambda dx_1 \nu dx_2 + \nu dx_1 \mu dx_2}{(\lambda + \nu) dx_1} \\ &= [\mu + \frac{\nu}{\lambda + \nu}(\lambda + h(x_1, x_2))] dx_2 \end{aligned} \tag{3.3}$$

Hence, given a type-L node at point x_1, the conditional intensity of a type-W node at x_2 is given by

$$\Lambda(x_2) = \mu + \frac{\nu}{\lambda + \nu}(\lambda + h(x_1, x_2)), \tag{3.4}$$

Note that the intensity of WiFi APs is non-homogeneous because of $h(x_1, x_2)$. Denote the circular area centred at x_1 (i.e., the given position of a type-L node) with radius r as C. The expected number of type-W nodes in C is given by [98]

$$\begin{aligned} \chi(r) &= \int_{x_2 \in C} \Lambda(x_2) dx_2 \\ &= ar^2 - be^{-cr^2} + b \end{aligned} \tag{3.5}$$

where

$$\begin{cases} a = (\mu + \dfrac{\lambda\nu}{\lambda+\nu})\pi \\ b = \dfrac{\nu}{\lambda+\nu} \\ c = \dfrac{1}{2(\sigma_f^2 + \sigma_g^2)} \end{cases} \tag{3.6}$$

In a homogeneous Poisson Point Process with intensity λ, the probability of finding k nodes in a bounded Borel C is given by [99]

$$P[\ k\ nodes\ in\ C\ ] = e^{-\lambda\mu(C)} \frac{\lambda\mu(C)^k}{k!} \tag{3.7}$$

where $\mu(C)$ is the standard Lebesgue measure of C, and $\lambda\mu(C) = \chi(r)$. Then the Complementary Cumulative Distribution Function (CCDF) of $D_{LW,n}$ can be interpreted as that there are less than n type-W nodes in C, and can be calculated as [98]:

$$\begin{aligned} F_{CCD,D_{LW,n}}(r) &= P\{D_{LW,n} > r\} \\ &= \sum_{k=0}^{n-1} e^{-\chi(r)} \frac{\chi(r)^k}{k!} \end{aligned} \tag{3.8}$$

3.2.1 General Probability of Overlap

Let us denote the distance between a type-L node and its nearest type-W neighbor as $D_{LW,1}$. The complementary cumulative distribution function (CCDF) of $D_{LW,1}$ can be calculated as:

$$\begin{aligned} F_{CCD,D_{LW,1}}(r) &= P\{D_{LW,1} > r\} \\ &= e^{-\chi(r)} \end{aligned} \tag{3.9}$$

which gives the probability of no type-W node being in C.

We define the *distance threshold* as $D_T = r_W + r_L$, where r_W and r_L are the coverage radius of a WiFi AP and an LTE-LAA small cell, respectively. Coverage overlap occurs when there is at least one WiFi AP within the circle centred at the LTE-LAA small cell with radius D_T. Thus, the probability of coverage overlap between LTE-LAA small cell and WiFi AP can be expressed as

$$\begin{aligned} P_{overlap} &= P\{D_{LW,1} \leq D_T\} \\ &= 1 - F_{CCD,D_{LW,1}}(D_T) \\ &= 1 - e^{-\chi(D_T)} \end{aligned} \tag{3.10}$$

An LTE-LAA small cell that is not in coverage overlap with any WiFi AP can fully utilize the unlicensed spectrum. Using probability $1 - P_{overlap}$, the corresponding unlicensed spectrum utilization in terms of channel occupancy time will be calculated for such LTE-LAA small cells in Section IV.

3.2.2 Probability of LTE-LAA Small cell Overlapping with One WiFi AP

A special case is that an LTE-LAA small cell overlaps with only one WiFi AP. Specifically, the distance between the LTE-LAA small cell and the nearest WiFi AP is less than D_T, while its distance to the second closest WiFi AP is beyond D_T. The probability of meeting the first condition is $P_{overlap}$ as given in (3.10).

Denote the distance between a type-L node and its second nearest type-W neighbor as $D_{LW,2}$. The probability of meeting the second condition is given by $F_{CCD,D_{LW,2}}(D_T)$, where $F_{CCD,D_{LW,2}}(r)$ is the CCDF of $D_{LW,2}$ expressed, according to Lemma 1 in [98], as:

$$F_{CCD,D_{LW,2}}(r) = e^{-\chi(r)}(1 + \chi(r)) \tag{3.11}$$

From (3.9) and (3.11), we can get the *pdf* of $D_{LW,1}$ and $D_{LW,2}$ respectively as:

$$\begin{aligned} f_{LW,1}(r) &= -\frac{dF_{CCD,D_{LW,1}}(r)}{dr} \\ &= e^{-\chi(r)}\frac{d\chi(r)}{dr} \end{aligned} \tag{3.12}$$

and

$$\begin{aligned} f_{LW,2}(r) &= -\frac{dF_{CCD,D_{LW,2}}(r)}{dr} \\ &= e^{-\chi(r)}\chi(r)\frac{d\chi(r)}{dr} \end{aligned} \tag{3.13}$$

The probability of an LTE-LAA small cell overlapping with only one WiFi can be interpreted as that the nearest WiFi neighbor is within distance less than D_T while the second nearest neighbor is further than D_T. These probabilities are respectively given as:

$$\begin{aligned} P_{inside,1} &= \int_0^{D_T} f_{LW,1}(r)dr \\ &= 1 - e^{-\chi(D_T)} \end{aligned} \tag{3.14}$$

and

$$\begin{aligned} P_{outside,2} &= \int_{D_T}^{\infty} f_{LW,2}(r)dr \\ &= e^{-\chi(D_T)}(1 + \chi(D_T)) \end{aligned} \tag{3.15}$$

Hence, the probability of an LTE-LAA small cell overlapping with only one WiFi AP can be calculated as:

$$\begin{aligned} P_{overlap,1} &= P_{inside,1} \cdot P_{outside,2} \\ &= (1 - e^{-\chi(D_T)})(1 + \chi(D_T))e^{-\chi(D_T)} \\ &= P_{overlap} \cdot F_{CCD,D_{LW,2}}(D_T) \end{aligned} \tag{3.16}$$

3.3 A New Coexisting Framework Scheme

For LTE-LAA small cells, the unlicensed band is only used for data traffic, while control messages are conveyed in the licensed band. Without loss of generality, we assume that WiFi APs and LTE-LAA small cells compete for the same unlicensed band, and once an LTE-LAA small cell or a WiFi AP obtains access to the unlicensed band it occupies the whole unlicensed band. Additionally, all user equipments (UEs) in the system are "smart devices" so that they can connect to both WiFi APs and LTE-LAA small cells.

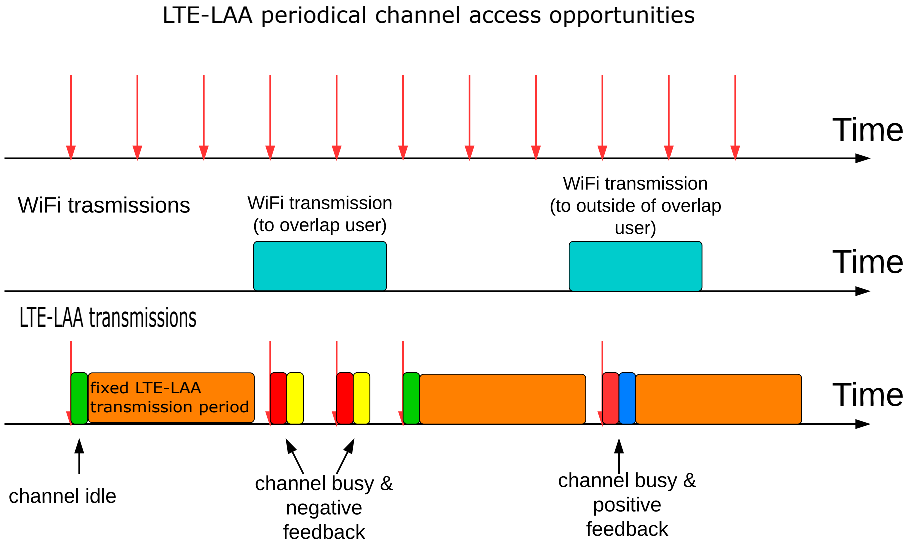


Figure 3.3: Proposed LTE-LAA channel access scheme in the unlicensed band.

We propose a new channel access scheme for LTE-LAA small cells in the unlicensed band as illustrated in Figure 3.3. The LTE-LAA small cell periodically attempts to access the channel. The time interval between two successive channel access attempts is $T_{attempt}$. At the beginning of attempt period $T_{attempt}$, the LTE-LAA small cell senses the unlicensed channel for a fixed period of time, $T_{sensing}$ (sufficiently smaller than $T_{attempt}$). If the channel is sensed to be idle for the whole duration of $T_{sensing}$, then the LTE-LAA small cell starts to transmit in the channel for a fixed period of time, $T_{tx,LAA}$. Otherwise, the LTE-LAA small cell broadcasts a short message to all UEs within its coverage through the licensed band at the end of $T_{sensing}$, to ask if any UE is currently being served by a WiFi AP. If according to feedbacks from all UEs, no UE within its coverage is being served by WiFi APs, the LTE-LAA small cell starts to transmit in the unlicensed channel; otherwise, the LTE-LAA small cell waits for the next channel access attempt. During data transmission in the unlicensed channel, the LTE-LAA small cell stops attempting the channel.

The frequency of LTE-LAA channel access attempts can be controlled by adjusting the value of $T_{attempt}$. The LTE-LAA data transmission duration $T_{tx,LAA}$ cannot be too long so that there would be fair opportunities for WiFi APs to occupy the unlicensed channel. The UE feedback delay T_{delay} is the time period required for the feedbacks of all associated UEs to be collected by the LTE-LAA small cell. In order to achieve a high spectral efficiency, both $T_{sensing}$ and T_{delay} need to be kept much shorter than $T_{attempt}$ and $T_{tx,LAA}$.

3.4 Performance of LTE-LAA Small cell Overlapping with One WiFi AP

The special case of an LTE-LAA small cell overlapping with just one WiFi AP is representative and important, because coverage overlaps between LTE-LAA small cells (or between WiFi APs) would have been largely avoided in operator deployed LTE-LAA (or WiFi) networks or become negligible in end-user deployed cases due to wall/floor penetration losses caused cell isolation. Moreover, the contention-based channel access mechanism of WiFi APs indicates that there would be at most one WiFi transmission in an unlicensed channel at any time in a WiFi network in which each WiFi AP can sense the transmissions from the others. Therefore, the complicated scenarios of an LTE-LAA small cell overlapping with multiple WiFi APs can always be decomposed into a series of events of the LTE-LAA small cell overlapping with each individual WiFi AP in time domain.

In this section, we analyze the performance of our proposed LTE-LAA channel access scheme for the case of an LTE-LAA small cell overlapping with just one WiFi AP. We first derive the probability of an LTE-LAA small cell successfully obtaining the unlicensed channel, $P_{LAA,succ}$. Based on this probability we then derive the fraction of time that the LTE-LAA small cell occupies the channel $t_{LAA,frac}$, which can be used as a criterion to evaluate spectrum utilization performance of our proposed scheme.

3.4.1 System Model

We consider an LTE-LAA small cell network collocated with a WiFi network, which consists of N (> 1) WiFi APs defined by the IEEE 802.11 WLAN standards. It is assumed that all UEs are uniformly distributed over the system coverage area, and all WiFi APs and LTE-LAA small cells always have data to transmit. A WiFi AP transmits to at most one UE within its coverage during each transmission. We consider the downlink of an LTE-LAA small cell, which overlaps with an arbitrary WiFi AP of the WiFi network. A WiFi transmission fails when it collides with transmissions from other WiFi APs or from LTE-LAA small cells. The exponential back-off mechanism [39] is used by WiFi APs to reduce collisions. We use CW_{min} and $CW_{max} = 2^m CW_{min}$ to denote the upper limits of the minimum and maximum back-off time, respectively, where CW_{min} is an integer and m is the maximum back-off stage. The back-off stage is initialized as $i = 0$ at each WiFi AP. When $i = 0$ or after each successful transmission of the WiFi AP, the back-off counter is set to a initial integer value randomly chosen from $(0, 2^i CW_{min} - 1]$. Then at the end of each time slot δ, if the channel has been sensed busy during that time slot, the back-off counter is "frozen" and will be resumed when the channel is sensed free. If the back-off counters of two or more WiFi APs reach zero at the same time, a collision happens which causes the back-off stage increased by 1 $(i = i + 1)$ at the next reset till the maximum back-off stage is reached. A WiFi AP transmits when its back-off counter drops to zero, and its transmission period depends on its payload and the data rate.

3.4.2 Derivation of $P_{LAA,succ}$

A WiFi AP can switch between the states of idle (continuous back-off), back-off frozen (due to a transmission from another WiFi AP), and transmission over time. For the case of an LTE-LAA small cell overlapping with just one WiFi AP in our proposed coexisting framework, the LTE-LAA small cell can obtain the unlicensed channel if it either senses the channel being idle (i.e., the WiFi AP is in idle or back-off frozen state), or detects from the specific UE feedbacks that the WiFi AP is transmitting to a UE outside their overlapped coverage area. The former case becomes true under the following two conditions. First, the start time of an LTE-LAA channel access attempt is within a channel idle period. Second, the channel is sensed being continuously idle for the duration of $T_{sensing}$.

The analysis of LTE-LAA successful transmission probability in [19] is based on the probabilities of the WiFi-only network being in the states of idle, collision, and transmission provided in [38, 39]. While in our scenario, we need to find the probabilities of each individual WiFi AP being in idle, back-off frozen, and transmission states. We use a "general slot" to represent three kinds of WiFi time periods: a back-off slot (with duration δ), a transmission period (with duration α), and a back-off frozen period (with duration β). A back-off slot δ is the basic time slot defined in IEEE 802.11 standards. The values of α and β depend on the transmission rates and average payloads of the WiFi APs, respectively. Depending on whether or not the request-to-send/clear-to-send (RTS/CTS) handshake mechanism is used, the time periods such as distributed interframe space (DIFS) and short interframe space (SIFS) defined in IEEE 802.11 standards can fit into different kinds of "general slots" according to (14) and (17) in [39].

By modelling the WiFi exponential back-off mechanism using the discrete-time Markov Chain [39], the probability τ of a WiFi AP transmitting in any "general slot" can be expressed as:

$$\tau = \frac{2(1-2p)}{(1-2p)(CW_{min}+1) + pCW_{min}(1-(2p)^m)} \tag{3.17}$$

Where the conditional collision probability p is expressed as:

$$p = 1 - (1-\tau)^{N-1} \tag{3.18}$$

A conditional collision (back-off frozen or transmission collision) occurs when at least one of the other $N-1$ WiFi APs are transmitting in the same "general slot", each with probability τ. We can see that (3.17) and (3.18) form a non-linear system with respect to τ and p, which can be easily solved within several iterations using numerical methods. It has been proven that there exists a unique pair of solutions to this system [39].

The three kinds of "general slots" have their probability of occurrence calculated as:

$$\begin{cases} P_b = (1-\tau)(1-p) \\ P_t = \tau \\ P_{bf} = (1-\tau)p \end{cases} \tag{3.19}$$

where P_b, P_t and P_{bf} are the probabilities of a WiFi AP being in idle back-off, transmission, and back-off frozen states, respectively. With these probabilities, the fractions of time that the WiFi AP is in idle back-off and back-off frozen states are given, respectively by:

$$\begin{cases} Q_b = \dfrac{P_b\delta}{P_b\delta + P_t\alpha + P_{bf}\beta} \\ Q_{bf} = \dfrac{P_{bf}\beta}{P_b\delta + P_t\alpha + P_{bf}\beta} \end{cases} \tag{3.20}$$

Accordingly, the probability of the start time of an LTE-LAA channel access attempt being within an idle back-off period or a back-off frozen period of the overlapping WiFi AP is given by Q_b and Q_{bf}, respectively. Assume that the idle back-off period is composed of L $(L = 1, 2, 3...)$ consecutive back-off slots, with a total duration of $L\delta$. Given the start time of $T_{sensing}$ located in a period of WiFi idle back-off or back-off frozen, the corresponding conditional probability P_{Q_b} or $P_{Q_{bf}}$, for the LTE-LAA small cell to successfully sense the channel being idle during the whole $T_{sensing}$ period can be calculated as:

$$P_{Q_b} = \sum_{L=\lceil T_{sensing}/\delta \rceil}^{\infty} \frac{L\delta - T_{sensing}}{L\delta}(P_b)^L P_t + \sum_{L=1}^{\infty}(P_b)^L P_{bf} \tag{3.21}$$

$$P_{Q_{bf}} = \frac{\beta - T_{sensing}}{\beta} + \sum_{L=\lceil T_{sensing}/\delta \rceil}^{\infty} \frac{T_{sensing}}{\beta}(P_b)^L + \sum_{L=1}^{\lceil T_{sensing}/\delta \rceil - 1} \frac{\beta + L\delta - 2T_{sensing}}{\beta}(P_b)^L \quad (3.22)$$

where $\lceil x \rceil$ denotes the smallest integer no less than x. The first part on the right-hand side of (3.21) is the probability that the idle back-off period $L\delta$ is followed by a WiFi transmission, $L\delta$ is no shorter than $T_{sensing}$ and the starting time of $T_{sensing}$ is in the first $(L\delta - T_{sensing})/L\delta$ portion of $L\delta$. The second part on the right-hand side of (3.21) is the probability that the idle back-off period $L\delta$ is followed by a back-off frozen period, in which case the LTE-LAA small cell will sense the channel being idle during the whole period of $T_{sensing}$, since the duration of a back-off frozen period β is usually larger than $T_{sensing}$. The first part on the right-hand side of (3.22) is the probability that the starting time of $T_{sensing}$ is within the first $(\beta - T_{sensing})/\beta$ portion of the back-off frozen period. The second part on the right-hand side of (3.22) is the probability that the starting time of $T_{sensing}$ is in the last $T_{sensing}/\beta$ portion of the back-off frozen period but the following idle back-off duration is longer than $T_{sensing}$. Then the third part on the right-hand side of (3.22) gives the probability that the starting time of $T_{sensing}$ is within the $(\beta + L\delta - 2T_{sensing})/\beta$ fraction of the back-off frozen period and the following idle back-off period is shorter than $T_{sensing}$.

The LTE-LAA small cell will also transmit in the unlicensed channel when it detects from the UE feedbacks that the overlapping WiFi AP is transmitting to a UE outside their coverage overlap area. As we assume uniform UE distribution and that each WiFi AP transmits to at most one UE at a time, we can calculate the probability of the WiFi AP transmitting to UE outside the overlap area as:

$$P_{WO} = 1 - \frac{A_{overlap}(d)}{\pi r_W^2} \quad (3.23)$$

where $A_{overlap}(d)$ is the area of coverage overlap between the LTE-LAA small cell and the WiFi AP, which is a function of their relative distance d and coverage radii r_W and r_L. Combining (3.20), (3.21), (3.22) and (3.23), we get the probability $P_{LAA,succ}$ of an LTE-LAA small cell (which overlaps with one WiFi AP) successfully obtaining an unlicensed channel as:

$$P_{LAA,succ} = Q_b P_{Q_b} + Q_{bf} P_{Q_{bf}} + (1 - Q_b P_{Q_b} - Q_{bf} P_{Q_{bf}}) P_{WO} \tag{3.24}$$

3.4.3 LTE-LAA fraction of channel occupancy time

The LTE-LAA channel access attempts can be considered as independent if $T_{attempt}$ is sufficiently larger than the SIFS and DIFS [19]. With the success probability $P_{LAA,succ}$ of each attempt, it requires an average of $1/P_{LAA,succ}$ attempts for the LTE-LAA small cell to obtain the unlicensed channel. Once the LTE-LAA small cell successfully obtains the channel, it transmits for a fixed period $T_{tx,LAA}$. Thus, the fraction of channel occupancy time $t_{LAA,frac}$ of the LTE-LAA small cell can be calculated as:

$$\begin{aligned} t_{LAA,frac} &= \frac{T_{tx,LAA}}{(1/P_{LAA,succ})T_{attempt} + \lceil \eta - 1 \rceil T_{attempt}} \\ &= \frac{\eta}{1/P_{LAA,succ} + \lceil \eta \rceil - 1} \end{aligned} \tag{3.25}$$

where $\eta = T_{tx,LAA}/T_{attempt}$, which can be used as a tuning factor for the LTE-LAA small cell to adapt its channel occupancy time. Note that there is a minor error in the derivation of an LTE-LAA small cell's fraction of channel occupancy time in [7, eq. (5)], where the denominator is overestimated by one more $T_{attempt}$. This minor error does not noticeably degrade the accuracy when the channel access success probability is very small or the value of η is very large.

3.4.4 Probability of Overlap

In this subsection, we evaluate the accuracy of the derived probability of overlap through simulation. In the simulation, we set $\sigma_f^2 = \sigma_f^2 = 1$, i.e., $f(x)$ and $g(x)$ follow isotropic standard normal distributions. The baseline intensity setting is equivalent to around 10 single LTE-LAA small cells, 20 single WiFi APs and 1 pair of LTE-LAA small cell and WiFi AP distributed over the area of a $2km \times 2km$ square following a spatial bivariate Poisson point process. We define the intensity index n (in the range of $[1, 20]$) to increase the intensities of the three types of events (as defined in Section II) by multiplying the three events' spatial intensities of the baseline setting by n.

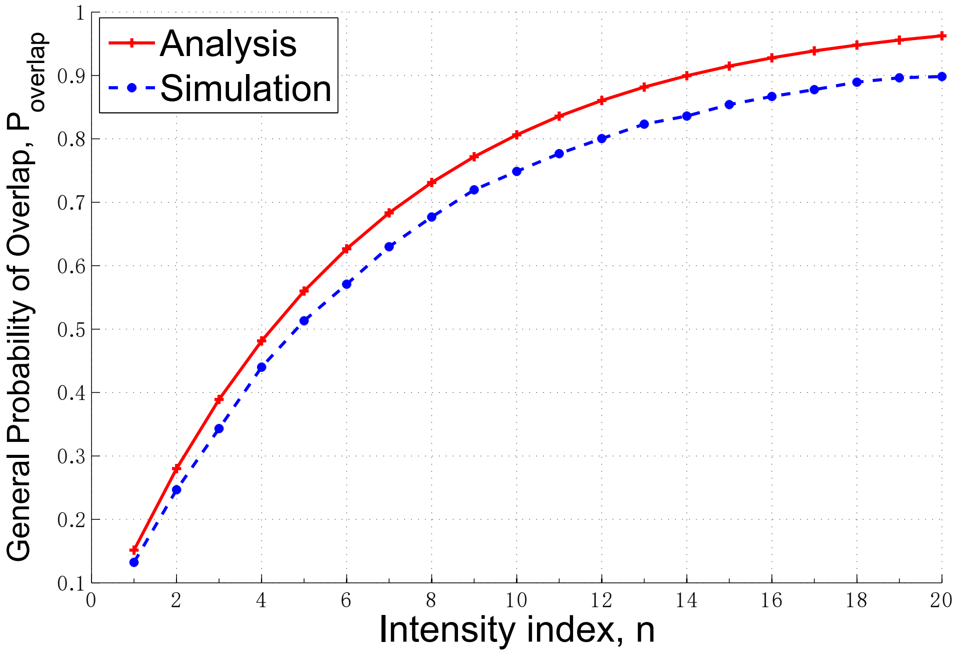


Figure 3.4: General probability of overlap

Analytical and simulation results of the general probability of coverage overlap between LTE-LAA small cell and WiFi AP and the probability of LTE-LAA small cell overlapping with only one WiFi AP are shown in Figure 3.4 and Figure 3.5, respectively, versus the intensity index n. Figure 3.4 is generated with Equation (3.10), and Figure 3.5 is generated with Equation (3.16). From the figures, we can see that our analytical expression slightly overestimate the probabilities but are reasonably close to the simulation results. The general probability of overlap monotonically increases with the intensity index, while the probability of LTE-LAA small cell overlapping with one WiFi AP first increases with the intensity index and then decreases with it after reaching a maximum value. This is because the chance of an LTE-LAA small cell having coverage overlap with WiFi APs gets higher with the increasing intensity index, but as the intensity further increases, the events of LTE-LAA small cells overlapping with multiple WiFi APs become

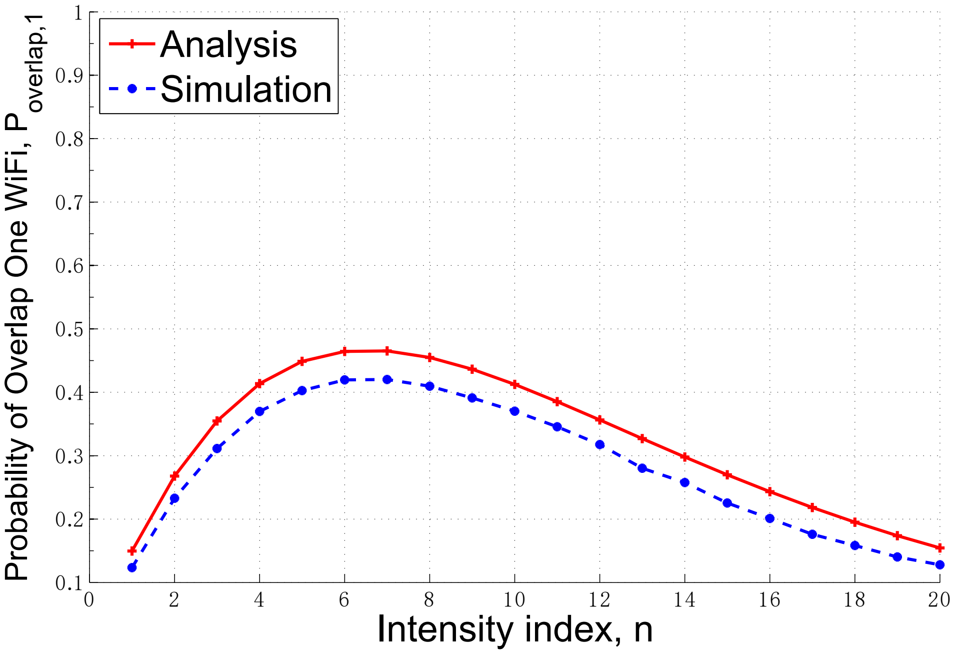


Figure 3.5: Probability of LTE-LAA small cell overlapping with one WiFi AP

dominant and the probability of an LTE-LAA small cell overlaping with only one WiFi AP drops.

3.4.5 Performance Evaluation

In this subsection, we present simulation results to compare the LTE-LAA small cell's fraction of channel occupancy time $t_{LAA,frac}$ of our proposed LTE-LAA and WiFi coexisting scheme with that of the scheme in [19] (which is denoted as "benchmark" in the figures), versus the normalized relative distance between an LTE-LAA small cell and a WiFi AP and for different values of η (as defined in (3.25)). The values of $t_{LAA,frac}$ calculated using our analytical expression is also included in the comparison. In the simulation, we consider the downlink of a WiFi network consisting of 10 WiFi APs, and the downlink of an LTE-LAA small cell overlapping with one random selected WiFi AP, with the distance between them given by $d \in [0, D_T]$, where $D_T = r_W + r_L$ as defined in Section II-A. All WiFi APs always have data to transmit with the same payload at the same data rate. The values of system parameters used in the simulation are given in Table (3.1).

Table 3.1: Simulation Settings

Slot Time	9 μs
SIFS	10 μs
DIFS	28 μs
$T_{sensing}$	18 μs
T_{delay}	27 μs
$T_{attempt}$	1 ms
Clear Channel Assignment (CCA) time	4 μs
CW_{min}	32
CW_{max}	1024
WiFi Transmission Rate	6.5 Mbps
WiFi Payload	1500 bytes
WiFi Coverage Radius	50 m
LTE-LAA Coverage Radius	50 m

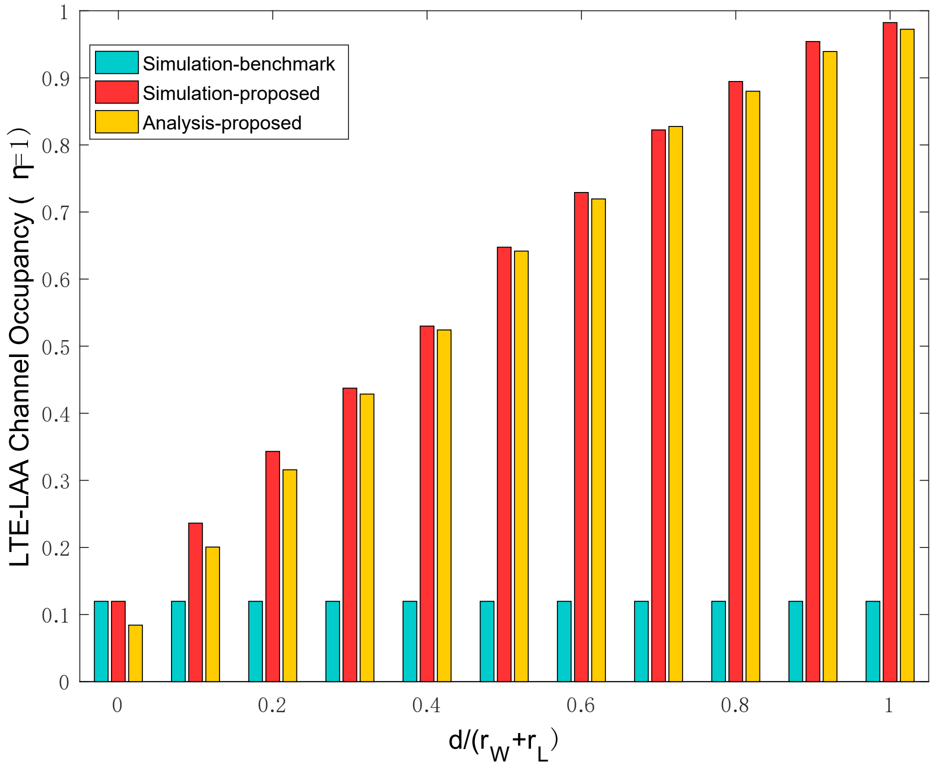


Figure 3.6: LTE-LAA smallcell's channel occupancy ($t_{LAA,frac}$), $\eta = 1$

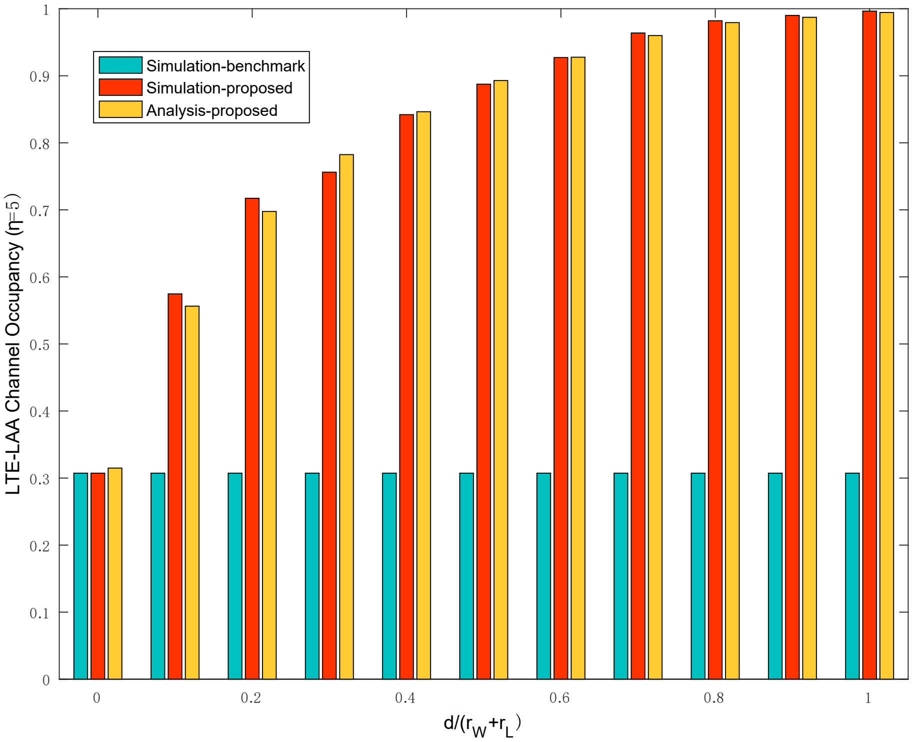


Figure 3.7: LTE-LAA smallcell's channel occupancy ($t_{LAA,frac}$), $\eta = 5$

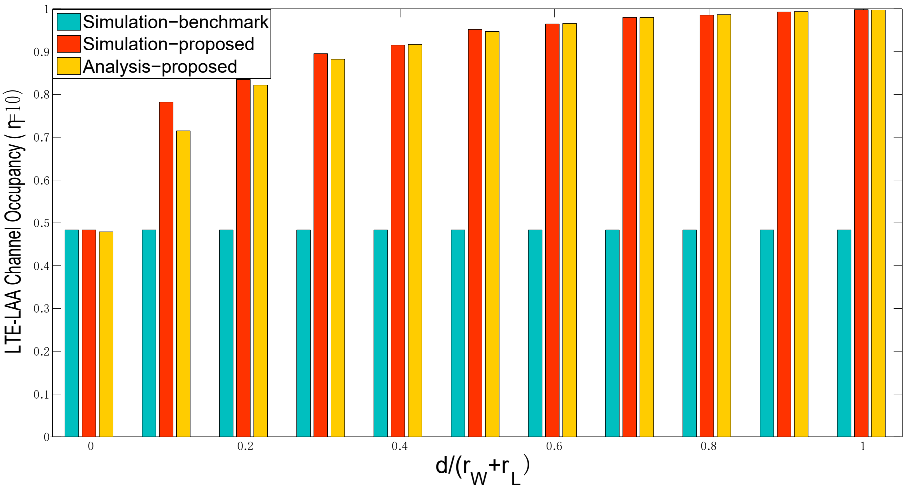


Figure 3.8: LTE-LAA smallcell's channel occupancy ($t_{LAA,frac}$), $\eta = 10$

Figure 3.6, Figure 3.7 and Figure 3.8 show the results for $\eta = 1$, $\eta = 5$ and $\eta = 10$, respectively. In these figures we can see that our proposed LTE-LAA and WiFi coexisting scheme dramatically increases the unlicensed-channel utilization for the LTE-LAA smallcell as compared to the scheme in [19]. The performance improvement becomes more evident at larger relative distances between the LTE-LAA smallcell and WiFi AP. The performance of the scheme in [19] is independent of the relative distance between an LTE-LAA smallcell and a WiFi AP. Our analytical calculation of $t_{LAA,frac}$ closely matches the simulation results. At $d/(r_{WiFi} + r_{LAA}) = 0$, our proposed scheme offers the same performance as the scheme in [19], because in this case the coverage areas of LTE-LAA smallcell and WiFi AP completely overlap and there is no extra transmission opportunity that can be exploited by the LTE-LAA smallcell in the unlicensed band. At $d/(r_{WiFi} + r_{LAA}) = 1$, our proposed scheme achieves a fraction of channel occupancy time close to 1 for the LTE-LAA smallcell. The LTE-LAA smallcell channel occupancy gain of our proposed scheme over the scheme in [19] mainly comes from the LTE-LAA smallcell's additional transmission opportunities when the WiFi AP transmits to a UE located outside their coverage overlap area.

Comparing Figure 3.6 with Figure 3.7 and Figure 3.8, we can see that the LTE-LAA smallcell's channel occupancy increases with η for both schemes. The advantage of our proposed scheme over the scheme in [19] is more significant for a lower value of η. LTE-LAA smallcells sharing the unlicensed band with WiFi APs need to use a relatively low value of η in order to protect the transmission opportunities of WiFi APs.

3.5 Summary

In this chapter, we have derived the probabilities of LTE-LAA small cells overlapping with WiFi APs when the collocate in an area. Based on the derived probability of an LTE-LAA small cell overlapping with one WiFi AP, we proposed a new scheme for an LTE-LAA small cell to coexist with a WiFi AP considering various probabilities of coverage overlap between them. The performance in terms of LTE-LAA small cell's channel occupancy is analytically evaluated and then verified through simulation. Simulation and analytical results have shown that our proposed scheme outperforms the existing scheme in terms of LTE-LAA small cell's channel occupancy time. And the improvement of our proposed scheme is more significant for a smaller η.

However, as the first attempt to exploit simultaneous LTE-LAA and WiFi transmission opportunities in the spatial domain, the proposed scheme in this chapter is rather idealistic with ideal assumptions such as circular LTE-LAA small cell and WiFi AP coverage areas and perfect knowledge of the locations LTE-LAA and WiFi receiving UEs. In real deployment scenarios, these assumptions may cause errors in deciding the cell coverage boundaries and transmission delay due to asynchronous feedback reports. Even with these potential problems, our first attempt shows the possibility of simultaneous transmission opportunities by exploiting the spatial domain, which is novel comparing to existing co-existence designs. In the next chapter, we manage to relax some of these ideal assumptions with the assistance of multi-antenna beamforming technology.

Chapter 4

Simultaneous LTE-LAA/WiFi Transmission Opportunities Utilizing Multi-antenna Beamforming Technology

In this chapter, we continue exploiting the spatial domain using multiple-antenna technology at LTE-LAA small cells and WiFi APs to create simultaneous transmission opportunities between the two systems in coexistence. We have proved in the last chapter that there can be extra simultaneous transmission opportunities for co-channel co-existing LTE-LAA and WiFi networks, instead of dividing channel access opportunities in the time domain. However, the co-existence scheme proposed in the last chapter is based on rather idealistic assumptions. The practicality in terms of implementing the scheme in real life is not very strong. As an academically attempt, it opens the door for us to see the possibility of more potential simultaneous LTE-LAA and WiFi co-channel transmission opportunities. So, driven by this possibility, we intend to find a more practical approach that may be able to be implemented in the future when LTE-LAA small cell deployment becomes ultra dense. The design concept stays, which is that 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.

As for the content of this chapter, we propose a co-existence 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.

4.1 Proposed Simultaneous Transmission Scheme

We intend to design a co-existence 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 Figure 4.1, upon sensing a ongoing WiFi transmission, the LTE-LAA small cell can steer its transmission beam pattern so that one of the generated nulls is pointing at the WiFi receiver. By doing so, the WiFi receiver will not be interfered by the simultaneous LTE-LAA transmission. The key information needs to be captured by the LTE-LAA small cell is the direction of the WiFi receiver, rather than its actual location.

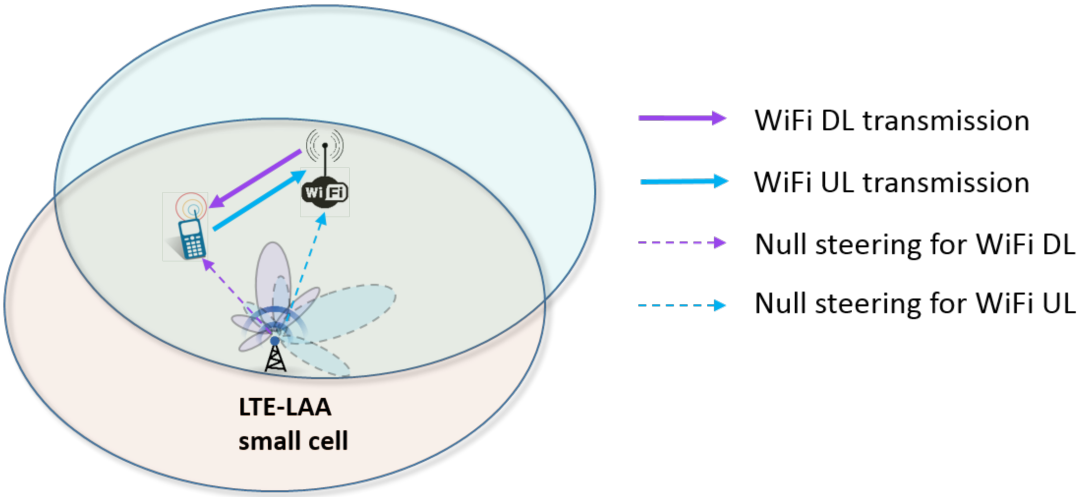


Figure 4.1: LTE-LAA small cell null steering for interference mitigation.

The system model is described in Section 4.1.1. There are two main steps in the proposed scheme: *capture of transmission timing* and *beam steering*. For the capture of transmission timing, the best type of simultaneous transmission opportunities for LTE-LAA small cell are those in "synchronization" with WiFi transmissions. This will be explained in details in Section 4.1.2. And for beam steering, it consists of two sub-steps, namely *DoA estimation* and *null steering*, which are discussed in Section 4.1.4 and Section 4.1.5, respectively.

4.1.1 System Model

We consider one LTE-LAA small cell whose coverage area is overlapped with that of a WiFi AP as depicted in Figure 4.1. 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 work. 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. There is no direct communication link for information exchange between the LTE-LAA small cell and the WiFi transmitter.

4.1.2 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. To be specific, in order to cause no disturbance to the WiFi channel sensing procedure and avoid potential collisions, the best time window for LTE-LAA simultaneous transmissions is the period between the starting point of one WiFi transmission and the starting point of the next WiFi channel sensing period. When one WiFi node is transmitting, the channel is already sensed busy by the other adjacent WiFi nodes, hence the simultaneous LTE-LAA transmission will not cause more impact on the WiFi network and the ongoing WiFi transmission will not be stopped as the WiFi channel sensing procedure has been completed. After one successful transmission, the WiFi AP will conduct another channel sensing procedure. As during the simultaneous LTE-LAA transmission, the beam steering is focused on creating nulls towards the WiFi receiver, hence the WiFi AP may still be able to hear it. And more importantly, the next WiFi transmission may send towards a different WiFi receiver with different direction to the LTE-LAA small cell, which means the previous null steering outcome may not be suitable for the new simultaneous transmission opportunity.

The 802.11ac Physical Layer Convergence Protocol (PLCP) defines a PLCP Protocol Data Unit (PPDU) format, as shown in Figure 4.2. 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 Figure 4.3. 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.

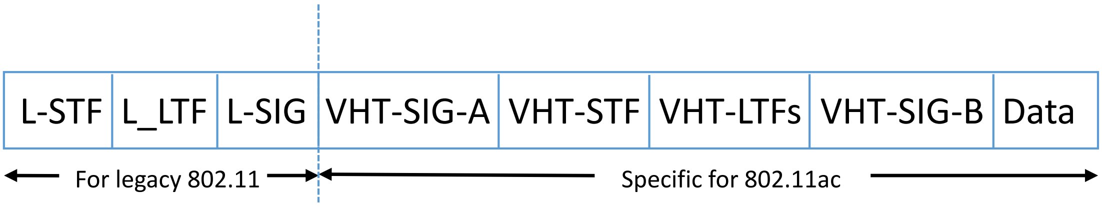


Figure 4.2: 802.11ac PPDU format.

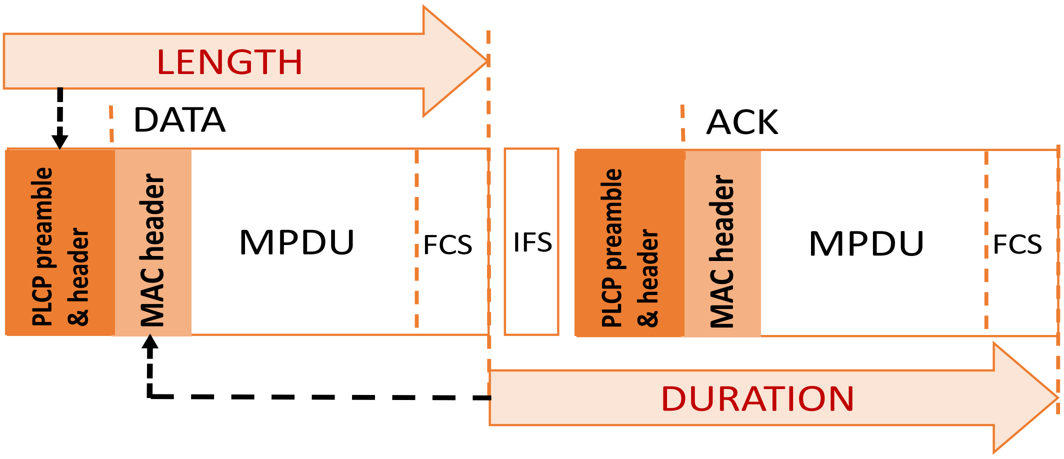


Figure 4.3: The LENGTH and DURATION fields in legacy 802.11.

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 Figure 4.4. In 802.11ac, the LENGTH indicator is moved from the PLCP header, which is transmitted at the lowest possible data rate, to the MPDU delimiter as part of the high data-rate payload [37]. 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.

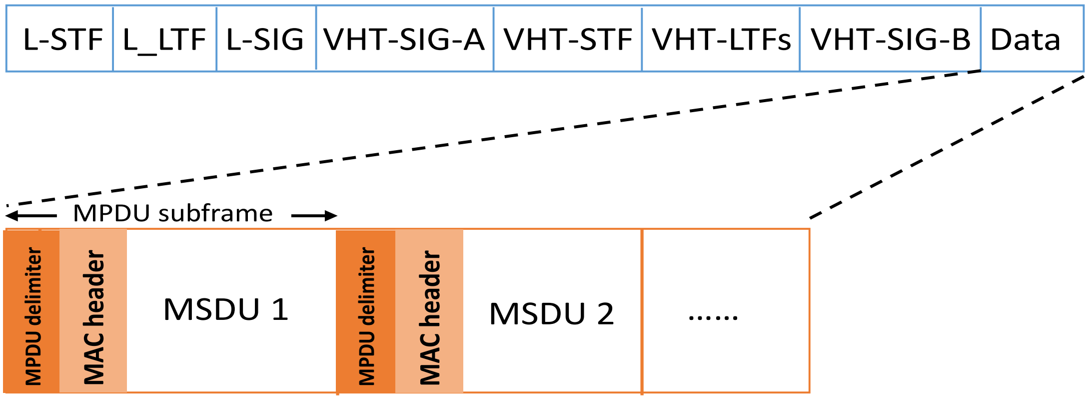


Figure 4.4: 802.11ac A-MPDU aggregation.

4.1.3 WiFi Beamforming

We propose to exploit the combination of Multiple Signal Classification (MuSiC) based Direction of Arrival (DOA) estimation and null beam steering [100] 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. Figure 4.5 depicts the 802.11ac VHT-SIG-A1 field which is the first part of the VHT-IG-A field shown in Figure 4.2. 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) [37]. 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.

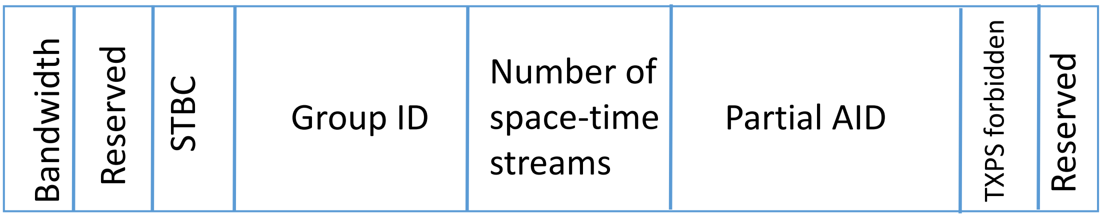


Figure 4.5: 802.11ac VHT-SIG-A1 field.

For WiFi downlink transmission, it is more complicated. Although still optional at WiFi APs, beamforming is enhanced in the 802.11ac standard [37]. 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 Figure 4.6. 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 [100], 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.

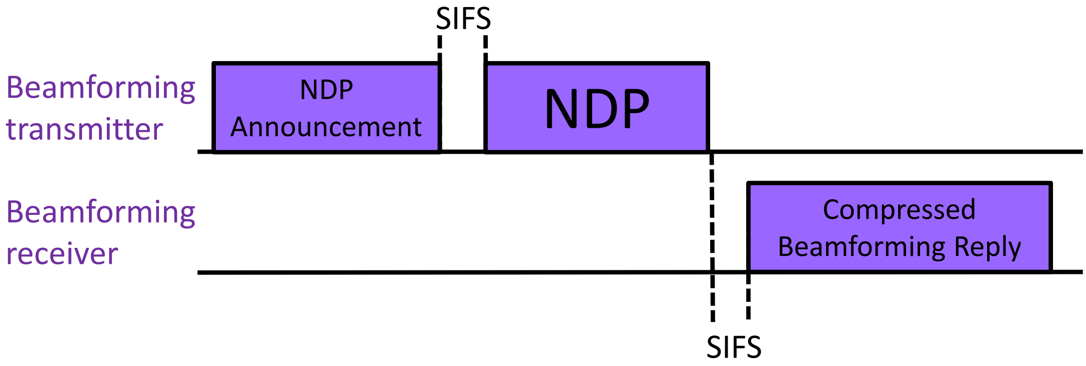


Figure 4.6: 802.11ac single-user channel calibration procedure.

4.1.4 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, *i.e.*, characterizing channel response by multipath propagation with M replicas, we have $\mathbf{h}$ vector containing channel coefficients:

$$\mathbf{h} = [\alpha_1 e^{j\phi_1}, \alpha_2 e^{j\phi_2}, \cdots, \alpha_M e^{j\phi_M}]^T \tag{4.1}$$

where α_i and ϕ_i are independent variables following Rayleigh and uniform distribution, respectively, for $i = 1, 2 \cdots, M$. Arriving at the antennas, the i-th signal replica forms the angle θ_i with array perpendicular. And the delay τ of the i-th signal replica between two consecutive antenna array elements is

$$\tau = \frac{d \sin(\theta_i)}{c} = \frac{\sin(\theta_i)}{2 f_0} \tag{4.2}$$

where c is the speed of light, d is the spacing between any two adjacent antenna elements and f_0 is the operational frequency. Denote T_s as the sampling period, as $\tau \ll T_s$, the arriving signal phase is rotated by $2\pi f_0 \tau$. Hence, the n-th signal sample received at the l-th antenna array element is

$$r_l[n] = \sum_{i=1}^{M} x[n - t_i]\alpha_i e^{j[\phi_i + (l-1)\pi \sin(\theta_i)]} + n_l[n] \tag{4.3}$$

where $x[n]$ denotes the n^{th} signal sample transmitted by the UE, t_i is the propagation delay of the i^{th} signal, $n_l[n]$ represents the additive white Gaussian noise (AWGN). Denote the L-elements steering vector $\mathbf{s}(\theta)$ containing $s_l(\theta) = e^{j\pi(l-1)\sin(\theta)}$, with $l = 1, 2, \cdots, L$.n The steering vector $\mathbf{s}(\theta)$ can be used to steer the antenna radiation pattern on direction θ. We then consider all signal incoming directions and denote with $\mathbf{S} = [\mathbf{s}(\theta_1), \mathbf{s}(\theta_2), \cdots, \mathbf{s}(\theta_M)]$ the steering matrix containing steering vectors of M incoming signal DoAs. The signals arrived at the array elements can be alternatively written in a matrix form as

$$\mathbf{r} = \mathbf{S}\mathrm{diag}(\mathbf{h})\mathbf{x} + \mathbf{n} \tag{4.4}$$

where $\mathbf{x} = [x[n - t_i]]^T$, and diag$(\cdot)$ denotes the diagonal matrix.

To conduct DoA estimation, we adopt the Multiple Signal Classification (MuSiC) method, which is based on eigenvalue decomposition of the array output auto-correlation matrix. The received signal auto-correlation matrix is defined as

$$\begin{aligned}\mathbf{R_r} &\triangleq E[\mathbf{r}\mathbf{r}^H] \\ &= E[\mathbf{S}\,\mathrm{diag}(\mathbf{h})\,\mathbf{x}\mathbf{x}^{\mathrm{H}}\,\mathrm{diag}(\mathbf{h})^{\mathrm{H}}\,\mathbf{S}^{\mathrm{H}}] + E[\mathbf{n}\mathbf{n}^{\mathrm{H}}] \\ &= \mathbf{S}\,\mathbf{P}\,\mathbf{S}^H + {\sigma_n}^2\mathbf{Id}_L = \mathbf{R}_s + {\sigma_n}^2\mathbf{Id}_L\end{aligned} \tag{4.5}$$

where $\mathbf{Id}_L$ is an $L \times L$ dimension identity matrix, $[\cdot]^H$ denotes the hermitian transformation, $\mathbf{P} = E[\mathrm{diag}(\mathbf{h})\,\mathbf{x}\mathbf{x}^{\mathrm{H}}\,\mathrm{diag}(\mathbf{h})^{\mathrm{H}}]$, and ${\sigma_n}^2$ refers to the noise power.

Note that in practice, the auto-correlation matrix is obtained by

$$\mathbf{R_r} = \frac{1}{N}\sum_{n=1}^{N}\mathbf{r}_n\mathbf{r}_n^H \tag{4.6}$$

with N being the number of data snapshots.

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 (4.7) give the estimated DOAs.

$$P_{SM}(\theta) = \frac{1}{\parallel \mathbf{s}^H(\theta)\mathbf{U}_N \parallel} \tag{4.7}$$

where $\mathbf{s}^H(\theta)$ is the steering vector, $\mathbf{U}_N$ denotes noise subspace and is an $L \times (L - M)$ matrix consisting of eigenvectors of correlation matrix corresponding to the $(L - M)$ smallest eigenvalues 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 (4.7), an alternative approach to estimate the DOAs is to compute its logarithm as in (4.8). This forms a more compressed shape and by taking second derivatives, the concavities is confirmed and the DOAs can be estimated.

$$P_{SM_{MOD}}(\theta) = \frac{d^2(\log_{10} P_{SM}(\theta))}{d\theta^2} \tag{4.8}$$

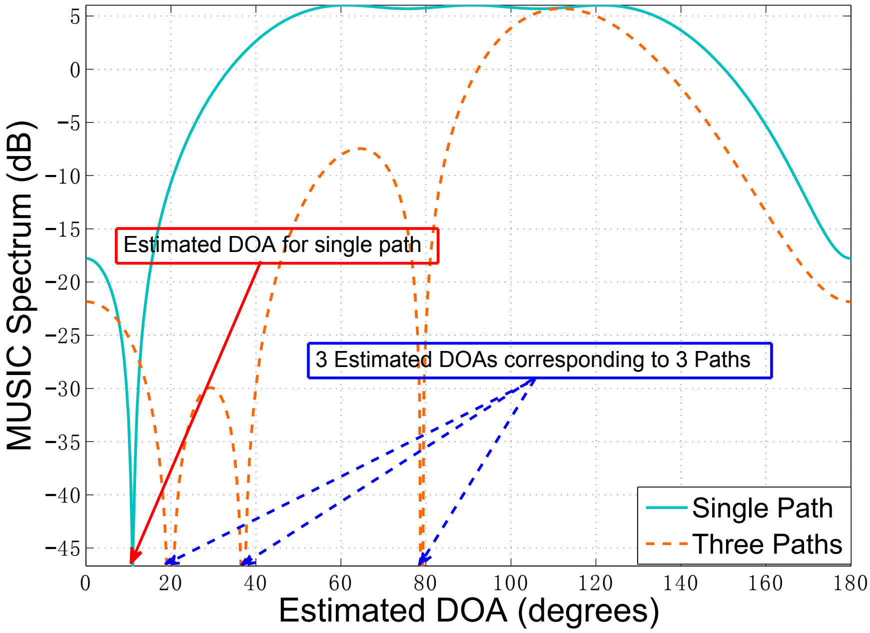


Figure 4.7: DOA estimation in single and multipath scenarios.

4.1.5 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 [101]. 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 M 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 (*i.e.*, $M \leq L-1$).

To generate a pattern with intended null beams, a main steering direction (look direction), denoted by ϕ, is required as input. This look direction is used by the LTE-LAA small cell to convey data to its scheduled users. In order to produce the intended antenna pattern, we need to obtain for each antenna element the weight which is corresponding to the citation and phase shift fed to the antenna element. The weight vector is obtained by imposing the steering vector of the main direction $\mathbf{s}(\phi)$ equal to 1, while the steering vectors of the intended null directions $\mathbf{s}(\theta_1), \mathbf{s}(\theta_2), \cdots, \mathbf{s}(\theta_M)$, equal to 0.

Denote the matrix that contains the steering vectors of interest, *i.e.,* main direction and null directions, as

$$\mathbf{A} \triangleq [\mathbf{s}(\phi), \mathbf{s}(\theta_1), \mathbf{s}(\theta_2) ..., \mathbf{s}(\theta_M)] \tag{4.9}$$

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 weight vector $\mathbf{w}$ is defined as

$$\begin{cases} \mathbf{w}^H = \mathbf{e}^T \mathbf{A}^{-1} & \mathbf{A}\text{ is square matrix} \\ \mathbf{w}^H = \mathbf{e}^T \mathbf{A}^{\mathrm{H}} (\mathbf{A}\mathbf{A}^{\mathrm{H}})^{-1} & \text{Otherwise} \end{cases} \tag{4.10}$$

Upon obtaining the weight vector, given a signal vector $\mathbf{X(t)}$ fed to the antenna array, the output signal is generated by multiplying the input signal with the weight vector:

$$\mathbf{y(t)} = \mathbf{w}^H \cdot \mathbf{X(t)} \tag{4.11}$$

The obtained antenna pattern has selective nulls with the shape similar to notch filter. The number of attainable nulls is related to the number of antenna array elements. With more antenna elements, it is easier to separate the noise subspace correctly.

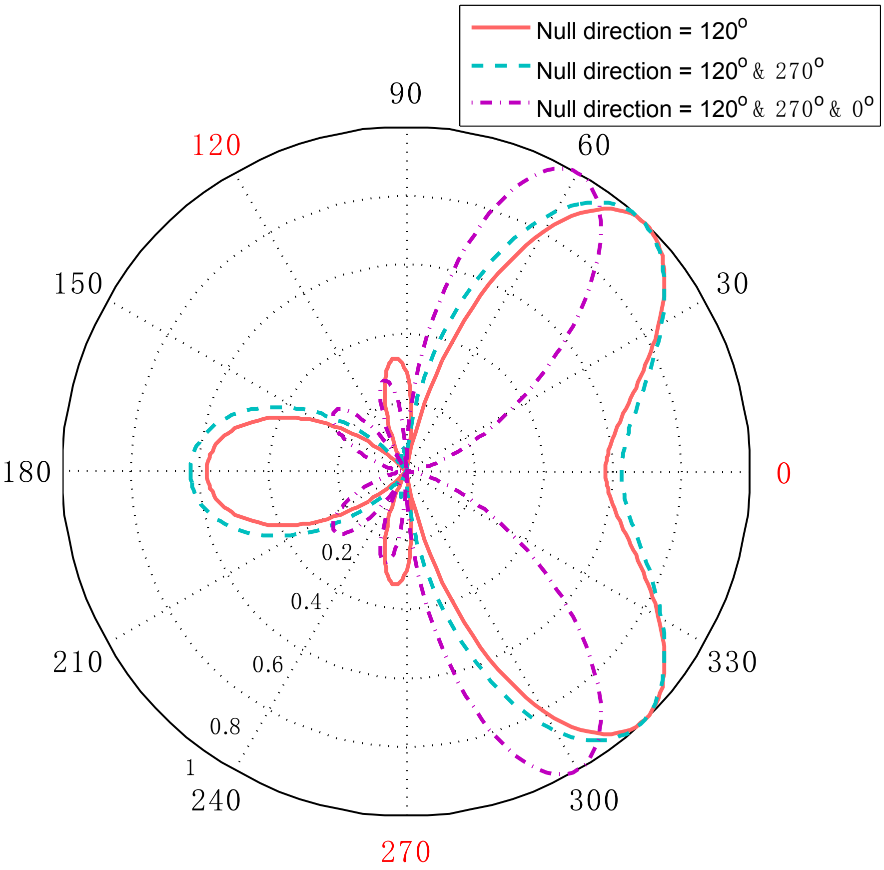


Figure 4.8: Null steering antenna radiation patterns (azimuth cut).

Figure 4.8 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 work.

4.2 Simulation and Performance Evaluation

In this section, we present simulation results and evaluations for the proposed scheme. Results are discussed and compared with the benchmark scheme.

4.2.1 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. Figure 4.9 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 Figure 4.7. Figure 4.9(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 Figure 4.9(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.

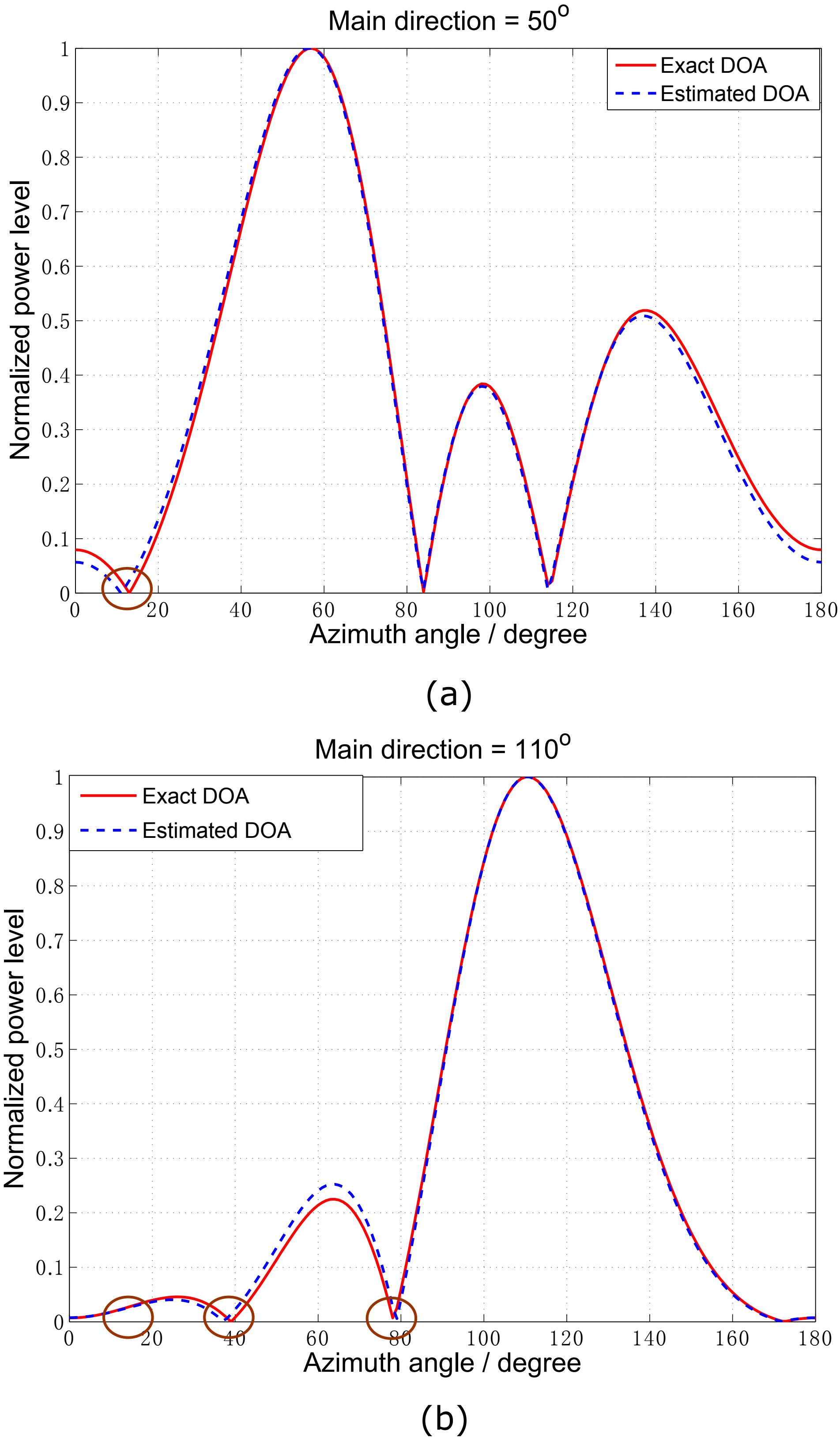


Figure 4.9: Normalized power level after null steering for: (a) single path (LOS) DOA, (b) three paths DOA.

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 [102], 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 [103]. 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 Figure 4.10 are averaged over 10 sets of random DOAs (single path and three paths, respectively) and different distance settings. Figure 4.10 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.

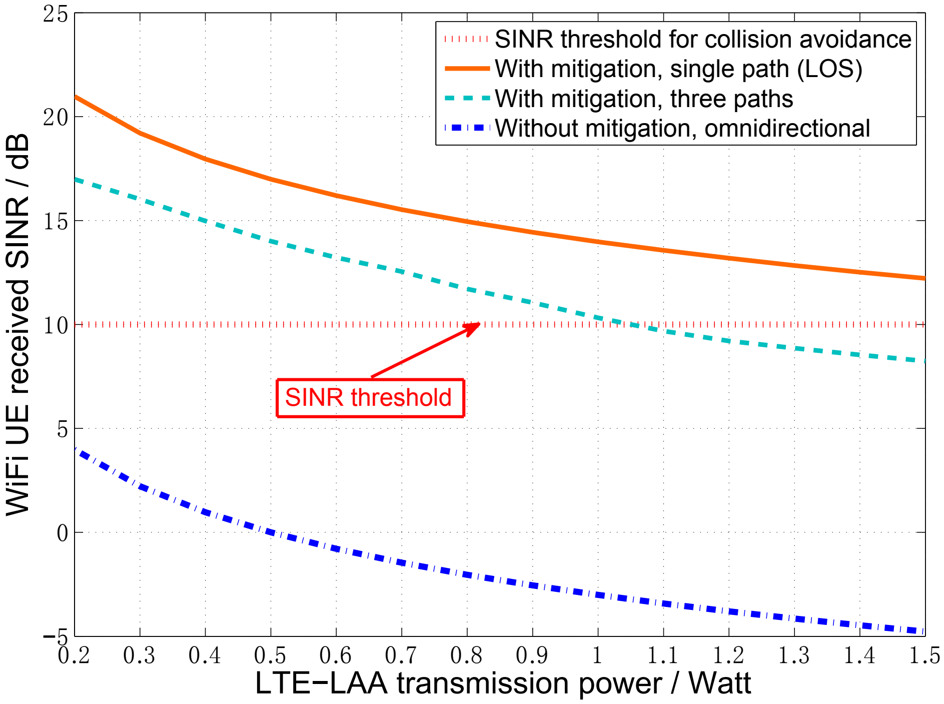


Figure 4.10: WiFi UE received SINR compared to the SINR threshold.

4.2.2 Channel Occupancy Time Ratio

In this subsection, we use the Channel Occupancy Time Ratio (COTR), which is also used in [19, 84], as the criterion to evaluate the performance gain of our proposed simultaneous scheme. The time-sharing channel access coexisting scheme proposed in [19] is considered as the benchmark. The simulation settings are listed in Table 4.1. Figure 4.11 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. Figure 4.11 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 4.1: 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

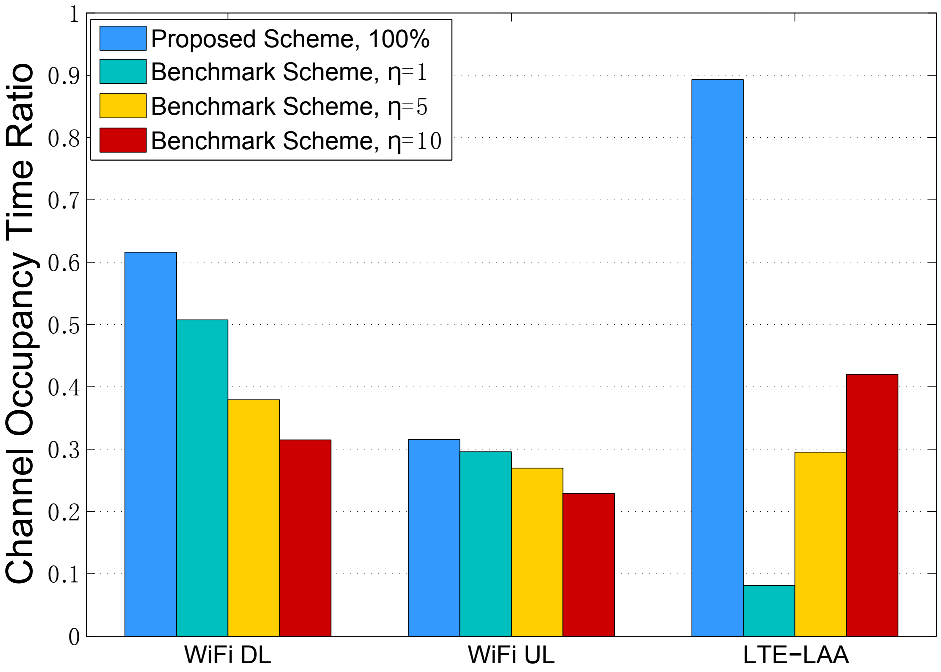


Figure 4.11: Comparison of COTR of proposed scheme and benchmark scheme with different η settings.

Figure 4.11 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. Figure 4.12 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 only consider simul-

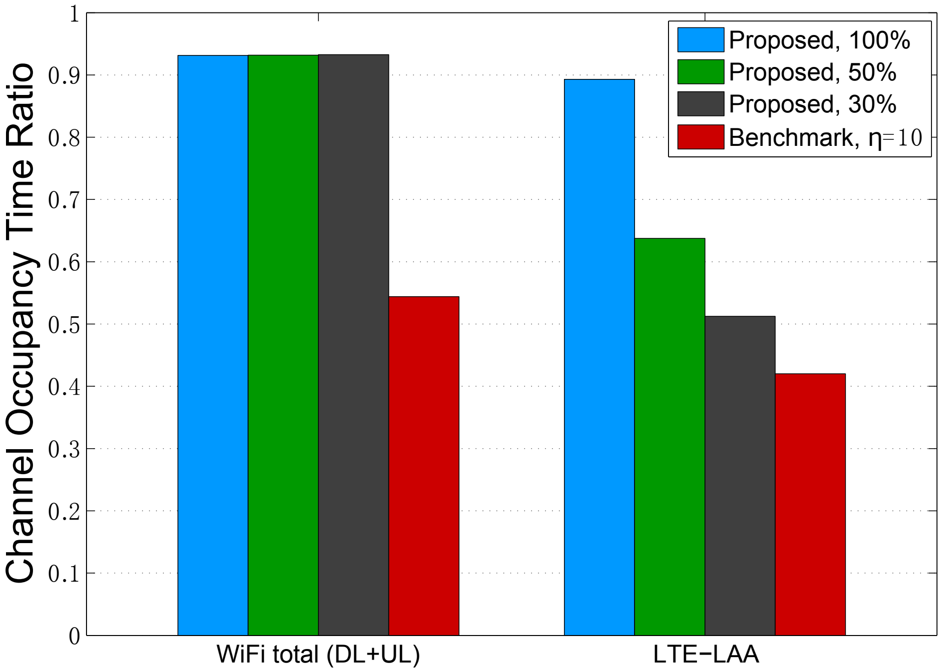


Figure 4.12: Comparison of COTR of proposed scheme with different percentages of safe transmission opportunities.

taneous 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 time division alternate access spectrum sharing schemes to achieve even higher LTE-LAA COTR. However, this comes at the cost of lowering the WiFi COTR.

4.3 Summary

In this chapter, 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. Some ideal assumptions in Chapter 2 are relaxed such as circular LTE-LAA small cell and WiFi AP coverage areas and perfect knowledge of the locations LTE-LAA and WiFi receiving UEs. And the consideration of transmission timing is proved to be crucial for successful simultaneous transmissions. 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.

Chapter 5

Scheme Improvements

From the previous two chapters, possible LTE-LAA simultaneous transmission opportunities with ongoing WiFi transmissions are exploited by looking into the spatial domain. The scheme in Chapter 4 extends our exploitation with the confidence obtained from the first attempt in Chapter 3. Without considering the presence of direct information exchange between LTE-LAA and WiFi systems, the key technologies that enable our co-existence scheme are DoA estimation and null steering. The null steering method used in Chapter 4 is based on the beamforming method in [7]. But there are remaining problems we need to solve in order to create the optimum beam pattern to support LTE-LAA simultaneous transmissions.

The first problem is that, information obtained from DoA estimation may contain errors which lead to imperfect null steering outcome. The proposed co-existence scheme in the last chapter considers no direct communication links between LTE-LAA and WiFi networks. This consideration is based on our intention of bringing as less modifications to the existing WiFi infrastructures as possible. However, we have seen works that suggest direct information exchanges between LTE-LAA and WiFi Self-organizing Network (SON) entities, such as [2]. With carefully designed direct information exchange, our simultaneous transmission scheme can be largely simplified and enhanced.

Another problem is that, as shown in Figure 4.9(a) and Figure 4.9(b), with multiple paths to null, there is a certain level of residual interference power. That means there still exists a probability of collision if the residual LTE-LAA interference power received by the WiFi receiver is high enough to cause WiFi transmission failure. And for creating safe simultaneous transmission opportunities, we try to eliminate such uncontrollable collisions.

In this chapter, we first discuss the simplifications and improvements can be made to our proposed scheme based on the existence of direct information exchange links between LTE-LAA and WiFi networks. Then, in order to obtain perfect and precise nulls towards victim WiFi UEs that may suffer from residual interferences from simultaneous LTE-LAA transmissions, we incorporate Schelkunoff Polynomial (SP) method for null steering into our scheme. Benefits and limitations of SP method are also discussed.

5.1 Scheme Simplification and Improvement with Direct Information Exchange between LTE-LAA and WiFi Networks

In our proposed co-existence mechanism in Chapter 4, there is no direct communication for information exchange needed between the LTE-LAA small cell and the WiFi transmitter, and every operation is done at the LTE-LAA small cell, to avoid more modification efforts for the WiFi standardization bodies. However, the lack of direct communications between these two types of nodes does bring some extent of inconvenience, and gives less of an optimal solution. Also, some of the assumptions can be relaxed and the procedures of our proposed co-existence scheme are going to be greatly simplified if direct communication links are allowed between LTE-LAA and WiFi networks. As reviewed in Chapter 2, information exchange is possible and is discussed in the patent about CSAT [2], as shown in Figure 2.4 in Chapter 2/Section 2.2.2. However, the information exchange process in Figure 2.4 is rather complicated and redundant for the purpose of our co-existence scheme. The reason being, the request-answer process between LTE-LAA and WiFi SONs and the transformations within each SON may take a long time to complete and both the LTE-LAA small cell and the WiFi AP have to allocate time slots for this communication during which period the shared channel needs to be remained idle. This not only causes delay overhead but also reduces the channel utilization efficiency. So we design a simple information exchange process for our co-existence scheme which requires minimal modifications to be made for current WiFi standards.

5.1.1 Information Exchange Design to Support the Proposed Co-existence Scheme

As discussed in previous sections, the key information to capture for the LTE-LAA small cell to successfully obtain simultaneous transmission opportunities with null steering are *transmission timing information* and *direction of the WiFi receiver*. So, these two are the information need to be exchanged, more specifically sent out by transmitting WiFi AP and received by the LTE-LAA small cell. The LTE-LAA does not need to send a request for these information, as with the randomness of WiFi transmissions it is uncertain for the LTE-LAA small cell to decide when to send out the request. That being said, the information exchange signal for LTE-LAA null steering is mono-directional which keeps the overhead minimal. The signal has to be a broadcast so that the LTE-LAA small cell can hear it.

As for the frame placement for this broadcast signal, it needs to be located after the successful WiFi CCA procedure and before the WiFi transmission. As shown in Figure 2.7 in Chapter 2/Section 2.2.3 illustrating WiFi CCA subframe placement, there is a Channel Usage Beacon Signal (CUBS) slot placed after all DCCA slots and before data transmission subframes, as shown in Figure 5.1. This CUBS slot conveys a broadcast beacon signal which indicates the CCA procedure of the WiFi node is successful and reserves the channel. So, this CUBS slot is perfect to convey the two aforementioned key information. We can modify this CUBS slot to also broadcast the transmission LENGTH/DURATION and transmitter/receiver locations information. As the location LTE-LAA small cell is stationary, with the captured WiFi transmitter/receiver location information, it is very easy for the LTE-LAA small cell to deduct the WiFi receiver's direction. It necessary for the modified CUBS to also broadcast the location of the WiFi transmitter, as the transmitter can be either the WiFi AP or a WiFi device. The location of the WiFi AP is stationary, but the WiFi user device may be mobile.

This information exchange design requires minimal modifications at the WiFi side and does not bring extra overhead.

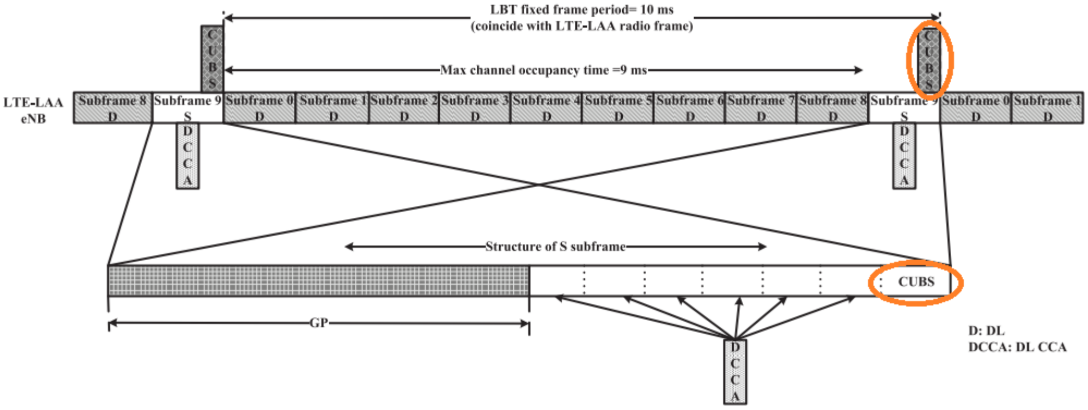


Figure 5.1: Channel Usage Beacon Signal Placement.

5.1.2 Scheme Simplification with Direct Information Exchange

The simplifications can be made to the proposed co-existence scheme are obvious. There is no need for the DoA estimation process with direct information from the WiFi transmitter, and the deduction of the WiFi receiver's location requires almost no effort. And the capture of the transmission timing becomes less complicated. All required information is captured as a bundle, so that the operations need to be done at the LTE-LAA small cell are greatly simplified to reduce computational cost and procedure time consumption.

5.1.3 Scheme Improvement with Direct Information Exchange

With direct information sent from WiFi, it actually improves the proposed co-existence scheme to be more practical to implement. The most obvious one is that, without the direct information exchange, the WiFi transmission has to be beamformed so that the LTE-LAA small cell is able to decode transmission timing and DoA information. With direct WiFi broadcast information, all WiFi transmissions, beamformed or non-beamformed, can be utilized by the LTE-LAA small cell to conduct simultaneous transmission attempts. Hence, the simultaneous transmission opportunities for LTE-LAA are increased. Also, as it takes two steps for the LTE-LAA small cell to capture transmission timing and DoA information without direct information exchange, due to channel uncertainty the chance of failure in capturing both information is higher than that with the bundled direct WiFi broadcast information. More importantly, the WiFi receiver information directly from the WiFi transmitter is more precise than that estimated from the DoA estimation process.

The improvements are not limited with direct LTE-LAA and WiFi information exchange. We only state those for the proposed scheme based on the specific design. We believe, for better co-existence between LTE-LAA and WiFi systems and inter-RAT scheduling, direct information exchange is necessary and will be further investigated in the future.

5.2 Schelkunoff Polynomial Method for Null Steering

The Schelkunoff Polynomial (SP) method was first proposed in [104] for create beam patterns with intended nulls. The antenna pattern can be expressed with the array factor, whose absolute value indicates the magnitude at each angle. With an N-element antenna array, we can place $N-1$ independent nulls in arbitrary directions using the Schelkunoff Polynomial method. The array factor of a uniform linear array (ULA) can be expressed as:

$$AF = \mathbf{w}^H * [\mathbf{s}(\theta)] \tag{5.1}$$

$$\mathbf{s}(\theta,\phi) = [1, e^{j2\pi d_n cos\theta sin\phi}, e^{j2\pi(2d_n)cos\theta sin\phi}, \cdots, e^{j2\pi((N-1)d_n)cos\theta sin\phi}]^T \tag{5.2}$$

where W is the complex weights' vector, $[\cdot]^T$ is the transpose operator, $S(\theta,\phi)$ is the steering vector in the direction of (θ,ϕ), $d_n = d/\lambda$ is the antenna element spacing d normalized to the wavelength λ, and and N is the number of antenna array elements. For a half-wavelength element-spaced array, its array factor on the azimuth plane ($\phi = 0$) can be rewritten as:

$$AF = \sum_{n=0}^{N-1} \mathbf{w}_n e^{-jn\pi cos\theta} \tag{5.3}$$

If we let $z = e^{-j\pi cos\theta}$, then the array factor can be rewritten as a function of z:

$$AF(z) = \sum_{n=0}^{N-1} w_n z^n \tag{5.4}$$

The expression (5.4) above is a polynomial of the complex variable z. A polynomial of order N has N zeros (which maybe complex). The polynomial above is of order $N-1$ and has $N-1$ zeros corresponding to $N-1$ nulls. If the zeros are numbered starting from zero, the zeros will be $0, 1, \cdots, N-2$. Then expression (5.4) can be rewritten as:

$$AF(z) = w_{N-1} \prod_{n=0}^{N-2} (z - z_n) \tag{5.5}$$

We can choose the zeros z_n to represent any null direction we need, and then figure out the corresponding complex weights' vector which should give us the antenna pattern we want. Here is an example for a 4-element array as follows.

As the weights are going to be normalized in the pattern generation process, for simplicity to start with, we can let $w_{N-1} = w_3 = 1$. Then (5.5) becomes:

$$\begin{aligned} AF(z) &= (z - z_0)(z - z_1)(z - z_2) \\ &= z^3 + z^2(-z_0 - z_1 - z_2) + z(z_0 z_1 + z_1 z_2 + z_0 z_2) + (-z_0 z_1 z_2) \end{aligned} \tag{5.6}$$

Comparing (5.4) and (5.6), we can have:

$$\begin{aligned} AF(z) &= z^3 + z^2(-z_0 - z_1 - z_2) + z(z_0 z_1 + z_1 z_2 + z_0 z_2) + (-z_0 z_1 z_2) \\ &= \sum_{n=0}^{N-1} w_n z^n \\ &= w_3 z^3 + w_2 z^2 + w_1 z + w_0 \end{aligned} \tag{5.7}$$

So the weights can be easily found to be:

$$\mathbf{w} = \begin{bmatrix} w_0 \\ w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{bmatrix} -z_0z_1z_2 \\ z_0z_1 + z_1z_2 + z_0z_2 \\ -z_0 - z_1 - z_2 \\ 1 \end{bmatrix} \tag{5.8}$$

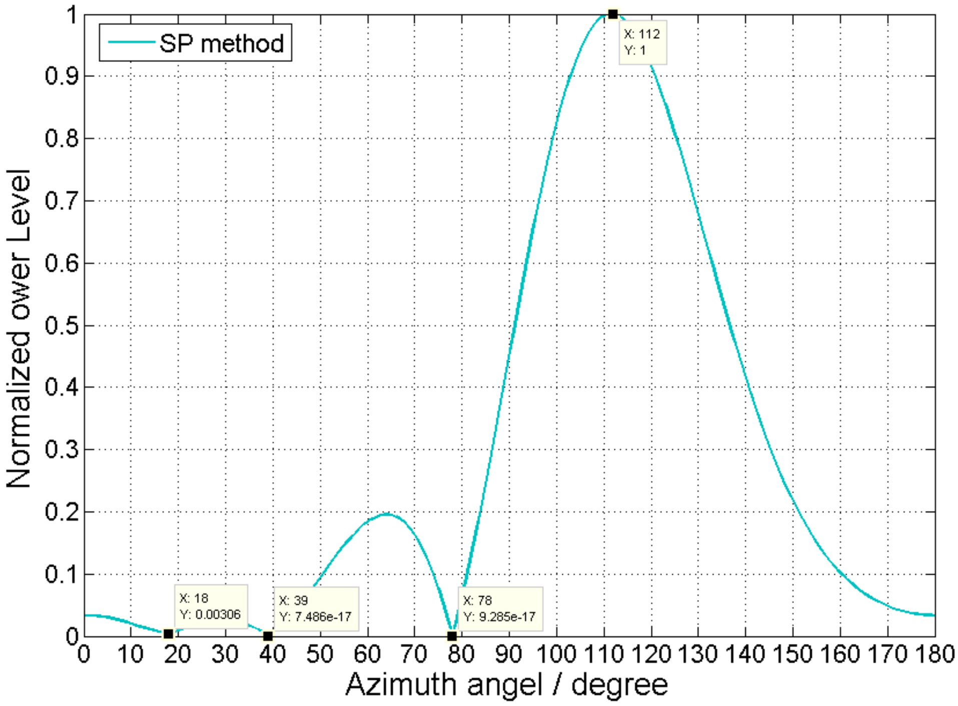


Figure 5.2: Null steering results using the SP method.

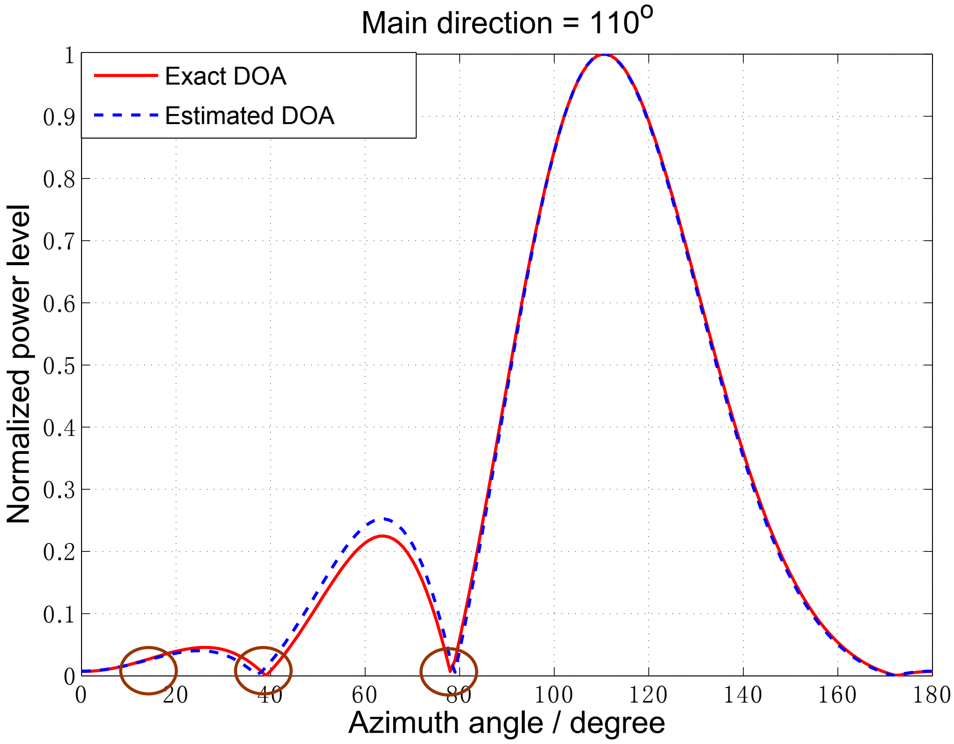


Figure 5.3: Null steering results using method in [7].

Figure 5.2 and Figure 5.3 show the better performance of the Schelkunoff Polynomial (SP) method over the method in [7] we use in Chapter 4 and our paper [85]. Note that, for a N-element array, the degree of freedom is $N-1$, thus with $N-1$ nulls the main direction is fixed. However, with the SP method, we do not need to input the main direction first, instead, we can calculate the main direction based on the null directions.

5.3 Incorporating the SP Method into Our Scheme

First we compare the SP method with the method in [7]. The benefit of the SP method is that it does not require the main direction as input, and the null steering results are also better. With the method in [7], not only we need to input the main direction at first, which can be really tough to determine for the best null steering results especially with $N-1$ nulls, but also the null steering results are not satisfying. The main direction input (110^o)in Figure 5.3 was obtained from multiple simulation trials. And the following figure shows that, with the same main direction input (112^o) calculated with the SP method, the null steering results are even worse. So, the SP method is more effective to serve our purpose.

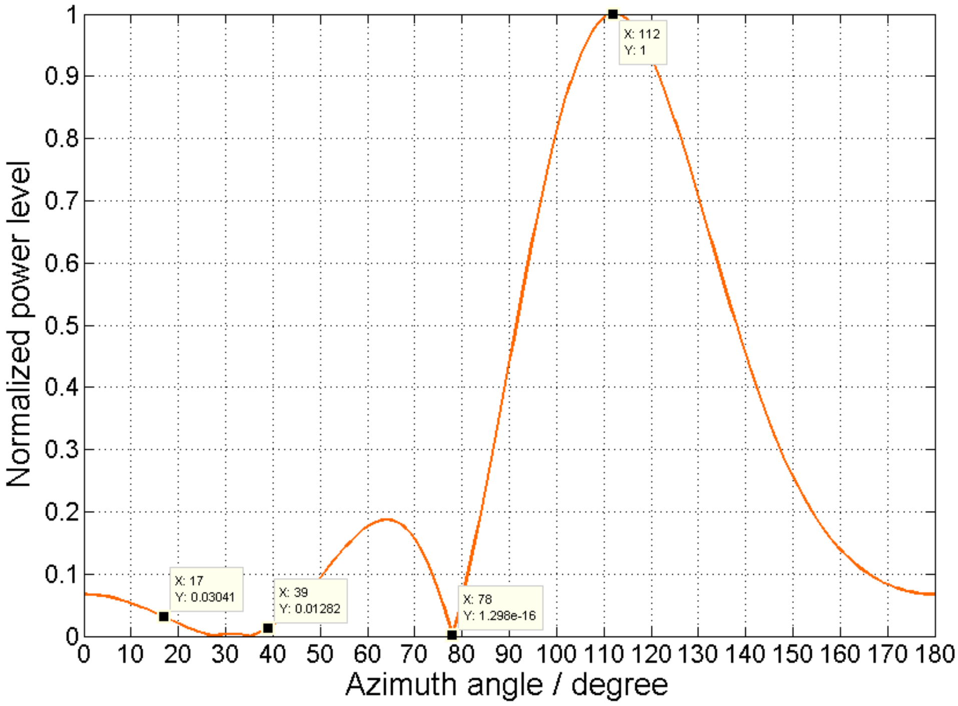


Figure 5.4: Null steering results using method in [7] with the same main direction input calculated with the SP method (112^o).

However, the limitation of the SP method exists. As it does not require the main direction as the input, we do not have direct control on steering the main beam towards our desired direction. This is not an issue if we have to place the maximum $N-1$ nulls, as there is only one fixed main direction. In this case, we just need to check if there exists a LTE-LAA small cell UE within the coverage of the main beam or side lobes that can receive good quality signal ($SINR \geq threshold$). If not, we can either increase the LTE-LAA small cell transmission power (theoretically the nulls are zeros, so increase transmission power will not cause increased power in null directions, but increasing power may cause potential problems to nearby LTE-LAA nodes or other RATs, so not recommended), or we can simply skip this simultaneous transmission opportunity.

However, it might not always be necessary to place the maximum number of nulls. For less than $N-1$ nulls, there are more degrees of freedom to choose the main direction. And with one less null, the method in [7] performs just fine, as shown in Figure 5.5. With the method in [7], we can have direction control of steering the main beam, however, the suitable range is still not determined. In this case, how can we utilize the SP method to steer the main beam more flexibly within a determined suitable range, thus creating more simultaneous transmission opportunities, is the key.

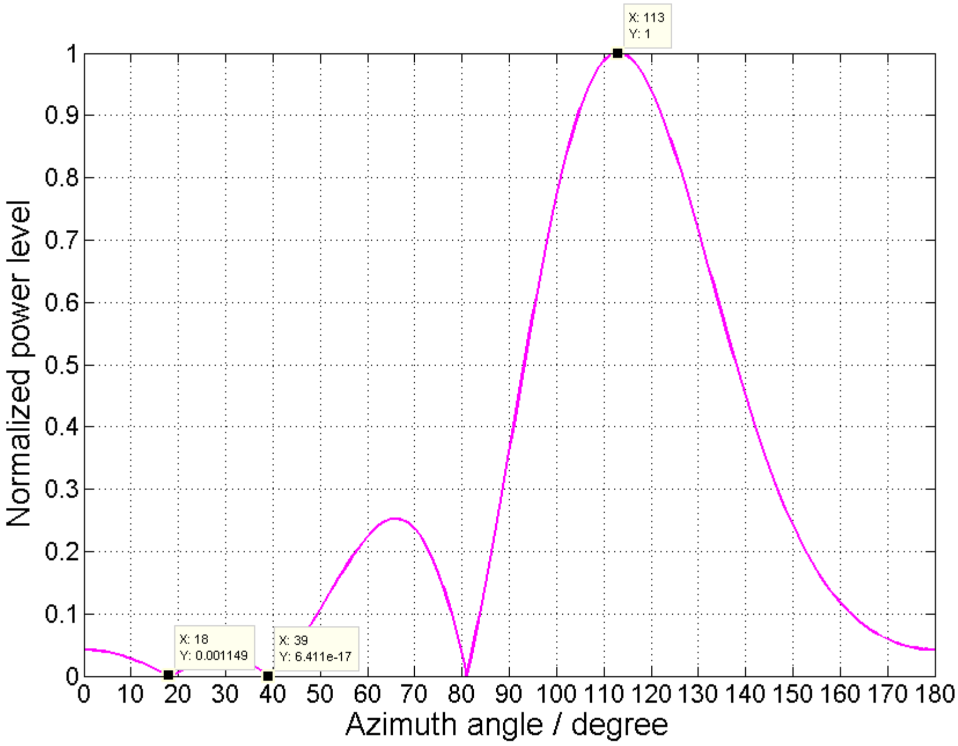


Figure 5.5: Null steering results using method in [7] with 2 intended nulls.

Recall the weights' vector (5.8), if there are only two nulls required, for example only zeros z_0 and z_1 are determined. We now have W being the function of the only variable z_2:

$$\mathbf{w}(z_2) = \begin{bmatrix} w_0 \\ w_1 \\ w_2 \\ w_3 \end{bmatrix} = \begin{bmatrix} -z_0 z_1 \cdot z_2 \\ z_0 z_1 + (z_1 + z_0) \cdot z_2 \\ (-z_0 - z_1) - z_2 \\ 1 \end{bmatrix} \tag{5.9}$$

where $z_2 = e^{-j\pi cos\theta_2}$, $\theta_2 \in (0, \pi)$, $\theta 2 \neq \theta_0$ and $\theta_2 \neq \theta_1$. By choosing different $\theta 2$, we can calculate different W, and with each W we can then determine one fixed main direction. By doing so, we can get a *lookup table* of suitable main direction choices with corresponding z_2. The following Figure 5.6 shows the changing main direction with different null direction settings. For each curve, only one null direction is changed compared to the original setting $(17^o, 39^o, 78^o)$. The main direction shift is sensitive to the choice of null direction setting. For example the red curve, the second null is changed by only one degree, and the main direction is shifted by one degree correspondingly. Theoretically, this *lookup table* is attainable, but the required computational power grows exponentially with larger antenna array.

We have compared and discussed the advantages and disadvantages of both null steering method. The better option is to adopt both null steering method into our simultaneous transmission scheme, as illustrated in Figure 5.7 below. When the number of required null beams is less than the degree of freedom of the antenna array, the LTE-LAA small cell uses the null steering method in [7] and input with the main direction (*i.e.*, the LTE-LAA UE's direction). If the nulls can be maintained, LTE-LAA small cell initiate a simultaneous transmission, otherwise skip this opportunity. And when the number of required nulls is equal to the degree of freedom, the LTE-LAA small cell uses the SP method to conduct null steering. In this case, only there is a scheduled LTE-LAA UE at or close to the determined main direction should the LTE-LAA small cell initiate a simultaneous transmission, otherwise, skip this opportunity.

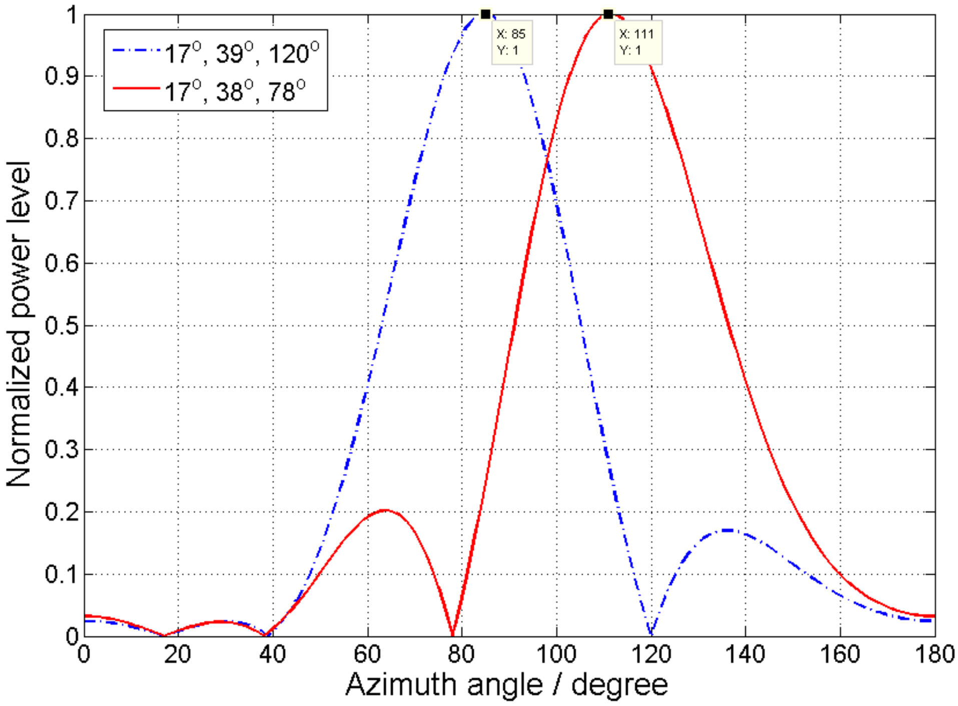


Figure 5.6: Null steering results using the SP method.

5.4 Summary

In this chapter, we give the design of direct information exchange from WiFi to LTE-LAA with minimal WiFi modifications and no extra overhead to support the proposed co-existence scheme. Simplifications and improvements to the scheme based on the designed information exchange are also discussed. With direct information exchange, the DoA estimation procedures is avoided, and aslo estimation error that comes with it. More importantly, the WiFi transmission does not have to be beamformed for the LTE-LAA small cell to capture essential information. Then, to solve the residual interference problem from imperfect null steering method, we incorporate the Schelkunoff Polynomial method to generate null beams towards the intended directions. Benefits and flaws of the SP method are discussed and compared with the original null steering method adopted in Chapter 4. Both null steering methods are adopted in our scheme to utilize their advantages, and the choice of null steering method is according to the number of required nulls. When the number of required null beams is less than the degree of freedom of the antenna array, the LTE-LAA small cell uses the original null steering method and input with the main direction, and when the number of required nulls is equal to the degree of freedom, the LTE-LAA small cell uses the SP method.

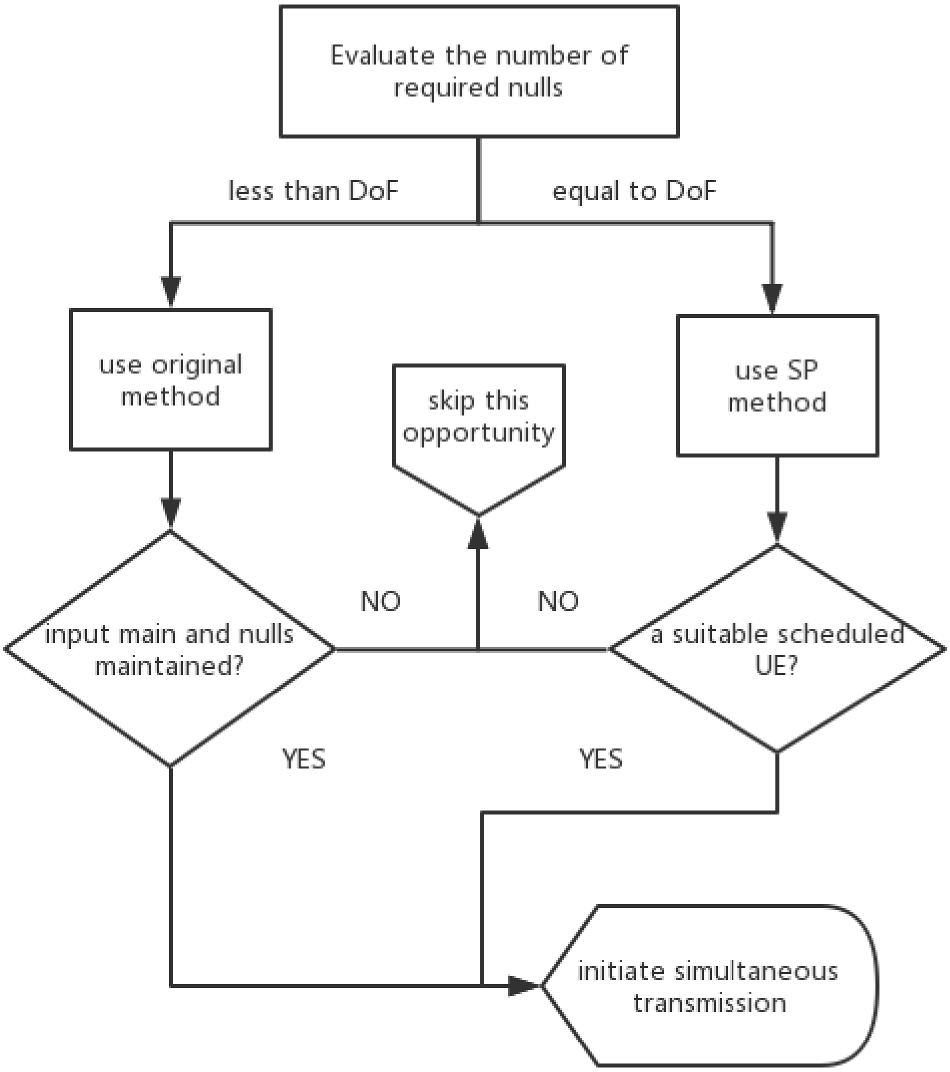


Figure 5.7: Flow chart incorporating both null steering methods.

Chapter 6

Future Work

To further improve the practicality of our proposed simultaneous transmission scheme in real deployment scenarios, there is more effort required about finding the optimum beam pattern. The optimum beam pattern created for each LTE-LAA simultaneous transmission should not only satisfy the null steering requirement, but also be controllable to accommodate the LTE-LAA small cell's own scheduling purpose. That means, the main direction of the synthesized beam pattern considering desired nulls should be able to be controlled to either point at a scheduled LTE-LAA UE or provide acceptable SINR for it. Based on these two considerations, in this chapter we first discuss feasible method that can be adopted into our LTE-LAA simultaneous transmission scheme in the future. Moreover, for LTE-LAA small cell simultaneous transmissions to be fully "invisible" to nearby WiFi devices, we also discuss the scenario where the LTE-LAA small cell places a persistent null towards the WiFi AP in this chapter.

6.1 Adaptive Beamforming in Indoor Multi-path Environment

When LTE-LAA small cells are deployed in indoor environments such as offices, interference mitigation for the victim WiFi UE can be more complicated due to unpredictable propagation environment brought by mutli-path effect. Generating null directions directly pointing at the angle of the victim WiFi UE and look direction directly at the intended LTE-LAA UE cannot guarantee the expectation most of the time, as the signals are bounced and scattered and may arrive at different angles. Thus, for this scenario, we need a more intelligent and dynamic approach to solve this issue. Adaptive beamforming is a closed-loop solution (where channel feedback is required from the receivers), and is able to effectively counteract multi-path effect. It involves three main steps. The first step is channel sounding where the transmitter (Tx) sends a pilot packet on the channel. The second step is channel estimation and feedback where the receiver (Rx) estimates the channel gain and feeds this information back to the transmitter. The third step is beam computation where the transmitter adapts the beam pattern based on the channel feedback from the receiver.

Compared to the outdoor scenario, adaptive beamforming in indoor case requires real-time channel estimations of both the victim WiFi UE link and the target LTE-LAA UE link (a closed-loop operation compared to the outdoor LoS case which is an open-loop operation). For the target LTE-LAA UE, the LTE-LAA small cell either sends a request for aperiodical feedback, or use the channel information from the latest feedback as indoor environment is low mobility and relatively slow time-varying[105] (retain for several tens of seconds or packets). And for the victim WiFi UE, we can reasonably assume symmetric (or reciprocity) channels between itself and the LTE-LAA small cell within a very short time period. With this assumption, the channel coefficient matrix can be estimated from the WiFi NDP channel calibration response signal (details in the ICC paper). However this assumption might be questioned, as in reality the channels are not always symmetrical [106], even though it is commonly assumed.

The modified channel estimation process considering oscillator induced phase offset for MISO and MIMO channels are given in [107]. Now we do not include much detail of the channel estimation procedure and start from the step where the channel coefficient vectors are already obtained, $h = [h_1, \cdots, h_L]^T$ for the target link and $g = [g_1, \cdots, g_L]^T$ for the victim link. For MISO channels, the baseband channel models with beamforming for the target link and the victim link are respectively given by:

$$y_{target} = h^T x + z \tag{6.1}$$

$$y_{victim} = g^T x + z \tag{6.2}$$

where y is the received signal and z is the additive White Gaussian noise. A beamformer is defined as a weight vector w which translates each transmit symbol s to the signal vector $x = ws$ to be transmitted from the L antenna elements. The aim of beamforming in our scheme is to maximize the SINR at the target LTE-LAA UE while at the same time keep the SINR at the victim WiFi UE above a certain threshold TH_{SINR}. The threshold T_{SINR} can then be translated into an interference threshold $TH_{interference}$, and the signal power towards the victim WiFi UE from the LTE-LAA small cell must be kept below $TH_{interference}$. This is equivalent to the following optimization problem:

$$\begin{aligned} & max\|h^T x \ + z|^2 \\ & s.t.\|g^T x + z\|^2 < TH_{interference} \\ & \|w\|^2 = 1 \end{aligned} \tag{6.3}$$

which is then equivalent to

$$\begin{aligned} & max\|h^T w\|^2 \\ & s.t.\|g^T w\|^2 < TH^{'}_{interference} \\ & \|w\|^2 = 1 \end{aligned} \tag{6.4}$$

By solving the above optimization problem, we can determine the optimum weight vector for the beamformer. The more antenna elements, the better signal strength separation between the target link and the victim link. A 12 dB and 22 dB RSSI separation are achieved through experimentations in [105]. And also, when the target link and the victim link have less correlated channels, it is easier to suppress interference to the victim WiFi UE.

The concern now is twofold. The ability of the LTE-LAA smallcell obtaining channel vector from the victim WiFi UE can be questioned. Without direct communication between the LTE-LAA smallcell and the victim UE, the estimation of channel vector of the victim link is not very safe to assume. And, the optimization problem may take a noticeable time to solve. In our scenario, it can be a concern as the simultaneous transmission opportunity is fleeting.

6.2 LTE-LAA Beamforming with Persistent Null Steered towards the WiFi AP

As our proposed simultaneous transmission scheme for LTE-LAA can be seamlessly combined with conventional time sharing co-existence mechanisms, there will still be LTE-LAA SDL transmissions happen within the WiFi idle periods. During these LTE-LAA transmissions, nearby WiFi nodes sense the channel being occupied and enter their back-off "frozen" state. Their back-off counter will continue to count down when the shared channel is sensed clear again. What if we can find a way not to freeze the WiFi back-off counter so that the back-off frozen caused by LTE-LAA transmission occupying the channel can be avoided? As the back-off frozen state actually lengthens the back-off period to a great extent comparing to the "unfrozen" back-off duration depending on the duration of ongoing LTE-LAA SDL transmission, by reducing the probability of triggering back-off "frozen" state the WiFi resource utilization efficiency and delay can be greatly improved.

This objective is not hard to achieve. The concept is that we always place a null towards the WiFi transmitter during its idle period, so that the WiFi transmitter will not hear the LTE-LAA small cell any more, thus back-off "frozen" state triggered by LTE-LAA SDL transmissions can be avoided. By doing so, the deployed LTE-LAA small cell's "invisibility" is improved. With the SP null steering method, it is simple to set the direction of the WiFi transmitter as one of the null inputs. And with GA method, we can set the null direction towards the WiFi transmitter as a constant constraint for beam pattern optimization.

There are some problems regarding this persistent null. For practical implementation, the WiFi transmitter can only be the WiFi AP, as it is stationary. For mobile WiFi devices, their location may be changed over time, and set a persistent null towards any mobile WiFi transmitter can be a waste of degree of freedom when creating the beam pattern. And speak of degree of freedom, another problem arises. That is, adding one persistent null during WiFi idle period decreases the freedom of the LTE-LAA main beam direction, thus limits the beam pattern variety. So, the higher priority is still placing nulls the WiFi receiver's DoA path(s), and if suitable, also place a null towards the WiFi AP.

6.3 Summary

As discussed in this chapter, there are some bottle neck problems need to be solved and improvements we can make to modify our co-existence scheme. An optimal beam pattern to support our co-existence scheme needs to strike a SINR balance between the desired LTE-LAA UE and the victim WiFi receiver. More simulation works need to be done to fully reveal the performance of our proposed scheme. And for the persistent null towards the WiFi AP, it also needs to be verified via simulations.

Chapter 7

Conclusion

In this thesis, by looking at the possibilities in the spatial domain, two LTE-LAA and WiFi co-existence schemes exploiting simultaneous LTE-LAA transmission opportunities with ongoing WiFi transmissions are proposed.

In our first attempt made in Chapter 3, we show the feasibility of such simultaneous transmission opportunities considering AP/UE location diversity and various coverage overlap situations between LTE-LAA small cell and WiFi AP. We conduct derivations of the probability of coverage overlap between LTE-LAA small cells and WiFi APs by modelling the network nodes with a spatial bivariate Poisson point process. Then we propose a coexistence scheme for LTE-LAA small cell and WiFi AP in the unlicensed spectrum with the consideration of various possibilities of coverage overlap between them. The theoretical analysis is conducted in simple scenario where an LTE-LAA small cell overlaps with one WiFi AP within a WiFi network. The analysis can be extended to a more general scenario where an LTE-LAA small cell overlaps with multiple WiFi APs with little effort. However, as the first attempt to exploit simultaneous LTE-LAA and WiFi transmission opportunities in the spatial domain, the proposed scheme in Chapter 3 is rather idealistic with ideal assumptions such as circular LTE-LAA small cell and WiFi AP coverage areas and perfect knowledge of the locations LTE-LAA and WiFi receiving UEs. In real deployment scenarios, these assumptions may cause errors in deciding the cell coverage boundaries and transmission delay due to asynchronous feedback reports. Even with these potential problems, our first attempt shows the possibility of simultaneous transmission opportunities by exploiting the spatial domain, which is novel comparing to existing co-existence designs.

Following the same motivation and with the purpose of relaxing some of the idealistic assumptions, we then further exploit simultaneous LTE-LAA and WiFi transmission opportunities by utilizing multi-antenna beamforming capability in Chapter 4. We manage to relax some of these ideal assumptions in Chapter 3 with the assistance of multi-antenna beamforming technology. We combine DoA estimation with null steering technologies to steer the LTE-LAA simultaneous transmission beam pattern so that nulls are generated towards the victim WiFi receiver 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. From the results, 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.

The co-existence schemes in Chapter 3 and Chapter 4 are proposed based on the fact that there is no direct communication link between LTE-LAA and WiFi networks. We also give the design of direct information exchange from WiFi to LTE-LAA with minimal WiFi modifications and no extra overhead to support the proposed co-existence scheme. Simplifications and improvements to the scheme based on the designed information exchange are also discussed. We believe, for better co-existence between LTE-LAA and WiFi systems and inter-RAT scheduling, direct information exchange is necessary and will be further investigated in the future.

We have thoroughly discussed and compared two different null steering methods. In Chapter 5, we give our proposed procedure to combine the benefits of both methods. To avoid LTE-LAA transmissions being too aggressive in unlicensed spectrum, and with the consideration of power efficiency, we force LTE-LAA small cell to skip simultaneous transmission opportunities when it fails to meet certain conditions.

The main challange identified for future works is to find an effective method to generate the optimal beam pattern that supports our co-existence scheme to strike a SINR balance between the desired LTE-LAA UE and the victim WiFi receiver. Moreover, to better enjoy the benefits of simultaneous transmission opportunities, modified scheduling scheme to support our co-existence mechanism is another aspect to work on. For example, delay-sensitive traffic is not appropriate to be scheduled with simultaneous transmissions as the beamforming optimization process causes delay overhead. And another aspect to consider the priority of UEs except QoS classifications and CSI reports is the beam pattern outcome, meaning that the priorities of those UEs located within the main beam lobe range of the coming simultaneous transmission opportunity are reasonable to be raised higher.

From the discussions and simulation results, we prove that there exist such simultaneous transmission opportunities which do not cause extra impact on WiFi networks, and the channel occupancy time of LTE-LAA can be greatly improved. However, problems and challenges are also identified that require future efforts.

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