COEXISTENCE OF WI-FI AND LAA-LTE IN UNLICENSED SPECTRUM

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Yubing Jian

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COEXISTENCE OF WI-FI AND LAA-LTE IN UNLICENSED SPECTRUM

Approved by:

Professor Raghupathy Sivakumar, Advisor
School of Electrical and Computer Engineering
Georgia Institute of Technology

Professor Gee-Kung Chang
School of Electrical and Computer Engineering
Georgia Institute of Technology

Professor Faramarz Fekri
School of Electrical and Computer Engineering
Georgia Institute of Technology

Date Approved: November 24 2015

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List of Abbreviations

3GPP	3rd Generation Partnership Project
AP	Access Point
ARPANET	Advanced Research Projects Agency Network
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
CCA	Clear Channel Assessment
CCCH	Common Control Channel
CDMA	Code Division Multiple Access
CQI	Channel Quality Indicator
CSI	Channel State Information
CSIRO	Commonwealth Scientific and Industrial Research Organization
CS/CCA	Carrier Sense/Clear Channel Assessment
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
DBA	Dynamic Bandwidth Adaptation
DCCH	Dedicated Control Channel
DCF	Distributed Coordination Function
DFS	Dynamic Frequency Selection
DIFS	Distributed Coordination Function Interframe Space
DL-SCH	Downlink Shared Channel
DTCH	Dedicated Traffic Channel
eNB	Evolved NodeB
E-UTRAN	Evolved Universal Terrestrial Access Network
FCC	Federal Communications Commission
HSPA	High Speed Packet Access

IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
LAA	License Assisted Access
LBT	Listen-Before-Talk
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
MAC	Media Access Control
MCS	Modulation and Coding Scheme
MCCH	Multicast Control Channel
MCH	Multicast Channel
MIMO	Multiple Input Multiple Output
MTCH	Multicast Traffic Channel
NI PXI	National Instruments PCI eXtensions for Instrumentation
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PCCH	Paging Control Channel
PCH	Paging Channel
PCF	Point Coordination Function
PSD	Power Spectral Density
PHY	Physical layer
RACH	Random Access Channel
RLC	Radio Link Control
SC-FDMA	Single-carrier Frequency-Division Multiple Access
SIFS	Short Interframe Space

TBS	Transport Block Size
TD-SCDNA	Time Division Synchronous Code Division Multiple Access
TPC	Transmission Power Control
U-NII	The Unlicensed National Information Infrastructure
UE	User Equipment
UL-SCH	Uplink Shared Channel
WARP	Wireless Open-Access Research Platform
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network

SUMMARY

The global mobile data usage has grown nearly 70% annually in recent years. The huge mobile data usage requirement drives the mobile industry to brace the formidable challenge and invent next-generation mobile technologies. LTE, as a successful cellular technology, has gained tremendous importance in recent years due to its high data-rates and improved data access method for mobile devices. Even though LTE still may not be able to meet the mobile data challenge due to current spectrum scarcity in licensed bands. Thus, cellular network faces serious challenges to provide high performance mobile service to end users in the near future.

In order to sustain the possible increase in mobile capacity demand, utilizing the unlicensed band as a supplementary band for LTE is being considered as a promising solution to expand the capacity of mobile systems. Based on the innovation of carrier aggregation, 3GPP has approved a study item on LAA-LTE, which will assist LTE by offloading mobile data in unlicensed band. Thus, LAA-LTE will operate in the spectrum that overlaps with WiFi, which is another popular unlicensed band technology. The concern is that LAA-LTE and WiFi are unlikely to have mechanisms to directly coordinate with each other, considering different core networks, backhauls and deployment plans of LAA-LTE and WiFi networks.

The overarching goal of my research is to investigate the following two aspects: 1) Investigate how LTE will impact on WiFi using experimental analysis when both of them share the same channel, 2) Develop a possible coexistence algorithm to trigger the coexistence between LAA-LTE and WiFi in unlicensed band.

CHAPTER I

INTRODUCTION

In this chapter, the history of wireless network will be briefly introduced, especially the wireless network history related to cellular and WLAN technologies. Then, the motivation to study the coexistence problem of LAA-LTE (cellular technology) and WiFi (WLAN technology) will be discussed. In the end of this chapter, thesis structure will be given.

1.1 History of Wireless Networks

According to Oxford Advanced American Dictionary, the definition of network is "a number of computers and other devices that are connected together so that equipment and information can be shared" [49]. According to this definition, network is a tool for different individuals to share equipment and information. The concept of network became an important research topic in both of academic and industrial fields in the early 1960s. After putting decade-long research effort on this topic, different versions of networks were developed in the late 1960s, e.g. Merit Network [1], ARPANET and Telenet [2]. However, research areas for networks were still limited to wired networks at that time.

In the early 1970s, ALOHAnet [3] was developed, which was capable of transmitting packets using wireless communication. It was a fascinating and innovative idea at that time. In the late 1970s, the 1G mobile system was developed by NTT and commercialized in Japan [4]. The technology of the 1G mobile systems utilized analogue radio signals for communications in licensed band, and it was purely designed for voice calls. Licensed band means the frequency band that individual companies are required to pay a licensing fee to get the exclusive right to use.

Due to the limited resource and restricted access of licensed band, the FCC defined ISM bands as unlicensed bands and released policies for using ISM bands in 1985, which was reserved for usage related to industrial, scientific and medical fields. Unlicensed bands can be used without paying any licensing fee, but the FCC policies have additional requirements for any technology to operate in unlicensed band, e.g. power limitation. Defining unlicensed bands can be regarded as an important step to boost the development and research of wireless networks and its applications. In 1991, NCR Corporation and AT&T developed a wireless system called WaveLAN, which was a precursor to IEEE 802.11 (IEEE 802.11 is a set of WiFi specifications). Meanwhile, the first 2G mobile system utilizing digital cellular standard, GSM service, was launched in Finland [4]. The 2G mobile system also operated in licensed bands, since licensed bands provided high reliability compared with unlicensed bands. Data service was first introduced in the 2G mobel systems, and peak data rate was limited to less than 0.5Mbps [6]. Applications of the 2G wireless systems were very limited at that time. In the 1990s, research related to wireless networks began to focus on developing wireless network systems, which could be as fast as wired network systems. Many industrial, academic and government organizations put many research efforts to achieve this goal at that time. CSIRO was one of those organizations who made major contributions to wireless technologies, including frequency domain interleaving, modulation and forward error correction, etc. [10]. After the FCC defined and approved U-NII bands as another unlicensed bands (unlicensed bands include ISM and U-NII bands), 802.11a was standardized to operate in 5GHz U-NII bands in 1999, and 802.11b was standardized to operate in 2.4GHz ISM bands in the same year. The peak data rate of 802.11a and 802.11b reached 54Mbps and 11Mbps, respectively. Since then, WiFi and cellular networks began to make a large impact on people's daily lives.

In 2001, NTT DoCoMo launched the first 3G mobile system in Japan, using the WCDMA technology [4]. To support the large amount of users using the 3G mobile systems, several licensed bands were approved for the 3G mobile systems to use, including 806-960 MHz, 1710-2025 MHz, 2110-2200 MHz and 2500-2690 MHz. After a few years, additional 3G mobile systems were developed, such as TD-SCDNA, HSPA+ and CDMA2000. Those 3G mobile systems shared the same core technology called spread spectrum. The peak data rate for 3G systems reached 63Mbps [6]. In 2003, 802.11g was standardized with 54Mbps peak data rate. 802.11g operated in 2.4GHz ISM bands. 802.11g provided higher data rate than 802.11b and better indoor performance than 802.11a.

In 2009, TeliaSonera and NetCom launched the first commercial 4G LTE mobile system in Stockholm and Oslo. OFDMA, SC-FDMA and MIMO were the major innovative technologies that were implemented in 4G mobile systems. The peak data rate for 4G LTE systems reached 300Mbps [6]. Additional licensed bands were approved to be used by 4G mobile systems, such as 703-803MHz and 1427.9-1510.9 [5]. Meanwhile, 802.11n was developed in 2009, with peak data rate reaching 300Mbps [7]. 802.11n provided higher data rate and better coverage area compared with preceding IEEE 802.11 technologies. OFDMA and MIMO were also the major technologies that were implemented in 802.11n. The frequency bands used by 802.11n were 2.4GHz ISM bands and 5GHz U-NII bands.

As the latest 802.11ac was launched in 2014 [8], the theoretical peak data rate for 802.11ac became 867Mbps [9]. Wider RF bandwidth, more MIMO spatial streams and high-density modulation were the major innovative technologies that were implemented in 802.11ac. Since 2.4GHz ISM bands became crowded (with many interference), 802.11ac was designed to only support 5GHz U-NII bands for wireless communications.

Nowadays, IEEE 802.11 family and cellular networks are the most popular wireless technologies. The performance of both cellular and WiFi technologies increased dramatically in the past few decades, since many advanced technologies were developed and implemented in cellular and WiFi network systems. Due to different application requirements of IEEE 802.11 and cellular networks, IEEE 802.11 and cellular networks operate in the unlicensed and licensed band, respectively. Thus, IEEE 802.11 and cellular networks never cooperate with each other in the history [1]. Since WiFi and cellular technologies has much better performance compared with other wireless technologies (e.g. Bluetooth and ZigBee, etc.), it can be easily conjectured that cellular and WiFi will still be the dominant wireless network technologies for people to access internet in the near future.

1.2 Motivation

Innovations in communication technology and densely deployed networks have brought about ubiquitous high-speed broadband access. Such broadband access makes our daily lives increasingly dependent on the Internet for a wide variety of content and services. Internet users constitute over 78% of the population in North America [11], and the mobile service revenue is estimated to become $270 billion in 2016 [12]. The global mobile data usage has grown nearly 70% annually in recent years, and it is expected to increase nearly tenfold between 2014 and 2019 [13]. In order to sustain the possible growth in mobile services, LAA-LTE [13] or LTE-U [14, 15] is emerging as a candidate technology for telecommunication companies to utilize unlicensed spectrum for wireless data traffic offloading. Based on carrier aggregation between licensed and unlicensed bands, LAA-LTE delivers cellular services to mobile users in the 5GHz unlicensed bands. Due to maximum power limitation in unlicensed bands, small cell

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[1] Cognitive radio networks are not considered to cooperate with cellular networks. It is only allowed for cognitive radio users to use licensed bands, if they will not interfere the licensed users. Thus, there are many restrictions for cognitive radio users to use licensed bands

is an ideal application to operate LAA-LTE. Small cell technology is a promising solution to offload cellular traffic, which can improve the local channel capacity in hot spots compared with macro cell [48]. Thus, combining LAA-LTE with small cell can further relieve the burden of overloaded cellular networks.

In reality, telecommunication companies have in the past introduced technologies in the unlicensed band such as carrier WiFi that were integrated with their licensed wireless/wireline infrastructure. Unlike carrier WiFi, which use the same MAC/PHY protocols as other WiFi networks provided by cable companies, LAA-LTE uses the technology based on LTE-A. From the view of telecommunication companies, LAA-LTE supplies a tighter integration with licensed LTE-A as an extension of the 3G/4G/LTE-A network with unified mobility, authentication, security, and management. This allows telecommunication companies to utilize the unlicensed spectrum more efficiently and seamlessly, compared with the integration of carrier WiFi and LTE-A services. Besides, by sharing the same core network, backhaul, and deployment plan, LAA-LTE can co-exist with carrier WiFi as friendly neighbors and even provide a small cell as a service (SCaaS) for cloud mobile network users [15].

Though the coordination between LAA-LTE and carrier WiFi can be foreseen, the cooperation of LAA-LTE and cable-co WiFi is harder to achieve, considering the different MAC implementation discussed in Chapter I, the different core networks, the random user-deployment, and unpredictable performance of WiFi networks. Therefore, coexistence between LAA-LTE and cable-co WiFi networks has been considered, and protection to neighboring cable-co WiFi networks will be provided by the anchoring controlled LAA-LTE network. Since WiFi with DCF MAC mechanism can only access the channel when channel is free and LAA-LTE tries to fully utilize the channel, it can be easily foreseen that as LAA-LTE directly coexists with WiFi, WiFi performance will degrade.

Thus, how cable-co WiFi networks deal with interference from LAA-LTE is an important issue. In order to answer this question, a quantified study of how LAA-LTE and WiFi networks may affect each other in terms of signal quality, coverage range, air-time fairness, and effective throughput is a preliminary step in this work. Based on the detailed study and analysis of the effect of LAA-LTE to WiFi networks, potential issues in the upcoming co-existence scenario can be revealed, and proper policy/mechanism can timely be deployed. The detailed study of the coexistence of LAA-LTE and WiFi networks also can trigger mechanisms of cooperation between LAA-LTE and WiFi networks for co-channel interference.

1.3 Thesis structure

The structure of this thesis is given below:

Chapter II introduces WiFi and LAA-LTE technologies, and also presents related work of coexistence of WiFi and LAA-LTE. In Chapter III, the experimental results and analysis between the coexistence of WiFi and LAA-LTE are presented. Chapter IV presents DUET, which is a coexistence mechanism between LAA-LTE and WiFi. Theoretical and simulation evaluations of DUET are also presented in Chapter IV. Finally, the conclusions of this work are presented in Chapter V.

CHAPTER II

BACKGROUND

In this chapter, we will introduce briefly about the technologies of LAA-LTE and WiFi, especially the MAC layer implementations of LAA-LTE and WiFi. After discussing the different MAC layer implementations, different properties of LAA-LTE and WiFi MAC can be identified, and the coexistence problem between LAA-LTE and WiFi can be clearly revealed. Related work about the coexistence of LAA-LTE and WiFi will be given at the end of this chapter.

2.1 Wireless technologies

In this section, we will briefly introduce LAA-LTE and WiFi technologies, especially the MAC layer implementations of LAA-LTE and WiFi.

2.1.1 WiFi Overview

WiFi is a WLAN technology, which allows devices like smart phones, tablets and computers to be able to:

1. Connect to the internet through a WiFi AP
2. Communicate with another WiFi device

The first function of WiFi allows people to utilize their devices to connect to the internet conveniently, as long as they stay in the transmission range of a WiFi AP. The second function of WiFi provides many potential functionality to further improve the network access methods, e.g. ad hoc network and IoT.

WiFi is designed to operate in unlicensed bands. One of the major reasons is that no licensing fee is required for technologies to operate in unlicensed bands. As WiFi operates in unlicensed bands, collisions between other technologies and WiFi is

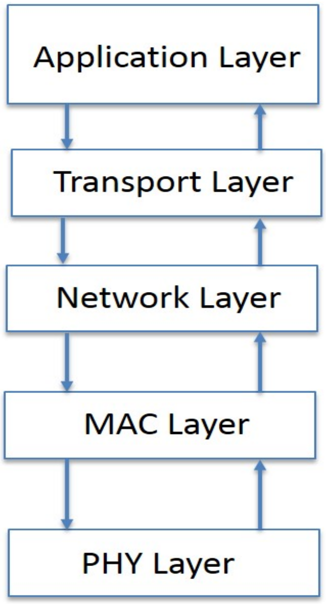


Figure 1: WiFi protocol stack

possible.

Due to high data rate, short round trip delay and low cost of WiFi networks, WiFi has become an extremely popular unlicensed WLAN technology. The popularity of WiFi technology drives people to continually invest in the development of WiFi networks, and more advanced technologies have been implemented in WiFi to further improve the performance of WiFi, e.g., wider RF bandwidth, more MIMO spatial streams and high-density modulation were implemented in 802.11ac, and the theoretical peak data rate of 802.11ac is nearly 3x faster than 802.11n. It can be easily foreseen that WiFi will still be one of the dominant wireless technologies in the near future.

Since we would like to study the coexistence problem of WiFi and LAA-LTE, the MAC layer mechanisms and properties of WiFi are briefly discussed below. The structure of WiFi protocol stacks is presented in *Figure 1* to illustrate the concept of WiFi MAC layer. MAC is the layer between network and PHY layers. The main functionality of Wi-Fi MAC is to control and maintain communications of WiFi networks by coordinating access of different WiFi devices to a shared channel. The

WiFi MAC enables different WiFi devices to share the same channel simultaneously. Moreover, the functionality of WiFi MAC also enables WiFi networks to achieve high performance and fairness at the same time. The standard of 802.11 introduces two types of MAC protocols [16]. Details of these MAC protocols are summarized below:

Distributed DCF mode: DCF is a contention-based distributed mechanism. DCF is based on CSMA/CA mechanism which basically means that WiFi station will only transmit when the channel is sensed idle. Backoff mechanism is implemented in WiFi stations to cooperate with CSMA/CA mechanism. In Backoff mechanism, the WiFi station will generate a random backoff number from $[0, cw]$, where cw is the contention window size. Then the backoff counter will decrease as long as the channel is sensed idle after DIFS. When the backoff counter reaches zero, it triggers the corresponding WiFi station to transmit a packet. After another WiFi station successfully receives the packet, it will transmit an ACK back to the first WiFi station after SIFS. However, it is possible that more than one stations choose the same backoff number. Then different stations will transmit at the same time and lead to a collision. If collision happens, cw will be doubled.

Centralized PCF mode: PCF is a contention free centralized mechanism. In PCF mode, AP is capable of controlling the communication within a WiFi network by polling each WiFi station. AP issues a polling message to one station. After receiving the polling message, the station can transmit data to respond to the AP. After receiving polling feedback from the WiFi station, AP will continue polling another WiFi station. In this case, WiFi stations can only transmit its packets after receiving the polling message from an AP in PCF mode.

Although PCF is a contention free mechanism, the two-way-handshake polling process consumes additional time for each transmission. Besides, if a station does not have any packet to transmit, the station will send a NULL packet to the AP which further decreases the efficiency of the PCF mode. Even worse, as the number of nodes in the network is large, stations need to wait a long time to transmit packets due to the polling process. Furthermore, a point coordinator should be implemented in the AP, in order to enable the PCF mode. On the other hand, although packet collisions can happen in DCF mode, DCF mode is a much more popular MAC mechanism, due to its scalability, simplicity and efficiency. Therefore, this work only studies WiFi with distributed DCF MAC for the coexistence problem.

2.1.2 LAA-LTE Overview

LTE (also called as E-UTRAN [19]) is a mobile communication standard, and it is designed to support the communications between mobile devices and data terminals. Due to its high data rate, convenient connection, high spectral efficiency and flexibility in bandwidth and frequency, LTE rapidly grabbed the market of the mobile networks. Since 2009 to 2015, the number of 4G LTE user increased from 1,000 to around 1,000,000,000 [17], and LTE has become the fastest developing mobile communication system in the history. Release 8 of LTE [18] was the first commercially launched LTE technology. After release 10 of LTE [18] was standardized in 2011, more advanced technologies were implemented in LTE, and LTE-A became the new name of LTE since then. LTE-A was able to deliver much higher performance compared with previous versions of LTE. It is also interesting to notice that LTE (before release 10) actually did not meet the 4G requirements (also called as IMT Advanced which is defined by the ITU). E.g., the peak data rate of LTE does not achieve 1Gb/s according to IMT Advanced requirements. LTE-A was the first mobile communication standard that satisfied all 4G requirements. Thus, to differentiate LTE-A and LTE, ITU defined LTE-A as "True 4G".

Nowadays, LAA-LTE (also called as LTE-U) has gained intensive attention recently from both academic and industrial fields, due to its capability to offload mobile data in unlicensed bands. To simplify notation, we will use LAA to represent

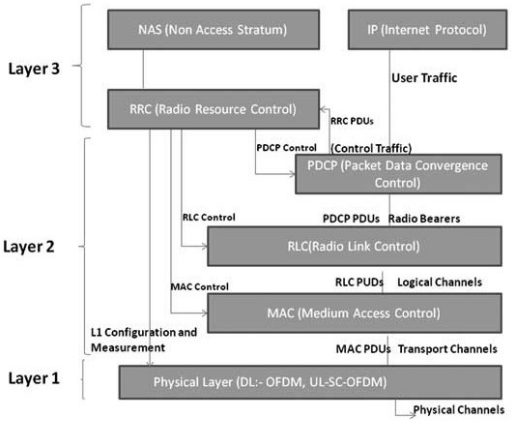


Figure 2: LTE-A protocol stack [19]

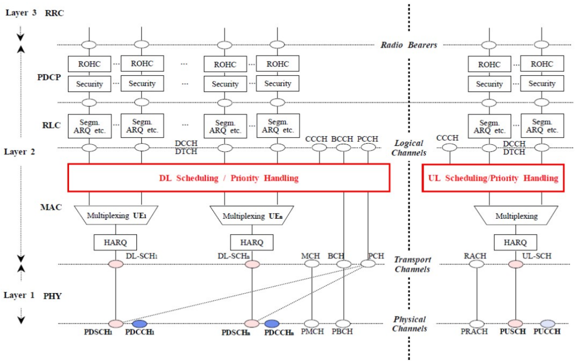


Figure 3: Detailed LTE-A protocol stack [20]

LAA-LTE in the rest of this work. The technology of LAA is designed based on LTE-A. Since the focus of LTE-A is to deliver extremely reliable and high performance service to users, LTE-A service is delivered in licensed bands. As only the licensed LTE-A users can transmit in the licensed bands, there is no interference from any unlicensed users interfering the licensed LTE-A users. The centralized MAC mechanism is implemented in LTE-A to let central controller (eNB) of LTE-A to control every transmission within the network to maximize the channel efficiency.

Since this work studies the coexistence problem of WiFi and LAA, the MAC layer mechanisms and properties of LTE-A will be briefly discussed (LAA MAC will be designed based on LTE-A). To illustrate the concept of LTE-A MAC, the structure of LTE-A from PHY layer (Layer 1) to network layer (Layer 3) is presented in *Figure*

Table 1: Logical channel information

Channel type	Channel name	Channel function
Control channel	BCCH	Broadcast system information in downlink channel
	PCCH	Transfer paging information in downlink channel
	CCCH	Transmit common control information
	DCCH	Transmit dedicated control information
	MCCH*	Transmit multicast control information
Traffic channel	DTCH	Transmit data for one specific user
	MTCH*	Transmit multicast data for several user

***note**: These channel are implemented since release 9 of LTE

2. MAC layer communicates with RLC layer through logical channels, and MAC layer communicates with PHY layer through transport channels. To optimize the channel efficiency, LTE-A defines different types of logical, transport and physical channels. Each logical, transport and physical channel has different functionality, and the explanations for logical channel and transport channels are given in *Table 1* and *Table 2*, respectively. It can be clearly observed that each channel can be used to transfer dedicated information. The mappings between logical channels and transport channels are shown in *Figure 3*.

Uplink and downlink scheduling are two important procedures for centralized LTE-A systems to achieve high spectrum efficiency. UL-SCH carries scheduled uplink transmissions, and DL-SCH conveys scheduled downlink transmissions. Both uplink and downlink transmission are scheduled by eNB. To assign proper resource for each uplink and downlink transmission, eNB of LTE-A can acquire UE side information through dedicated channels. E.g., CSI reporting is an important mechanism in LTE-A, in which UE can report CQI (channel estimation parameter in LTE-A) to eNB through control channels. After eNB receives the CSI report from all UEs, eNB can assign proper frequency and time resource to each UE. Besides, CQI parameter

Table 2: Transport channel information

Channel type	Channel name	Channel function
Downlink channel	BCH	Transmit/Receive information to/from BCCH
	DL-SCH	Transfer downlink data
	PCH	Transmit/Receive information to/from PCCH
	MCH	Transmit/Receive information to/from MCCH
Uplink channel	UL-SCH	Transfer uplink data
	RACH	Transfer initial access information from users

also suggests what modulation and coding rate should be used for the corresponding downlink transmission. By utilizing the uplink and downlink scheduling mechanisms in LTE-A systems, frequency and time resource can be properly managed, and high channel efficiency of LTE-A network can be achieved.

LTE-A traffic is scheduled by central controller, and there is no collision in LTE-A network. WiFi transmission is contention-based, where each transmission generates significant contention overhead. Collisions is also possible in WiFi networks. Thus, in the perspective of channel utilization, LTE-A networks utilize channels much more efficient than WiFi networks. On the other hand, the technology LTE-A is much more complex than technology of WiFi, and it is also much more expensive to deploy compared with WiFi networks. In such case, if LTE-A network coexists with WiFi network without any coexistence algorithm, performance of WiFi network will be significantly reduced. Since LTE-A eNB tries to maximize the channel efficiency of LTE-A network and always transmits, WiFi station needs to hold its transmission until LTE-A network stops transmitting.

2.2 Related work

2.2.1 Offloading cellular data to LAA networks

There are some existing works studying the coexistence of LAA and WiFi networks in very recent years. Through experimental analysis, [22] and [23] show clearly that LTE has significant impact on WiFi performance in different scenarios. In [24]-[26], fairness allocation between LAA and WiFi are studied through theoretical and simulation analysis. In [24]-[25], node-based fairness model is proposed, and Jains fairness index is utilized in [26].

MAC layer coexistence mechanisms between LAA and WiFi are proposed in [27]-[35]. [27]-[29] introduce coexistence algorithm by implementing contention based algorithm in LAA, e.g. Listen-Before-Talk (LBT). However, LBT introduces extra delay due to the contention time overhead, which can lead to inefficient channel usage. [30]-[31] propose channel selection/sensing mechanisms to enable the coexistence of LAA and WiFi. However, if clean channel is absent, LAA has to hold until the channel becomes idle again. In [32], several LAA MAC mechanisms for coexistence of LAA and WiFi networks are proposed. Simulation results show that LAA gains high throughput performance without harming WiFi performance with the proposed MAC mechanism. However, this conclusion only holds when the coexisting channel model can accurately simulate the interfering condition between LAA and WiFi transmissions. In [33], coexistence of LTE-A and WiFi has been studied in the TV White Space band. Simulation results indicate that LTE interference can degrade WiFi throughout significantly even when LTE and WiFi nodes are randomly deployed. In [34], a physical layer framework is presented for the coexistence of LTE and WiFi networks. Simulation results indicate that the proposed framework can protect WiFi performance from severe degradation in the presence of LTE interference. The overhead is that the change of physical layer framework is required. An approach using LTE uplink power control to solve the coexistence issue of LTE and WiFi networks is proposed in [35]. Simulation results show that the proposed power control mechanism can improve the performance of both types of networks. However, power control can not solve coexistence problem of LAA and WiFi in the dense deployment scenario.

2.2.2 Offloading cellular data to WiFi networks

Offloading cellular data to WiFi networks is another method to relief the burden of cellular networks. Systems to offload mobile traffic to WiFi network are introduced in [36]-[39]. In [36], cross-system learning framework is proposed to let WiFi and cellular network transmit simultaneously in multi-mode small cell base stations, and the cell-edge UE throughput can be improved significantly in the proposed framework. [37] proposes an architecture to integrate cellular and WiFi networks to offload mobile data traffic to WiFi networks in city-wide scenarios, and shows that half of mobile data can be offloaded to WiFi network in evaluated scenarios. [38] shows that 65% of total mobile data traffic can be offloaded to WiFi networks and 55% of power saving can be achieved by evaluating 100 iPhone users, and traffic and energy gain savings increase beyond 29% and 20%, if mobile data transfer can be delayed by 1 hour. [39] indicates that offloading cellular traffic through WiFi network can result in non-negligible delay, and an incentive framework for mobile users to leverage the traffic offloading delay tolerance is proposed.

Although above related work shows that it is possible to offload cellular data to WiFi networks, offloading cellular data to WiFi networks can generate extra overhead for the system-level communications between different networks (cellular and WiFi networks), due to the different mobility, authentication, security, and management between LAA and WiFi. Thus, offloading cellular data to WiFi networks can not achieve seamless and efficient communication between LAA and WiFi networks, compared with the integration of cellular and LAA services.

CHAPTER III

COEXISTENCE EVALUATION OF LAA AND WIFI

In this chapter, we study the interference impact of LAA on WiFi under various network conditions using purely experimental analysis in indoor environments. The following three questions are specifically considered in this chapter: (1) What are the implications of LAA usage on WiFi? (2) How should LAA or WiFi be configured for WiFi to be less impacted? (3) How should the LAA MAC protocol be designed to be gracefully co-exist with WiFi? To answer the above questions, we present comprehensive experimental results and give insights based on the results.

Evaluation setup for both LAA and WiFi will be introduced first, including the platforms of LAA and WiFi, scenario, experimental parameters and experimental evaluation methodology. Then, the experimental results and analysis will be discussed. The perspective on LAA MAC designs from the experimental evaluation results will be illustrated in the end of this chapter.

3.1 Experimental Evaluation Setup

3.1.1 Experimental platforms

In this section, we describe the experiment platforms that are used to evaluate the impact of LAA interference on WiFi performance.

1) $LAAplatform$: The NI PXI testing system [40] was used as LAA testbed as shown in *Figure 4*. The standard-based PHY of LTE-A (release 10) is implemented on the NI PXI system. The equipment details are listed in *Table 3*. The system is able to provide many advanced and user-defined operability on signal transmission and reception, such as subcarrier modulation scheme, OFDM parameters, carrier frequency offset, and timing offset estimation.

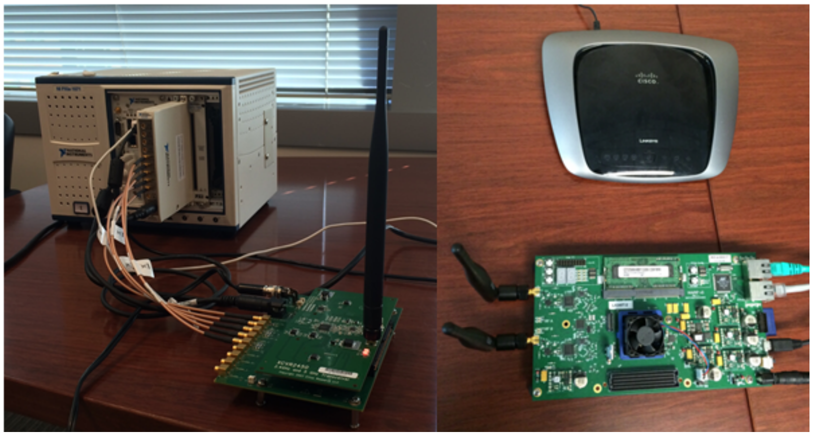


Figure 4: Left: LAA platform; Right: WiFi platform (WARP and Router)

Table 3: Experimental testbed for LAA

Equipment	**Model**	**Specification**
Chassis	PXIe-1071	
Controller (Host)	PXIe-8133RT	1.73GHz Quad Core
FPGA	7965R FlexRIO	Virtex 5; 512MB DRAM; P2P streaming with other modules
Baseband Transceiver	NI-5781	ADC; 14bit DAC; 40 MHz BW
RF Frontend	XCVR 2450	2.4-2.5GHz & 4.9-5.9GHz

2) $WiFiPlatform$: The Cisco-Linksys WRT320N router and Wireless open-Access Research Platform (WARP [41]) v3 are used for the WiFi testbed (see *Figure 4*). The off-the-shelf WiFi routers, supporting both 802.11a and 802.11n in 5GHz band, can represent typical commercial WiFi nodes. On the other hand, since WARP supports modification and monitoring of parameters and functions in both the MAC and PHY layer of WiFi, it provides ways to gain detailed information and evaluation. WARP is capable of communicating with off-the-shelf WiFi nodes, but only 802.11a in 5GHz band is implemented in WARP.

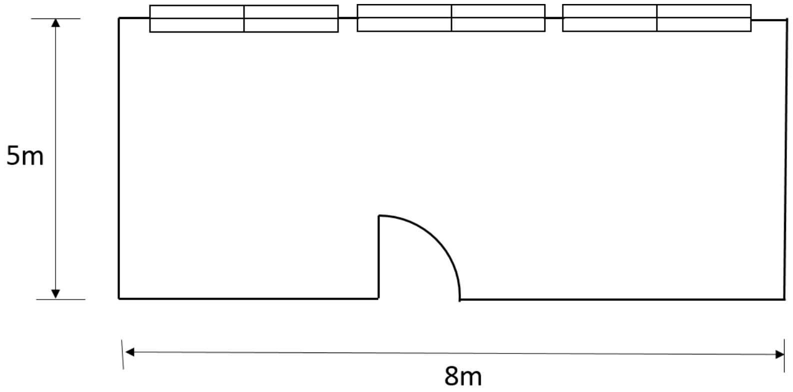


Figure 5: Experimental scenario

3.1.2 Evaluation scenarios and parameters

All experiments are carried out in a typical indoor office with size 8x5x2.7m^3, and the logical graph for the office is shown in *Figure 5*. *Table 4* lists the default settings of LAA and WiFi parameters. We mainly use throughput of WiFi as a metric to evaluate the impact of LAA's interference on WiFi performance. Other metrics, such as number of packets transmitted in the PHY layer, can also be collected using WARP, for cases that requires detailed evaluation. In our experiments, the LAA Tx always transmits, which is similar to the transmission of LTE-A in licensed bands. Also, the LAA transmission PSD is chosen such that LAA interference power is around CCA threshold of WiFi communications.

3.1.3 Evaluation Methodology

We design **five** experiments to explore LAA interference effects on WiFi performance:

1) *LAA bandwidth*: LTE-A supports different bandwidths for DBA and spectral efficiency in license bands. Since LAA uses the same technology as LTE-A, it is possible that LAA also supports different bandwidths. While most WiFi nodes use bandwidth of 20MHz, possible bandwidths of LAA can be 1.4/3/5/10/15/20MHz. The bandwidth change can affect the crosstalk interference. Thus, we would like to explore how LAA interference with different bandwidth affects WiFi performance.

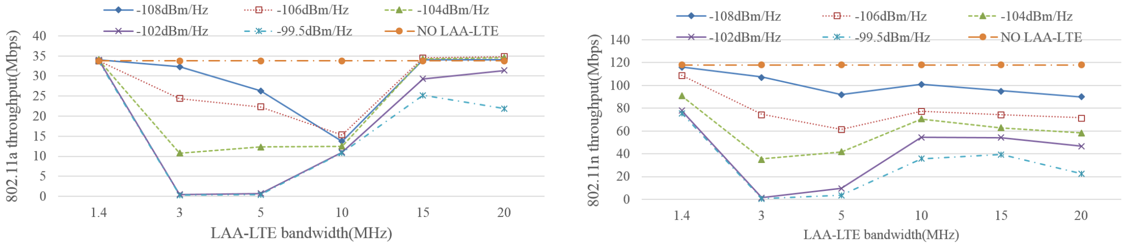
Table 4: Default Experimental Settings

Parameters	**Default settings**
Center frequency	5.18 GHz
WiFi bandwidth	20MHz
WiFi standard	802.11a/n
WiFi ARC	On
WiFi transport protocol	UDP
LAA bandwidth	20MHz
LAA modulation scheme	16-QAM
LAA transmission PSD	-108/-106/-104/-102/-99.5dBm/Hz
Antenna gain	3dBi
Antenna type	Isotropic
Number of Tx/Rx antenna	1/1
Distance between two links	4m
Distance between WiFi Tx/Rx	2m
WiFi throughput testing tool	Iperf

2) *LAA center frequency*: Since LAA supports smaller bandwidth than WiFi, it is possible for an LAA channel to use different center frequencies and overlap with different portion of a WiFi channel. Since different sub-carriers in a WiFi channel has different functionalities (some with pilot signals, and no signal is transmitted on the center carrier [16]), overlapping with different portion of the channel can have different effects. Thus, we would like to know how WiFi performance changes when different portions of its channel overlaps with an LAA channel.

3) *CCA threshold*: In WiFi networks, nodes perform CCA before transmissions. If CCA indicates channel busy, nodes do not transmit. It is possible for LAA interference to trigger channel busy indication during CCA and make WiFi nodes not transmit, which causes throughput degradation. Thus, we would like to explore how LAA interference impacts WiFi CCA under different situations.

4) *WiFi MIMO*: Since MIMO has become an important element in WiFi network, it is important to understand how LAA interference affects MIMO transmissions of WiFi. Since LAA is a competitive technology with relatively large bandwidth and power, the impact can be much severe compared to other unlicensed technologies.



(a) 802.11a throughput vs. LAA bandwidth (b) 802.11n throughput vs. LAA bandwidth

Figure 6: LAA bandwidths impact on WiFi throughput

Thus, we would like to examine the impact of LAA on WiFi with and without MIMO.

5) *Distance and Obstacles*: Distance between two networks changes the impact of interference. In open space, the interference effect decreases as distance increases. However, this property does not always hold in indoor environment due to heavy multipath fading. Other than distance, existence of obstacles can also change the signal propagation and interference condition. Thus, we study the impact of distance and existence of obstacles between LAA and WiFi networks on WiFi performance.

3.2 Evaluation Results and Analysis

In this section, we present results of the five experiments described in Section 3.1.3. The experiment configurations are presented in Section 3.1.2. Each experiment is performed for a duration of 20s and repeated 3 times.

3.2.1 LAA bandwidth

Since it is possible for LAA to support different bandwidths, we investigate the impact of LAA bandwidth on WiFi performance. In this experiment, we set up an LAA transmission using the same center frequency as a WiFi transmission, and change the bandwidth of the LAA transmission. *Figure 6* (a) and (b) show the WiFi throughput vs. LAA bandwidth when the WiFi transmission operates 802.11a and 802.11n respectively with different LAA transmission PSD.

Results in *Figure 6* indicate that different LAA bandwidths have different impacts on WiFi throughput. *Surprisingly, the impact is NOT proportional to LAA bandwidth.* There is almost no impact when the bandwidth is 1.4MHz. When the bandwidth is 15/20MHz, WiFi throughput gradually decreases as LAA transmission PSD increases. When the bandwidth is 3/5/10MHz, the impact is surprisingly much larger than that of 15/20MHz. When the LAA transmission PSD grows to -102dBm/Hz, there is almost no throughput for 3/5MHz.

The unexpected degradation of WiFi throughput when the interfering LAA bandwidth is 3/5/10MHz (especially 3/5MHz) is consistently observed in all the experiments. Later in the 3rd experiment, WiFi CCA, we will be able to see more insights into this phenomenon with help from an instrumented WARP platform.

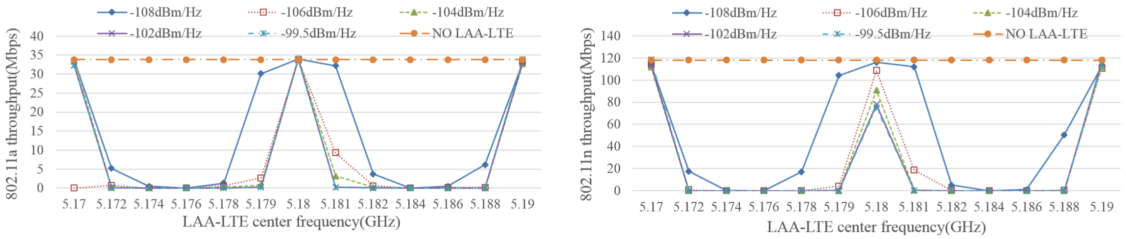
Comparing *Figure 6* (a) and 2(b), one can observe that the throughput of 802.11a and 802.11n have a similar trend, and LAA interference has larger impact on 802.11n. A more detailed evaluation of the difference in impact between 802.11a and 802.11n will be presented later in the 4th experiment, WiFi MIMO.

We conclude results from this experiment with the following insight:

WiFi throughput can be heavily degraded by LAA transmissions with 3/5/10MHz bandwidth (especially 3/5MHz)

3.2.2 LAA center frequency

Since different sub-carriers in a WiFi channel have different functionalities (some with pilot signals, and no signal is transmitted on the center carrier [16]), we investigate the impact of an LAA channel overlapping with different portions of a WiFi channel. In this experiment, we set up an LAA transmission with 1.4MHz (we use the smallest bandwidth for the best resolution) and change its center frequency to overlap with different channel portion of a WiFi transmission. The LAA center frequency is varied



(a) 802.11a throughput vs. LAA center frequency(b) 802.11n throughput vs. LAA center frequency

Figure 7: LAA center frequency impact on WiFi throughput

from 5.17 to 5.19GHz and the WiFi channel is located in 5.17∼5.19GHz. The measured WiFi throughput vs. LAA center frequency is shown in *Figure 7* (a) and (b) when the WiFi transmission operates 802.11a and 802.11n respectively with different LAA transmission PSD.

Results in *Figure 7* indicate that overlapping in different channel portion does have different impact on WiFi throughput. There is almost no impact when the 1.4MHz LAA channel is located in the guard band of the WiFi channel. The impact is much smaller when the LAA channel is located in the center frequency of the WiFi channel, where no WiFi signal is transmitted ([16]), compared to that of other channel portions. The WiFi throughput is almost zero when the LAA channel allocates around middle part of each sideband (5.174∼5.176GHz, and 5.184∼5.186GHz), even when the transmission PSD of LAA is relatively small (-108dBm/Hz).

Again, comparing *Figure 7* (a) and (b), similar trend of the throughput of 802.11a and 802.11n can be observed.

We conclude results from this experiment with the following insight:

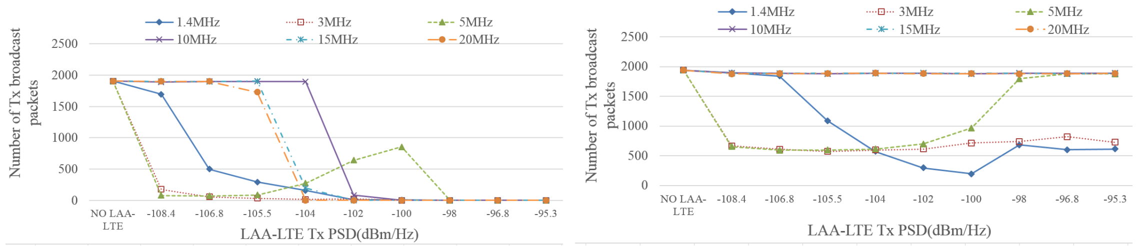
LAA transmissions can have small impact on WiFi throughput when using a 1.4MHz channel with center frequencies located on the guard bands or the center frequencies of WiFi channels.

3.2.3 WiFi CCA

To figure out the cause of throughput degradation in the previous two experiments, we investigate the impact of LAA bandwidth on WiFi CCA. CCA indicates channel busy in the following two conditions: 1) CS/CCA: the PHY layer detects a WiFi preamble successfully; 2) CCA threshold: the PHY layer detects signal power above a predefined CCA threshold [16]. In this experiment, we set up an LAA transmission using the same center frequency as a WiFi transmission, and change the bandwidth of the LAA transmission. Two WARP v3 nodes carry out the WiFi transmissions. In order to prevent the ACK timeout from increasing the backoff CW, we make the WiFi Tx transmit broadcast packets, which does not trigger ACK transmissions. The application layer of the WiFi Tx sends down to the MAC layer 100 broadcast packets per second with packet size of 168Bytes. The total number of packets transmitted by the PHY layer of WiFi vs. LAA transmission PSD is shown in *Figure 8* with different LAA bandwidth. *Figure 8* (a), (b), and (c) shows the results when WiFi CCA works normally, when the CCA threshold (-62dBm) is disabled (only CS/CCA is functioning), and when CCA is totally disabled respectively.

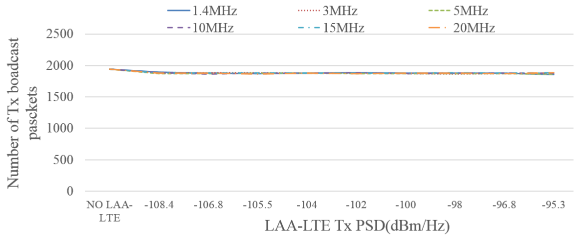
Results in *Figure 8* (a) indicate that different LAA bandwidths have different impacts on WiFi CCA. The impact is severe when LAA bandwidth is small, such as 1.4/3/5MHz. This indicates that the LAA interference impact on WiFi CCA is an essential cause of the throughput degradation in previous experiments.

Comparing *Figure 8* (a) and (b), one can clearly observe that the LAA interference impacts on WiFi CS/CCA. Theoretically, LAA interference should not trigger channel busy indication when only CS/CCA is functioning. In *Figure 8* (b), when the LAA bandwidth is 10/15/20MHz, the channel busy indication is not triggered, and the number of transmission keeps the same; we can infer that the decrease in *Figure 8* (a) when the LAA Tx PSD is around -103dBm/Hz is caused by CCA threshold. However, surprisingly, the number of transmitted packets decreases severely



(a) Number of transmitted broadcast packets vs. LAA Tx PSD (CCA works normally)

(b) Number of transmitted broadcast packets vs. LAA Tx PSD (Only CS/CCA is functioning)



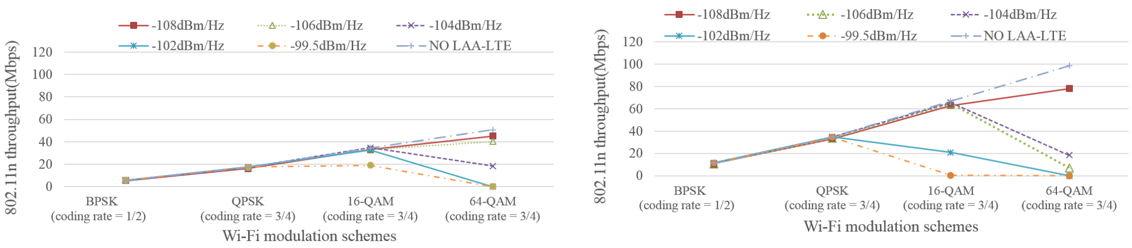
(c) Number of transmitted broadcast packet vs. LAA Tx PSD when CCA is totally disabled

Figure 8: LAA impact on WiFi CCA

when the LAA bandwidth is 1.4/3/5MHz in *Figure 8* (b). When the bandwidth is 5MHz, this anomalous condition occurs only when the LAA Tx PSD is smaller than -98dBm/Hz; and we can infer that the second decrease of 5MHz bandwidth in *Figure 8* (a) around -98dBm/Hz is due to CCA threshold. The anomalous situation when the LAA bandwidth is 1.4/3/5MHz indicates that LAA can trigger CS/CCA of WiFi and cause throughput degradation. However, since WARP implements cross-correlation in CS/CCA for preamble detection, the probability of false alarm is expected to be very small. Currently, we cannot explain this specific anomaly and our ongoing work is exploring potential reasons.

In *Figure 8* (c), when CCA is totally disabled, LAA interference cannot impact the transmission of WiFi, and thus the number of transmitted packets remains the same. Comparing *Figure 8* (b) and (c), we can further confirm that the impact on the number of transmitted packets in *Figure 8* (b) is caused by CS/CCA.

We conclude results from this experiment with the following insight:



(a) 802.11n throughput vs. MCSs without MIMO (b) 802.11n throughput vs. MCSs with MIMO

Figure 9: LAA impact on WiFi MIMO

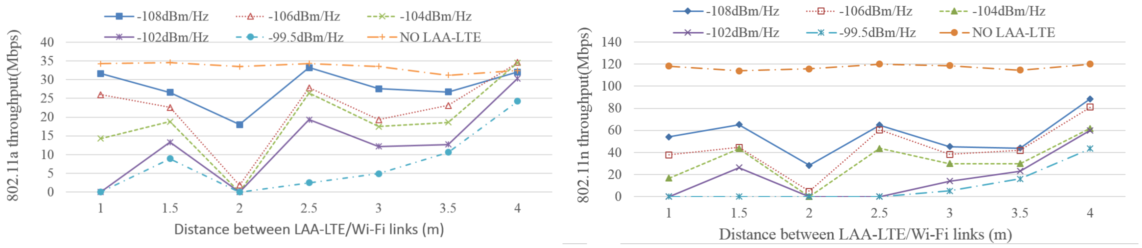
LAA transmissions with 1.4/3/5MHz bandwidth can trigger WiFi CS/CCA and thus heavily impact WiFi performance.

3.2.4 WiFi MIMO

Since MIMO has become an essential element of WiFi standards, we examine the impact of LAA interference on MIMO transmissions of WiFi nodes. In this experiment, Cisco-Linksys WRT320N routers are used as WiFi nodes. We set up a LAA transmission using the same center frequency and bandwidth as a WiFi transmission, and change the MCSs of the WiFi transmission. *Figure 9* (a) and (b) shows WiFi throughput vs. WiFi MCSs when the WiFi transmission operates without and with MIMO respectively with different LAA transmission PSD.

As shown in *Figure 9* (a) and (b), WiFi throughput degrades faster for higher modulation rates as the LAA interference power increases. This indicates that higher modulation rates are more sensitive to interference.

Comparing the results in *Figure 9* (a) and (b), one can observe that 802.11n throughput with MIMO is even lower than the throughput without MIMO when the LAA interference power is high and the modulation rate is high. This implies that MIMO is more vulnerable to interference, and may degrade the performance of WiFi when interference is strong. Although this throughput degradation can also be



(a) 802.11a throughput vs. distance

(b) 802.11n throughput vs. distance

Figure 10: Impact of distance between LAA and WiFi

caused by other unlicensed wireless transmission (e.g. 802.15), LAA has relatively large bandwidth and transmission power, which makes it easier to cause severe impact to MIMO transmissions of WiFi.

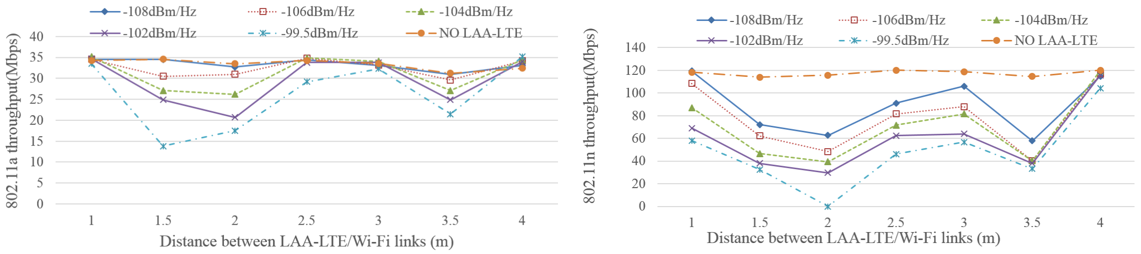
We conclude results from this experiment with the following insight:

> *WiFi with MIMO can perform worse than WiFi without MIMO when LAA interference is strong.*

3.2.5 Distance and Obstacles

Distance and obstacles between two networks changes the impact of interference. In this experiment, we set up an LAA transmission using the same center frequency and bandwidth as a WiFi transmission, and move the WiFi link to change the distance between the LAA and the WiFi link. The distance is varied between 1m to 4m in step of 0.5m. *Figure 10* (a) and (b) shows the WiFi throughput vs. distance for 802.11a and 802.11n respectively. To test the effect of obstacles, a 1.07x0.57x1.04m^3 metal desk is placed in the LOS of the 2 links. The WiFi throughput with the obstacle vs. distance is shown in *Figure 11* (a) and (b) for 802.11a and 802.11n respectively.

As shown in *Figure 10* and *Figure 11*, WiFi throughput is not inversely proportional to the distance between the LAA and the WiFi link. This is due to heavy multipath fading in indoor environment. Even when there is no interference from



(a) 802.11a throughput vs. distance with obstacle(b) 802.11n throughput vs. distance with obstacle

Figure 11: Impact of a obstacle between LAA and WiFi

LAA, WiFi throughput slightly changes with distance due to different multipath condition in different location.

Comparing *Figure 10* (a) and *Figure 11* (a) or *Figure 10* (b) and *Figure 11* (b) respectively, one can observe that as LOS between LAA and WiFi is blocked by obstacles, throughput of WiFi increases.

We conclude results from this experiment with the following insight:

Increasing distance between LAA and WiFi links does not necessarily decrease the impact of interference in indoor environment. On the other hand, blocking LOS between LAA and WiFi links can effectively help decrease the impact of interference.

3.3 Perspectives on LAA MAC design

Since the MAC protocol for LAA is still under development, we present below a few perspectives based on our experimental results that could guide the design of the MAC protocol: 1) In the *LAA bandwidth* experiment, we concluded that LAA with smaller bandwidths can cause severe performance degradation of Wi-Fi. Special care is thus required when simulating the coexisting channel model and designing mechanisms for channel/bandwidth selection. 2) As shown in the *LAA center frequency* experiment, LAA with a 1.4MHz bandwidth does not have a big impact on Wi-Fi transmissions when the center frequency is set to the center or guard bands of Wi-Fi channels. This observation can be utilized for the design of coexisting mechanisms. 3) Indicated by the *Wi-Fi CCA* experiment, Wi-Fi nodes may interpret LAA signals as Wi-Fi signals and become too conservative when contending for transmission. When designing LAA MAC, this situation needs to be considered, so that LAA and Wi-Fi networks can fairly share the unlicensed band.

CHAPTER IV

COEXISTENCE MECHANISM OF LAA AND WIFI

LAA has gained intensive attention recently from both academic and industrial fields, due to its capability to offload mobile data to unlicensed bands. To let LAA offload data to unlicensed bands, LAA should be able to coexist with WiFi, which is another popular technology in unlicensed bands. Because of different core networks, backhauls and deployment plans of LAA-LTE and WiFi systems, they are unlikely to coexist with each other. Within this broad paradigm, we present DUET in this chapter. DUET is a MAC layer mechanism, which can enable the coexistence of LAA and WiFi systems efficiently and fairly with the following properties: (1) no WiFi framework change requirement, (2) work conservation within static and dynamic load scenarios, (3) robustness to partially observed network.

In this chapter, we will restate the coexistence problem between LAA and WiFi in a more general way. Coexistence model and fairness model are defined for the coexistence between LAA and WiFi. Based on the coexistence and fairness model, we present DUET algorithm in fully and partially connected scenarios with static and dynamic load for LAA and WiFi. Then, the NS-3 [46] simulation results for the coexistence of LAA and WiFi will be presented in aforementioned scenarios. Finally, the issues and future work for DUET will be discussed.

4.1 Background and Problem Restatement

In this Section, we restate the coexistence problem of LAA and WiFi in a more general way. To study the coexistence problem of LAA and WiFi, we first define the coexistence and fairness model.

4.1.1 Network with centralized and distributed MAC

For networks with centralized MAC (e.g. LTE/LAA), a central controller assigns the time and frequency resource for each station to transmit packet. Since the central controller has the control over every transmission within the network, maximal channel efficiency can be achieved by assigning proper resource to each station. In networks with distributed MAC (e.g. WiFi), each station transmits packets based on its own mechanism and information. Thus, the traffic pattern is unpredictable and uncontrollable. Also, LBT is implemented in WiFi to sense the channel before transmission. If channel is sensed busy, transmission will be held back until the channel becomes idle.

In this case, if LAA and WiFi coexist without any coexistence algorithm, throughput of WiFi network will be significantly reduced. This phenomenon can be observed in Sec V. Since LAA central controller tries to maximize the channel efficiency of LAA network and always transmit, WiFi nodes needs to hold its transmission until LAA network stops transmitting. Besides, LAA and WiFi packets can also collide. Therefore, a coexistence algorithm is required to achieve good channel efficiency and fair resource allocation between LAA and WiFi.

4.1.2 Coexistence model

To study the coexistence problem of LAA and WiFi, the coexistence model is introduced first. Consider the scenario as shown in *Figure 12*, with one LAA small cell, N_{laa} UEs and N_{wifi} wifi nodes. LAA UEs are in the transmission range of LAA small cell. We simply consider a fully connected WiFi network. Since we handle coexistence problem between LAA and WiFi, the WiFi hidden terminal problem is beyond the scope of DUET. There are existing work [42]-[44] solving the hidden terminal problem in WiFi networks. The connectivity between each LAA UE i and WiFi node j is represented by connectivity matrix M,

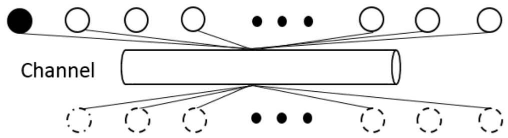


Figure 12: Coexistence model between LAA and WiFi, where black, white and dotted white node represents LAA small cell, LAA UE and WiFi node, respectively

$$M = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & x_{m3} & \dots & x_{mn} \end{bmatrix}$$

where $x_{i,j}$ is defined as below:

$$x_{ij} = \begin{cases} 1 & \text{if LAA UE } i \text{ can hear WiFi node } j \\ 0 & \text{if LAA UE } i \text{ can't hear WiFi node } j \end{cases}$$

To evaluate coexistence mechanism of LAA and WiFi, fairness is an important metric. Without defining fairness metric between LAA and WiFi, LAA or WiFi can selfishly grab more resource for its own transmission without harming the overall network performance.

4.1.3 Fairness model

In this section, we introduce two well-known fairness models viz proportional and max-min fairness models in LAA and WiFi coexistent network. Fairness model with different granularity can be applied to heterogeneous wireless network coexistence. E.g. technology, network, node and link wide. We utilize link wide fairness model, since link represents the basic communication elements in a network.

4.1.3.1 Proportional fairness

The fundamental objective of this fairness model is to allocate the same time resource to each LAA and WiFi link. For the time usage of WiFi link, we consider the WiFi airtime, including successful transmission, contention time (e.g. DIFS, SIFS and backoff time), collisions and transmission delay. Although contention time and collisions cause extra overhead to the time usage of WiFi network, it is still necessary for WiFi network to operate regularly. Link wide proportional fairness is reached when the $LAA_{proportional}$ (average airtime of LAA network) and $WiFi_{proportional}$ (average airtime of WiFi network) is equal:

$$WiFi_{proportional} = LAA_{proportional} \tag{1}$$

The average airtime of WiFi network is defined as:

$$WiFi_{proportional} = \frac{C_{wifi}}{L_{wifi}} \tag{2}$$

The average airtime of LAA network is:

$$LAA_{proportional} = \frac{C_{laa}}{L_{laa}} \tag{3}$$

Here L_{laa} and L_{wifi} represent the number of links in the LAA downlink transmission and the number of WiFi links, respectively. Similarly, C_{wifi} and C_{laa} represents WiFi and LAA transmission time, respectively.

4.1.3.2 Max-min fairness

The fundamental objective of this fairness model is to allocate the same throughput to each LAA and WiFi link. Link wide max-min fairness is reached as $LAA_{max-min}$(average throughput of LAA network) and $WiFi_{max-min}$(average throughput of WiFi network) is equal:

$$WiFi_{max-min} = LAA_{max-min} \tag{4}$$

The average throughput of WiFi network is defined as:

$$WiFi_{max-min} = \frac{\sum_i D_{wifi,i} * M_{wifi,i}}{C_{wifi} * L_{wifi}} \tag{5}$$

and the average throughput of LAA network is:

$$LAA_{max-min} = \frac{\sum_i D_{laa,i} * M_{laa,i}}{C_{laa} * L_{laa}} \tag{6}$$

Here, let $D_{wifi,i}$ denote the airtime of WiFi packet i, and $M_{wifi,i}$ represent the modulation rate of WiFi packet i. Similarly, $D_{laa,i}$ and $M_{laa,i}$ represent the airtime and modulation rate of LAA packet i, respectively.

In DUET mechanism, both proportional and max-min fairness metric can be applied. In the rest of the paper, we will focus on achieving proportional fairness between LAA and WiFi network in DUET mechanism. As allocating time resource between heterogeneous networks is technology agnostic, it is considered to be fair in most of the scenarios.

4.2 DUET MECHANISM

In DUET mechanism, we first consider fully observed network where all WiFi nodes can be observed by all LAA nodes. Then, partial observed network are considered, where each WiFi node can be observed by at least one LAA UE.

4.2.1 Baseline Algorithm

Consider the coexistence model with a fully observed scenario, which means that $x_{i,j}$ equals to 1 for all i and j. Within this scenario, we introduce DUET-Baseline. Implementing ON/OFF duty cycle or LBT in LAA are two possible coexistence algorithm. Since LBT generates extra contention overhead leading to performance decrease, DUET is designed and based on ON/OFF duty cycle coexistence mechanism.

DUET achieves coexistence of LAA and WiFi network through the following steps: 1) LAA network information (L_{laa} and $D_{laa,i}$) is gathered in LAA small cell, 2) the WiFi interface of LAA UE gathers WiFi network information ($D_{wifi,i}$ and L_{wifi}) and LAA UE reports corresponding information to LAA small cell, 3) LAA small cell allocates the time resource to LAA and WiFi transmission by defining LAA ON and OFF duty cycle length. LAA transmits in LAA ON period, and the LAA small cell will measure the actual transmission time of LAA traffic in LAA ON period. Similarly, the period of LAA OFF duty cycle length is used for WiFi transmission, since WiFi will transmit when the channel is idle. The WiFi interface of LAA UE will estimate the transmission time of WiFi traffic in LAA OFF period. The sum of LAA ON and OFF duty cycle length is defined as duty cycle period. Based on the transmission time of LAA and WiFi traffic with corresponding LAA/WiFi duty cycle length, the LAA small cell can calculate the channel utilization of LAA and WiFi network. Thus, the LAA small cell can assign a duty cycle length to both LAA and WiFi traffic of the next cycle according to the channel utilization of the current cycle.

4.2.1.1 Channel Utilization Estimation

In this section, we describe how channel utilization estimation is performed in both LAA and WiFi systems. Since LAA uses centralized MAC, LAA transmission time can be easily measured by LAA small cell. WiFi channel utilization is measured by the WiFi interface of LAA UE. Let T_e represents the estimated time usage of WiFi, and Bk_e represents the estimated backoff number, which is calculated based on [45]. The overhead to calculate Bk_e is that each WiFi interface of LAA UE needs to maintain a MAC address list of WiFi links, and the address list is required to be updated periodically. D_{packet} and D_{ack} represent the packet duration of packet and ACK, which can be accessed through preamble decoding or CCA measurement. Propagation delay is represented by D_{prop}. D_{prop} is negligible compared to other parameters, since the transmission range of small cell is limited. The estimated channel utilization is in the range of [0,1]. WiFi channel utilization is piggybacked to LAA packet, and report to LAA small cell at the start of LAA ON period. The algorithm for WiFi interface of LAA UE to estimate the channel utilization time is shown in Algorithm 1.

Algorithm 1 WiFi Channel Utilization Estimation

```
$T_e = 0$
if Receive a data packet then
    $T_e += difs + Bk_e + D_{packet} + D_{prop}$
else if Receive an ACK then
    $T_e += sifs + D_{ack} + D_{prop}$
else if Collision happens then
    $T_e +=$ Channel utilization time of largest packet
end if
```

4.2.1.2 LAPA Algorithm

In proportional adaptation mechanism, duty cycle length of LAA and WiFi is proportional adapted based on measured channel utilization of LAA and WiFi. In linear adaptation mechanism, duty cycle length of LAA and WiFi is linearly adapted toward fairness based on measured channel utilization of LAA and WiFi. An example is given below: in a scenario where L_{laa} equals to L_{wifi}, as $wifi_{cu}$ and laa_{cu} are 50% and 100%, where $wifi_{cu}$ and laa_{cu} denote the channel utilization of WiFi and LAA transmission in the previous cycle, respectively. C_{wifi} and C_{laa} are $100ms$ and $80ms$. If proportional adaptation is utilized, C_{wifi} and C_{laa} will be $50ms$ and $130ms$ in the next cycle. If linear adaptation is utilized, C_{wifi} and C_{laa} will be $99ms$ and $81ms$ in the next cycle. Since proportional adaptation converges aggressively, over adaptation is possible in this mechanism. On the other hand, linear adaptation converges slowly, and required converging time is large. Thus, we define *Thres* as channel utilization threshold to trigger linear or proportional mechanism properly, and the range of *Thres* is [0,1]. If *Thres* is set closer to 1, the algorithm will trigger proportional adaptation

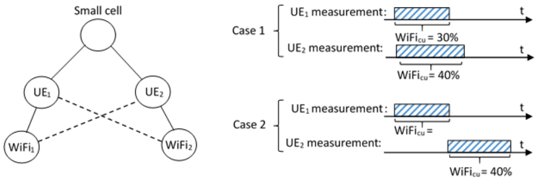


Figure 13: Example scenario, where solid line and dotted line represent overhear is possible and impossible

mechanism much often, and adapt more aggressively. Algorithm 2 illustrates the Proportional Adaptation and Linear Adaptation (LAPA) algorithm of DUET.

Algorithm 2 LAPA

```
if $wifi_{cu} >= Thres$ and $laa_{cu} < Thres$ then
    Proportionally adapt $C_{laa}$ and $C_{wifi}$
else if $wifi_{cu} < Thres$ and $laa_{cu} >= Thres$ then
    Proportionally adapt $C_{laa}$ and $C_{wifi}$
else if $wifi_{cu} >= Thres$ and $laa_{cu} >= Thres$ then
    Linearly adapt $C_{laa}$ and $C_{wifi}$ towards fairness
else if $wifi_{cu} < Thres$ and $laa_{cu} < Thres$ then
    Linearly adapt $C_{laa}$ and $C_{wifi}$ towards fairness
end if
```

4.2.2 Partial Observed scenario

In this section, we consider partially observed scenario, where elements in connectivity matrix can be either 1 or 0. In this scenario, we propose DUET-Slotted channel utilization (SCU) to handle partial observation problem.

4.2.2.1 Slotted channel utilization

In DUET-Baseline, LAA UE reports only the WiFi channel utilization to LAA small cell. In a partially observed network, this information is not enough for the LAA small cell to decide the duty cycle length of LAA and WiFi for next cycle. This is because, each LAA UE has a different view of the network and hence has different WiFi channel utilization information. E.g., as shown in case 1 and 2 in *Figure 13*, UE$_1$ and UE$_2$ detects WiFi using the channel with 30% and 40% of WiFi duty cycle

Table 5: NS-3 Parameters

Parameters	**Default Settings**
Frame size	1500bytes
Transport protocol	UDP
Adaptation threshold	90%
Initial LAA and WiFi duty cycle length	90ms
Minimal LAA and WiFi duty cycle length	10ms
Duty cycle period	180ms
Propagation loss model	Friis propagation loss model
WiFi Tx power	20dbm
WiFi basic transmission rate	6Mbps
WiFi data transmission rate	54Mbps
WiFi CCA Threshold	-62dBm
WiFi CS/CCA Threshold	-82dBm
LAA small cell Tx power	20dbm
LAA transmission rate	dynamic rate control

length, respectively. In this example, WiFi$_1$ and WiFi$_2$ transmit at different times and hence, 40% and 70% of channel utilization should be reported to LAA small cell in case 1 and 2, respectively. Thus, the channel utilization value is not useful without the timing information. In other words, how much was the channel utilized and when was the channel utilized is required for LAA small cell to make a fair and efficient duty cycle length adaptation for the next cycle.

Intuitively, reporting time information of each WiFi packet to LAA small cell can be a solution. However, it requires tight time synchronization and generates significant overhead. Thus, we introduce slotted channel utilization measurement to solve partial observation problem. We define each slot as a time block. The WiFi interface of each LAA UE is required to measure the channel utilization during each slot with duration D_{slot} according to Algorithm 1. $WiFi_{scu}$ for each slot is set according to:

$$WiFi_{scu} = \begin{cases} 1 & \text{if } WiFi_{cu} > \text{ half of } D_{slot} \\ 0 & \text{if } WiFi_{cu} <= \text{ half of } D_{slot} \end{cases}$$

$WiFi_{scu}$ is reported to LAA small cell periodically by LAA UE. Since Channel State Information (CSI) can be reported to small cell by LAA UE periodically, $WiFi_{scu}$ can be piggybacked with CSI update. A trade off for setting D_{slot} can be observed. As D_{slot} is set to be large, the UE report overhead is small, but the accuracy of channel utilization becomes low.

4.3 EVALUATION

In this section, we evaluate DUET using simulations in NS-3 [46]. We present the performance evaluation of LAA and WiFi with and without DUET mechanism. The simulation parameters are shown in *Table 5.* Parameters of WiFi follow 802.11a[1] and LAA follows LTE standard. Each AP is connected to 1 client for WiFi setup. Traffic is generated for LAA downlink transmission and between each pair of WiFi nodes. For all scenarios, we evaluate the network performance with static and dynamic load. Both fully and partially observed topologies are considered. We evaluate both normal and slotted channel utilization estimation. To prevent WiFi transmission during LAA ON duty cycle length, we only allow WiFi to transmit during LAA OFF period in the simulation, which can be achieved by letting the WiFi interface of LAA UE to broadcast CTS-to-self periodically with specific NAV duration.

4.3.1 Fully observed scenario

The fully observed scenario is set up by uniformly distributing 8 LAA UEs and 8 WiFi nodes into a circle with radius of 50m. The LAA small cell is located in the center of the circle.

4.3.1.1 Static load scenario

In this section, we analyze the performance of DUET in a static load scenario. We first evaluate the accuracy of estimated channel utilization from Algorithm 1. *Figure 14* (a)

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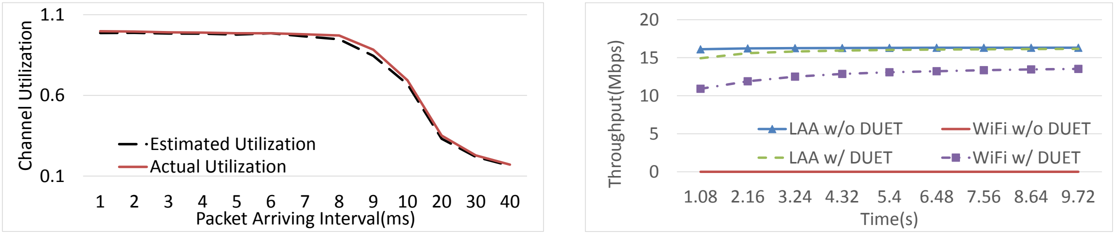
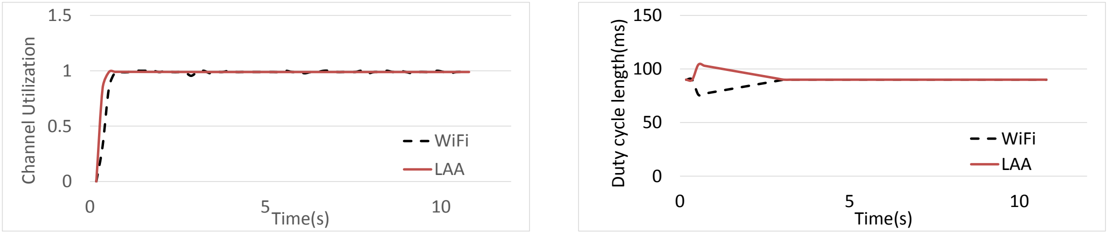
[1] currently, LAA is designed to operate in 5GHz band



(a) Channel utilization verification

(b) Network throughput



(c) Channel utilization

(d) Duty cycle length

Figure 14: Static load with fully observed scenario

shows the estimated WiFi channel utilization versus actual channel utilization with varying application layer packet arriving interval. It can be seen that the estimated channel utilization is close to actual channel utilization with varying network load, and the maximum difference between these channel utilization is 3.8%.

Figure 14 (b) shows the application layer throughput performance of both LAA and WiFi networks. We can clearly observe that when DUET is not enabled, the WiFi throughput is nearly 0. This is because LAA small cell will always transmit and WiFi always detects the channel to be busy. When DUET is enabled, we can observe that WiFi throughput increases significantly, since WiFi node can transmit without LAA interference in LAA OFF duty cycle length. Also, the overall network throughput is increased by 81% as DUET is enabled. Another point to notice is that LAA throughput is almost not impacted after sharing time resource with WiFi. Since WiFi performance is heavily impacted as DUET is disabled, it means LAA always transmit to keep the channel busy when possible. However, as DUET is enabled, LAA only transmits during a partial fraction of total time, and also the throughput is not impacted. This is because if the size of packet from upper layer is smaller than the TBS in LAA network, the packet will be padded with 0 until it reaches the TBS.

Figure 14 (c) shows the channel utilization of both LAA and WiFi network. The channel utilization of both LAA and WiFi network converges to 1. Thus, DUET enables efficient channel resource utilization. *Figure 14* (d) measures the duty cycle length of both LAA and WiFi networks with good fairness.

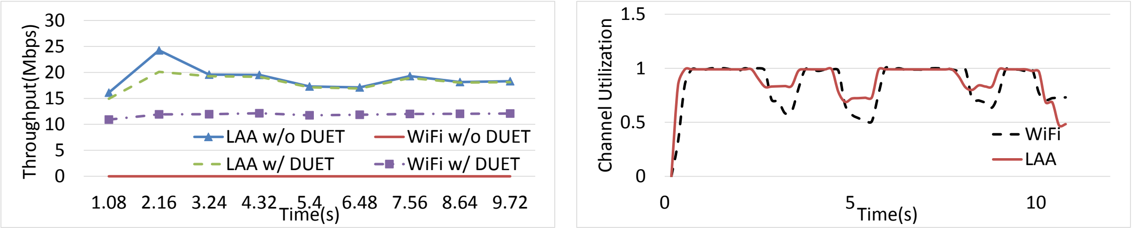
4.3.1.2 Dynamic load scenario

In this section, we analyze the performance of DUET in a dynamic load scenario. The network load is randomly varied between high and low load every 5 duty cycle periods for both LAA and WiFi.

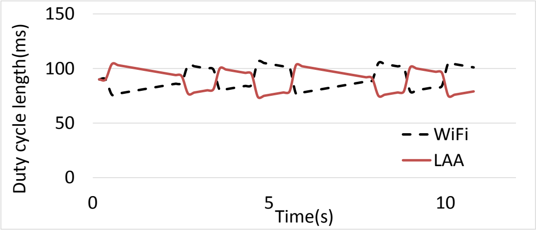
Figure 15 (a) shows the throughput performance of both LAA and WiFi networks. Overall network throughput performance increases by 65%, when DUET is enabled. As shown in *Figure 15* (b) and (c), the duty cycle length of LAA and WiFi adapts according to channel utilization, and channel utilization of both LAA and WiFi converges to 1 in dynamic load scenario. For example, the channel utilization of LAA and WiFi decreases after 2.16s. Then WiFi duty cycle length is proportionally increased, and LAA duty cycle length is proportionally decreased. It is interesting to notice that LAA channel utilization decreases before WiFi around 2.16s in *Figure 15* (b), because there are still packets in the packet queue of WiFi. After channel utilization of WiFi and LAA reaches a relative stable state when network load is low, LAA channel utilization is higher than WiFi. The reason is that LAA will pad 0 to packets with size less than TBS. Thus, channel utilization of LAA is higher than WiFi in low network load scenario.

To conclude, in fully observed scenario with static and dynamic network load:

> *DUET-Baseline achieves high throughput of LAA and WiFi networks with good channel utilization and fairness.*



(a) Network throughput (b) Channel utilization



(c) Duty cycle length

Figure 15: Dynamic load with fully observed scenario

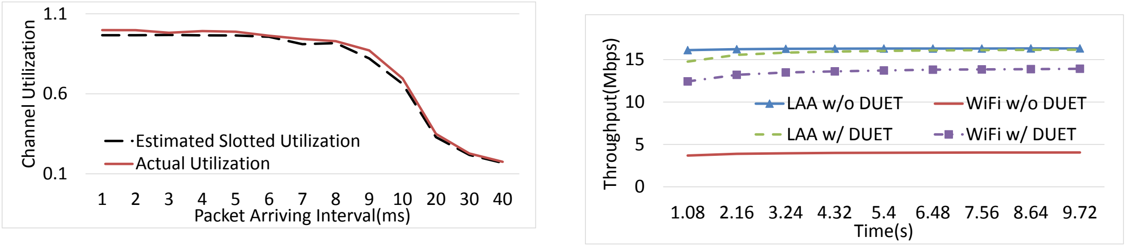
4.3.2 Partially observed scenario

In order to make sure partially observed scenario is generated, we generate a deterministic scenario with connectivity matrix as shown below.

$$M = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 1 & 1 \end{bmatrix}$$

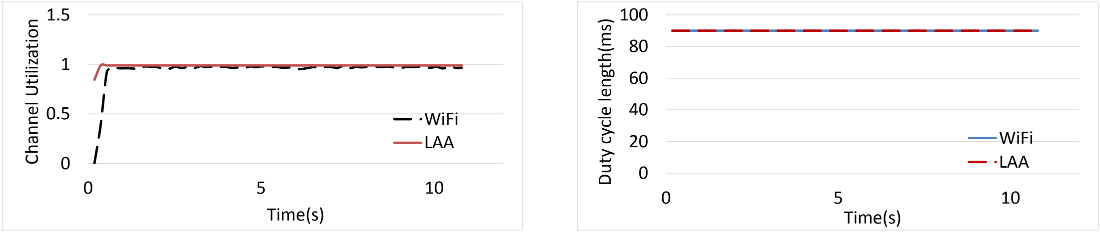
4.3.2.1 Static load scenario

In this section, we analyze the performance of DUET based on the static load scenario. We set the D_{slot} to be $100\mu s$. *Figure 16* (a) presents the verification of slotted channel utilization estimation versus actual channel utilization. It can be seen that the slotted channel utilization is close to actual channel utilization. The maximum difference



(a) Channel utilization verification

(b) Network throughput



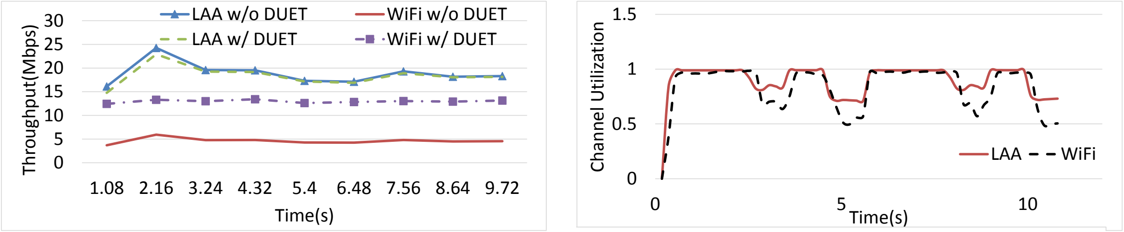
(c) Channel utilization

(d) Duty cycle length

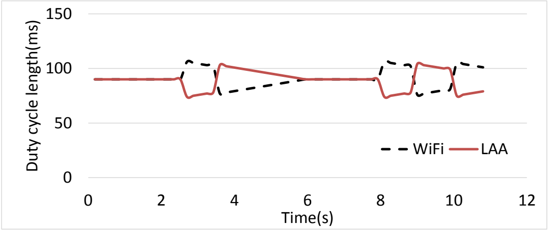
Figure 16: Static load with partially observed scenario

between them is 5%. For slotted channel utilization to work properly, we piggyback the WiFi$_{scu}$ information with CSI update. The CSI update interval is set to be 2ms. Thus, 20bits of WiFi$_{scu}$ is piggybacked to each of the CSI update. The overhead does not result in performance degradation, since LAA UE uplink traffic operates in licensed spectrum.

Figure 16 (b) illustrates network throughput performance with DUET enabled and disabled. One can observe that WiFi network throughput increases compared to fully observed scenario. The reason is that LAA small cell has less interference on several WiFi nodes, which allows WiFi nodes to transmit while LAA is also transmitting. When DUET is enabled, it results in a 47% increase in overall network throughput. In *Figure 16* (c) and (d), the channel utilization and duty cycle length of LAA and WiFi network are presented, respectively. It can be observed that LAA and WiFi network channel utilization converges to 1.



(a) Network throughput (b) Channel utilization



(c) Duty cycle length

Figure 17: Dynamic load with partially observed scenario

4.3.2.2 Dynamic load scenario

In this section, we analyze the performance of DUET in a partially observed dynamic load scenario. The dynamic load model is the same as Sec V-A.

Figure 17 (a) shows the LAA and WiFi network throughput performance. As DUET is enabled, the overall network throughput increases by 37%. *Figure 17* (b) and (c) present the channel utilization converging to 1, based on duty cycle adaptation.

To conclude, in partially observed scenario with static and dynamic network load:

> *DUET-SCU achieves high throughput of LAA and WiFi networks with good channel utilization and fairness.*

4.4 Issues and Future Work

We presented DUET algorithm is this chapter, which provides a solution to trigger the coexistence of LAA (network with centralized MAC) and WiFi (network with distributed MAC), while not changing the framework of WiFi. Under scenarios with different traffic load and connectivity, DUET can provide good channel utilization and able to converge to proportional/max-min fairness between LAA and WiFi networks. There are some constraints for DUET to work properly: 1) Each LAA UE needs to be equipped with a WiFi interface and it is required to be turned ON, which generates extra energy cost, 2) Only downlink transmission of one LAA small cell is considered to be coexisted with WiFi networks, 3) WiFi packet is assumed to be always decodable. 4) Only use channel utilization information in the very last duty period to set (predict) current duty cycle length, which may not be accurate. The future work of DUET is to overcome the above constraints.

CHAPTER V

CONCLUSIONS

The global mobile data usage has grown nearly 70% annually in recent years, and it is expected to increase nearly tenfold between 2014 and 2019 [47]. In order to sustain the possible growth in mobile services, LAA [13] or LTE-U [14, 15] is emerging as a candidate technology for telecommunication companies to utilize unlicensed spectrum for wireless data traffic offloading. Based on carrier aggregation between licensed and unlicensed bands, LAA/LTE-U can deliver cellular services to mobile users in the 5GHz unlicensed band.

The focus of this work is to identify and resolve the coexistence problem between LAA and WiFi.

To *identify the coexistence problem*, we have conducted the experimental evaluation to study the impact of LAA interference on WiFi performance in indoor office environments. We study how WiFi performance is impacted by LAA interference in five different scenarios and provide analysis and insights. Based on the analysis and insights, we also provide perspectives for LAA MAC designs to deal with coexistence issues between LAA and WiFi networks. Based on the experimental observations, we get two surprising results: 1) Small bandwidth of LAA(1.4/3/5/10MHz) has large impact on WiFi performance. 2) LAA signals with LAA can trigger channel busy indication of CS/CCA in WiFi. We will explore potential reasons of these anomaly as future works.

Through experimental analysis, our work shows clearly that LAA has significant impact on WiFi performance in different scenarios. Thus, an coexistence mechanism is necessary for LAA and WiFi coexistence. To *resolve the coexistence problem*, we introduce DUET coexistence algorithm, which provides a solution to trigger the coexistence of LAA and WiFi, while not changing the framework of WiFi. Under scenarios with different traffic load and connectivity, DUET can provide good channel utilization and able to converge to proportional/max-min fairness between LAA and WiFi networks.

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