Advanced Technologies Enabling the Efficient and Fair Coexistence Between LTE-U Systems and WiFi Networks

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I would like to dedicate this thesis and everything I do to my parents. I would not be who I am today without their love and support.

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Yuan Gao
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Last but not the least, I would like to thank my family: my parents, my grandparents for supporting me spiritually throughout my life.

Abstract

Deploying LTE in the unlicensed spectrum (LTE-U) is regarded as one of the most promising solutions to face significant data demand in the near future. According to regional regulations to access the unlicensed spectrums, LTE-U can be divided into two types: with listen-before-talk (LBT) and without LBT. The former type is regarded as the most promising global solution for LTE-U networks coexisting with WiFi networks and is a key feature in the Release 13 of 3GPP, denoted as licensed-assisted access (LAA). While, the latter employs a duty cycle-based access scheme, which requires fewer modifications on the LTE side, enabling it to be deployed in the short term. The coexistence and performance optimization between LTE-U and Wi-Fi is the major scope of this thesis.

In Chapter 3, the performance of LAA coexisting with WiFi is explored. The first major contribution is the more precise and comprehensive Markov Chain models developed to model the performance of baseline LBT and distributed coordinated function (DCF), which overcomes the limitations of current Markov Chain models. The second contribution is the contention window (CW) size based optimization scheme to maximize the LAA system throughput while guaranteeing minimum WiFi throughput. The third contribution is the reinforcement learning-based algorithm developed to optimize the initial CW size according to the environment, e.g., the number of cellular users, the traffic demand of WiFi users, etc.

In Chapter 4 RRM between LTE-U without the LBT scheme, i.e., duty cycle based scheme, and WiFi networks is studied. We are the first to formulate the RRM problem as a many-to-one matching with incomplete preference lists. The major contribution is the 2-step matching-based algorithm proposed to obtain Pareto efficient energy efficiency of each CU in a computational complexity efficient manner.

In Chapter 5, the context is extended: CU can be allocated either an unlicensed band or licensed band while WUs are allocated unlicensed bands. The major contribution is the matching-based algorithm, which is extended to integration of many-to-one and one-to-one matching to optimize the utility of each CU while guaranteeing minimum throughput of each CU and WU under various pricing strategies.

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Chapter 1

Introduction

1.1 Scope of this Thesis

Deploying LTE on the unlicensed spectrum is regarded as the most promising solution to meet the cellular traffic explosion in the near future. Utilising the unlicensed spectrum can effective enhance the network throughput. However, deploying LTE on the unlicensed spectrum will affect the performance of Wi-Fi, which is the major player on the unlicensed spectrum. This thesis studied the fairness and optimal resource allocation problem between Wi-Fi and LTE-U technologies. List of Abbreviations can be found in Table. 1.1.

1.1.1 Organization of this Thesis

The thesis is organized as follows. Chapter 2 reviews the background, literature review of LTE-U technologies and the methodologies used in this thesis. Chapter 3 focuses on the coexistence of LAA and Wi-Fi in terms of performance evaluation, CW-based performance evaluation and self-organizing. Markov chain models are developed and exploited throughout these three topics. Chapter 4 studies the resource management problems in ABS-based LTE-U and Wi-Fi networks coexisting scenarios. Matching-based algorithms are developed to optimize every CU's energy efficiency and utility. We study a traffic offloading between unlicensed and unlicensed bands problem in an ABS-based LTE-U and Wi-Fi networks coexisting scenarios in Chapter 5. We conclude the thesis and discuss future directions in Chapter 6.

Table 1.1 List of Abbreviations

5G	the 5-th Generation
ABS	Absolute Blank Subframe
ACK	Acknowledgement
AP	Access Point
ARQ	Automatic Repeat-reQuest
BS	Base Station
Cat 3/4	Catogary 3/4
CCA	Clear Channel Assessment
CoMP	Coordinated Multi-Point
CSAT	Carrier Sense Adaptive Transmission
CSMA/CA	Carrier Sense Multiple Access with Collision Avoid
CU	Cellular User
CW	Contention Window
D2D	Device-to-Device
DCF	Distributed Coordinated Function
DL	Downlink
ECCA	Enhanced Clear Channel Assessment
eICIC	enhanced Inter-Cell Interference Coordination
eLAA	enhanced License-Assisted Access
eNB	evolved Node Base station
ETSI	European Telecommunications Standards Institute
FBE	Frame-based Equipment
GHz	Giga Hertz
GS algorihtm	Gale-Shapley algorithm
HARQ	Hybrid Automatic Repeat-reQuest
ICIC	Inter-Cell Interference Coordination
ILP	Integer Linear Problem
ISM	Industrial Scientific Medical
KPI	Key Performance Indicator
LAA	License-Assisted Access
LBE	Load-based Equipment
LBT	Listen Before Talk
LTE-U	LTE-unlicensed
LWA	LTE-WLAN Aggregation

MBS	Macro Base Station
NP	Non-deterministic Polynomial
OFDMA	Orthogonal Frequency Division Multiple Access
OSDL	Opportunistic Supplemental Downlink
PCC	Primary Component Carrier
PDCP	Packet Data Convergence Protocol
QoS	Quality of Service
RAT	Radio Access Technology
RB	Resource Block
RRM	Radio Resource Management
RTS/CTS	Request To Send/Clear To Send
SCBS	Small Cell Base Station
SCC	Secondary Component Carrier
SDL	Supplementary Downlink
SM	Stable Marriage
SPA	Student Project Allocation
UE	User Equipment
UL	Uplink
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WU	Wi-Fi User

1.2 Contributions

In Chapter 3, we focused on LAA. First, we extended the work to evaluate the impact of Cat 3 and 4 coexisting with Wi-Fi in terms of throughput and transmission delay of LAA and Wi-Fi. To overcome the limitations in transition probability in previous Markov Chain models[2], we established 3 comprehensive Markov chain models for Cat 4 LBT scheme, Cat 3 LBT scheme, and Wi-Fi DCF to evaluate LAA and Wi-Fi performance in coexisting scenarios. A lot of work has been done to optimize the LAA performance in LAA-WiFi coexistence scenarios and optimization algorithms have been proposed while the complexity of these algorithms has not studied [3, 4]. Then, we derive the explicit expressions for the relationships between Wi-Fi (LAA) throughput and Wi-Fi & LAA initial CW sizes, which have not been achieved by existing works. Based on the expressions, we developed an optimization algorithm to find the optimal LAA and Wi-Fi CW combination to maximize LAA throughput while guaranteeing Wi-Fi throughput above a certain threshold. The proposed algorithm showed great accuracy and effectiveness compared with an exhaustive-search based algorithm. Further, we extended our work to develop a self-organizing optimization scheme based on RL to solve the above optimization problem in real time, which has not been studied in existing works. Simulations results have shown that the complexity of finding the LAA and Wi-Fi CW combination to achieve maximum LAA throughput while guaranteeing minimum Wi-Fi throughput is further reduced, which enables its potential implementation in real communications systems.

In Chapter 4, we aim to solve the unlicensed resource allocation problem between CUs (cellular users) and WUs (Wi-Fi users) by adaptively tuning the ABS ON/OFF ratio to optimize the EE of each CU on the uplink while guaranteeing minimal throughput of each WU. We are the first to formulate the RRM problem as a many-to-one matching with incomplete preference lists. We develop a novel matching-based framework to solve this problem. Different from the current matching-based models aiming to obtain optimal system performance as a whole for resource allocation problems [5–7], we aim to optimize the QoS (such as throughput) of each user. In addition, another limitation of the above works is that preference lists are complete. This is because in the real world, the preference lists of these CUs are incomplete because some bands may fail to achieve a CU's QoS requirement, due to its availability and channel variation, meaning that some bands are not acceptable to certain users. To solve the matching with incomplete preference lists (one of the major contributions of this framework), we develop a semi-distributed 2-step matching-based algorithm, which is the major contribution of this chapter. The 1-st step is a many-to-one matching based on the Gale-Sharply algorithm and the 2-nd step is basically a reallocation scheme containing a re-matching stage which enables more CUs to be served. The stability, Pareto efficiency, and convergence of each step are proved.

In Chapter 5, we study resource allocation and traffic offloading problem in an LTE-U and Wi-Fi coexistence scenario, where CUs can access both licensed and unlicensed bands. We are the first to formulate a multi-objective optimization problem in the Wi-Fi and LTE-U coexistence scenario. In the previous traffic offloading problems, the objective function is the sum throughput or other KPI [8–10], while in this chapter, the offloading problem is studied with respect to each UE. We aim to maximize the utility (defined as a function of CU's throughput and corresponding monetary cost) of each CU while guaranteeing the throughput requirements of both CUs and WUs. CUs and the licensed & unlicensed bands form two agents, and the constraints of the optimization problem are transformed into the preference lists of these two agents. The potentially different prices that a CU may have to pay for accessing the unlicensed and licensed bands are included in our problem formulation. We prove the stability, Pareto optimality, and convergence of the proposed matching-based algorithm and evaluated its performance through simulation.

1.2.1 List of Publications

Publications

[1] Gao, Yuan, Haonan Hu, Yue Wu, Xiaoli Chu, and Jie Zhang, "Energy efficient and fair resource allocation for LTE-unlicensed uplink networks: A two-sided matching approach with partial information," *Transactions on Emerging Telecommunications Technologies*, 29, no. 10 (2018): e3500.

[2] Gao, Yuan, Yue Wu, Haonan Hu, Xiaoli Chu, and Jie Zhang, "Licensed and Unlicensed Bands Allocation for Cellular Users: A Matching-based Approach," *IEEE Wireless Communications Letters*, Sep. 2018.

[3] Gao, Yuan, Bolin Chen, Xiaoli Chu, and Jie Zhang, "Resource allocation in LTE-LAA and Wi-Fi coexistence: a joint contention window optimization scheme," *2017 IEEE Global Communications Conference (GLOBECOM)*, pp. 1-6. , 2017.

[4] Gao, Yuan, Xiaoli Chu, and Jie Zhang, "2016 IEEE Performance analysis of LAA and Wi-Fi coexistence in unlicensed spectrum based on Markov chain," *2016 IEEE Global Communications Conference (GLOBECOM)*, pp. 1-6. IEEE, 2016.

[5] Hu, Haonan, Yuan Gao, Xiaoli Chu, Baoling Zhang, and Jie Zhang, "On the Performance of LTE-LAA Networks Coexisting with Wi-Fi Networks Sharing Multiple Unlicensed Channels."

[6] Chen, Bolin, Jiming Chen, Yuan Gao, and Jie Zhang, "Coexistence of LTE-LAA and Wi-Fi on 5 GHz with corresponding deployment scenarios: A survey," *IEEE Communications Surveys & Tutorials* 19, no. 1 (2017): 7-32.

Submitted

[7] Gao, Yuan, Xiaoli Chu, and Jie Zhang, "Coexistence of LTE-LAA and Wi-Fi: a Reinforcement Learning Based Contention Window Approach," *2018 IEEE International Communications Conference (ICC)*, Oct. 2019.

Chapter 2

Literature Review and Methodology

2.1 LTE-U Technologies

In recent years, we have seen the number of connected user equipment (UE) growing exponentially, which is expected to reach 50 billion at the end of 2020 [11]. How to provide such a huge number of UEs with particular services requiring diverse quality of service (QoS), especially bandwidth-hungry service types, such as high revolution live steam, remains a critical problem for the fifth-generation (5G) cellular networks. Several new technologies have been proposed to provide UEs with massive data service and employing the industrial, scientific and medical (ISM) spectrum is one of them. The idea of deploying LTE in unlicensed spectrum is first proposed by Qualcomm in 2013 [12] and in the next year, LTE-U forum was created by Verizon together with Qualcomm, Ericsson, Alcatel-Lucent, and Samsung. In 2015, Ericsson created the concept of licensed-assisted access (LAA), which was adopted in the standardization of 3GPP Rel. 13 mainly for the fair coexistence of LAA and Wi-Fi [13]. In 2016, LTE-WLAN radio level aggregation (LWA) is also included in 3GPP Rel. 13, and enhanced LAA and enhanced LWA are included in the standardization of 3GPP Rel. 14.

The reasons why deploying LTE in the unlicensed spectrum has attracted worldwide attention to meet the explosive traffic increase can be explained in three aspects:

- The first reason is the abundant resource available in the 5 GHz unlicensed spectrum. Among the major markets, approximately 300 to 580 MHz spectrum resource in 5 GHz spectrum is open to access. Other unlicensed spectrums are also under consideration, including 60 GHz and 2.4 GHz. However, the range of 60 GHz spectrum is quite limited to be used by the industry or public, and 2.4 GHz is already heavily congested [14].

- Unlicensed spectrum can be exploited by LTE in a wide range of scenarios, covering both indoor and outdoor. Licensed spectrum and unlicensed spectrum are aggregated for a higher data rate in most scenarios, while in areas where licensed spectrum is not available, communications are carried out in unlicensed spectrum alone [1].

- As the two major players in the wireless communications, scheduling-based LTE and contention-based Wi-Fi apply different frame structures, channel access schemes, interference management algorithms, and retransmission policies, making LTE provide more reliable and predictable service than Wi-Fi does. Also, LTE outperforms Wi-Fi in spectral efficiency [14, 1].

2.1.1 Available Spectrum In 5 GHz Unlicensed Spectrum

The ISM spectrum under current consideration of deploying LTE is the 5 GHz because there is a substantial amount of unlicensed spectrum available with very similar band plans: 325 MHz in China, 580 MHz in U.S. & Canada, 455 MHz in Europe, 480 MHz in Korea and 425 MHz in Japan. 5.15-5.35 GHz (200 MHz bandwidth) spectrum is open for access in major markets, e.g. China, U.S., Canada, Europe and Korea, and a transmission power limit of 23 dBm is imposed. The usage of 5.15-5.35 GHz spectrum bands are also regulated for:

- indoor usage only in China and Japan;

- both indoor and outdoor usage in the U.S. and Canada;

- indoor usage only (5.15-5.25 GHz) and both indoor and outdoor usage (5.25-5.35 GHz) in Europe and Korea.

The availability of the 5.47-5.85 GHz spectrum varies from country to country:

- only 5.725-5.85 GHz spectrum is open to both indoor and outdoor usage in China, 125 MHz in total;

- the whole spectrum is open to both indoor and outdoor usage in the U.S. and Canada, 380 MHz in total;

- only 5.47-5.725 GHz spectrum is open to both indoor and outdoor usage in Europe and Japan, 225 MHz in total;

- only 5.47-5.65 GHz and 5.725-5.825 GHz spectrum are open to both indoor and outdoor usage in Korea, 280 MHz in total.

The detail of the available bandwidth, usage and power limitations for accessing the 5 GHz spectrum in major markets can be found in Table. 1.1 [1].

Table 2.1 An overview of 5GHz spectrum in major markets [1]

<table>
<tr><th>Country (available bandwidth)</th><th>5.15-5.25 GHz</th><th>5.25-5.35 GHz</th><th>5.47-5.65 GHz</th><th>5.65-5.725 GHz</th><th>5.725-5.825 GHz</th><th>5.825-5.85 GHz</th></tr>
<tr><td>China (325 MHz)</td><td colspan="2">Indoor 23 dBm</td><td>NA</td><td>NA</td><td colspan="2">Indoor/outdoor 30 dBm</td></tr>
<tr><td>U.S. (580 MHz)</td><td colspan="2">Indoor/outdoor 23 dBm</td><td colspan="4">Indoor/outdoor 30 dBm</td></tr>
<tr><td>Canada (580 MHz)</td><td colspan="2">Indoor/outdoor 23 dBm</td><td colspan="4">Indoor/outdoor 30 dBm</td></tr>
<tr><td>Europe (455 MHz)</td><td>Indoor 23 dBm</td><td>Indoor/out- -door 23 dBm</td><td colspan="2">Indoor/outdoor 30 dBm</td><td>NA</td><td>NA</td></tr>
<tr><td>Korea (480 MHz)</td><td>Indoor 23 dBm</td><td>Indoor/out- -door 23 dBm</td><td>Indoor/out- -door 30 dBm</td><td>NA</td><td>Indoor/out- -door 30 dBm</td><td>NA</td></tr>
<tr><td>Japan (425 MHz)</td><td colspan="2">Indoor 23 dBm</td><td colspan="2">Indoor/out- -door 30 dBm</td><td>NA</td><td>NA</td></tr>
</table>

2.1.2 Scenarios for LTE Exploiting 5 GHz

In Fig. 2.1, typical scenarios for exploiting the unlicensed spectrums by the cellular networks are presented. The most common scenario generally consists of one macro base station (MBS) and multiple small cell base stations (SCBSs) providing licensed bands and Wi-Fi access points (APs) or base stations (BSs) providing unlicensed bands. Variations of this scenario can be further extended to scenarios without MBS coverage or (and) SCBSs coverage, the allocation of licensed bands in the MBS and SCBSs, ideal or non-ideal backhauls, which are summarized as follows:

- **Scenario 1**: The licensed spectrum is provided by an MBS while the unlicensed spectrum is provided by a Wi-Fi AP or BS. The MBS and Wi-Fi AP or BS are connected with ideal backhaul link (e.g., optical fiber). The MBS covers a large area thus guaranteeing mobility management. This scenario is considered for both indoor and outdoor deployment.

- **Scenario 2**: The licensed spectrum is provided by an SCBS while the licensed spectrum is provided by a Wi-Fi AP or BS. The SCBS and Wi-Fi AP or BS are connected with ideal backhaul link (e.g., optical fiber). This is a collocation scenario, which is suitable for indoor deployment in absence of MBS coverage.

- **Scenario 3**: Both an MBS and an SCBS provide the same licensed bands and the unlicensed spectrum is provided by a Wi-Fi AP or BS. The SCBS and Wi-Fi AP are collocated and connected with ideal backhaul. The MBS and the SCBS are connected with ideal or non-ideal backhaul. This scenario is suitable for both indoor and outdoor deployment.

- **Scenario 4**: An MBS and an SCBS use different licensed bands, the unlicensed spectrum is provided by a Wi-Fi AP or BS. The SCBS and Wi-Fi AP are collocated and connected with ideal backhaul. The MBS and the SCBS are connected with ideal or non-ideal backhaul. This scenario is suitable for both indoor and outdoor deployment.

- **Scenario 5**: Only unlicensed spectrum is available in this scenario, which is called 'stand-alone'. This is suitable for situations lacking licensed spectrum, cable operators, wireless internet service providers or hotspot network operators.

2.1.3 Strengthes of LTE over Wi-Fi

Apart from the abundant spectral resource in 5 GHz, exploiting the unlicensed spectrum by the cellular networks have the following advantages:

- **Frame Structure**: As shown in Fig. 2.2, in LTE systems, time is slotted into frames, consisting of 10 sub-frames, each lasting 1 ms. The spectrum resource can be further divided into resource blocks (RBs), which consists of a slot (half a sub-frames of 0.5 ms) and 12 sub-channels of 180 kHz. Continually LTE transmissions are scheduled over RBs among multiple users [15, 16]. The detail of the LTE frame structure can be found in [17–19]. While Wi-Fi systems can only occupy the channel based on the traffic demand and channel condition, which means the channel is not always occupied. Wi-Fi networks are expected to be impacted greatly by coexisting LTE networks, while the performance of LTE networks is much less affected. This is due to the fact that Wi-Fi networks keep backoffing when the LTE systems are transmitting continuously.

- **Channel Access Scheme**: LTE has a centralized controller in the BS for scheduling and managing DL/UL links and resource allocation. The control signaling carried by licensed channels has the highest priority according to the QoS Class Identifier [20], which provides high spectrum efficiency and reliable performance. While Wi-Fi applies distributed coordination function (DCF) for channel accessing based on carrier

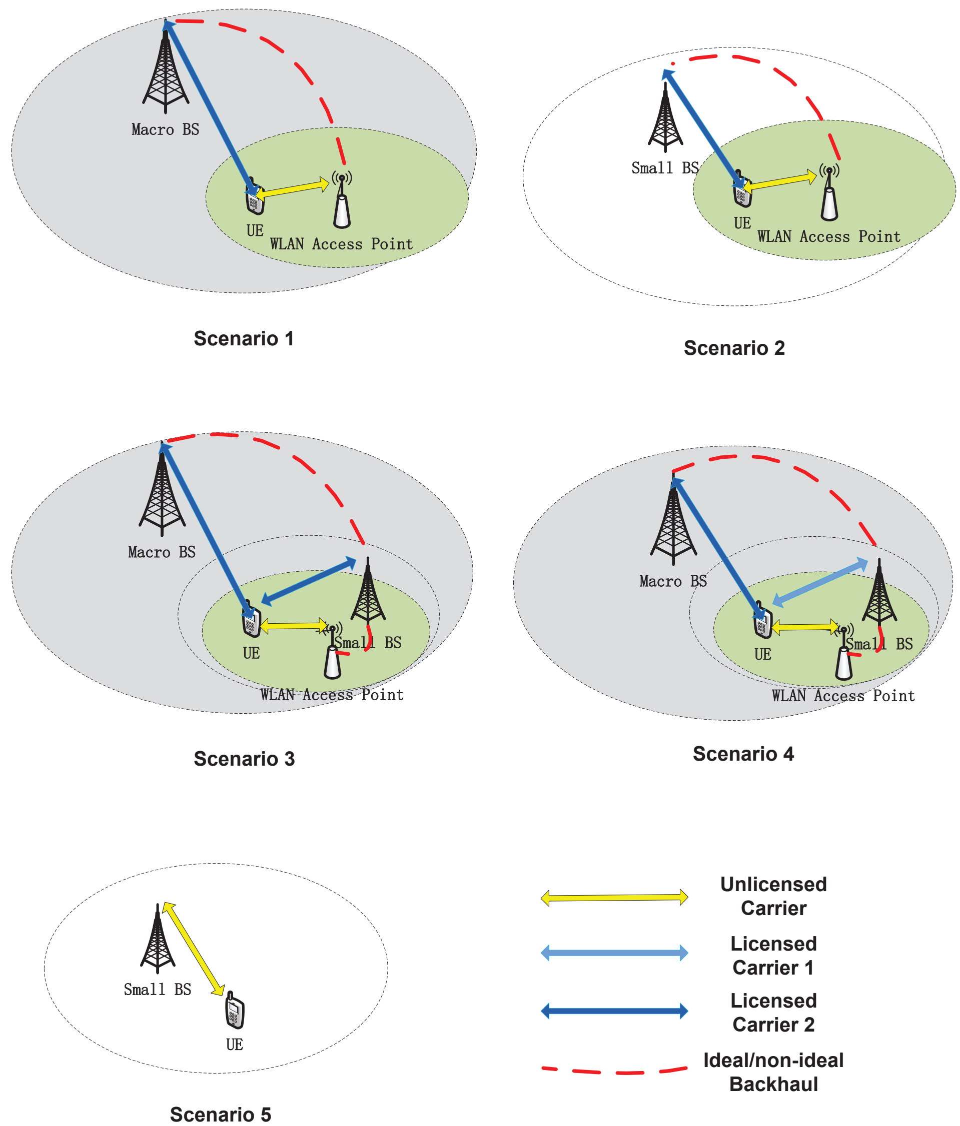

Fig. 2.1 Scenarios for LTE Exploiting 5 GHz

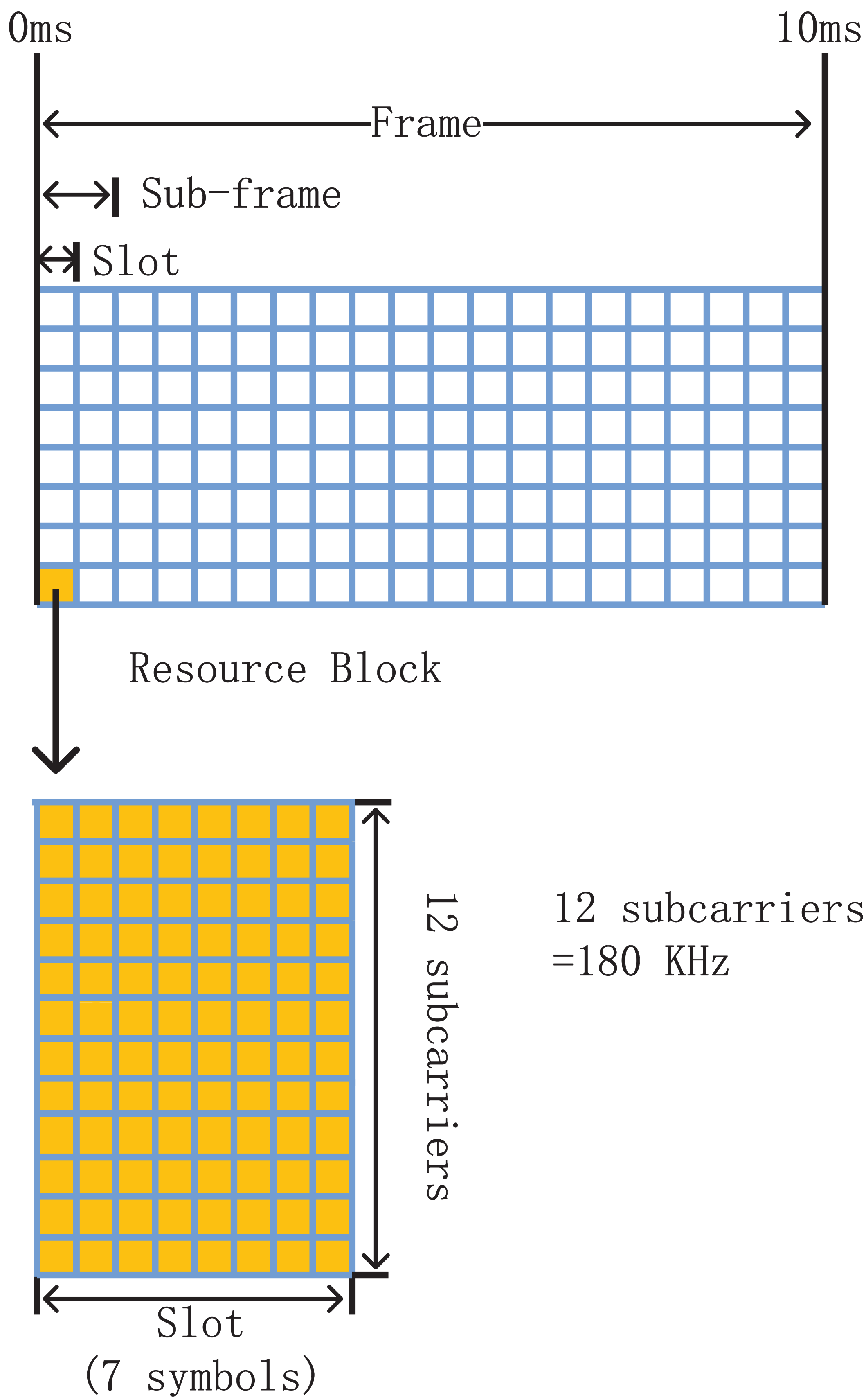

Fig. 2.2 Frame Structure of LTE

sense multiple access with collision avoidance (CSMA/CA). The performance of Wi-Fi is contention-based and a Wi-Fi device keeps backoff if the channel is sensed to be busy or a collision is observed, which means that Wi-Fi performance will be affected by heavy traffic load [21, 17, 16].

- **Interference Management**: Advanced interference management schemes, such as inter-cell interference coordination (ICIC), enhanced ICIC (eICIC) and coordinated multi-point (CoMP), have been developed in LTE to cope with inter-cell, cross-tier interference to provide better service quality for cell-edge users [22, 23]. With eICIC, cell-edge users are better served by avoiding co-channel interference from MBS using ABS or increase received by coverage expansion. With CoMP, coordination between multiple BSs enables cell-edge users to be served by two or more adjacent base stations jointly, which increase the received signal power and throughput [23, 24]. Wi-Fi users, especially edge users, suffer from hidden and exposed node problems, leading to interference or waste of spectrum resources. Request-to-send/clear-to-send (RTS/CTS) in CSMA/CA has been proposed to solve the former one.

- **Retransmission**: LTE systems employ a hybrid automatic repeat request (HARQ) retransmission scheme which combines the failed transmission data with the retransmission data [19]. Upon receiving data packets with error, a re-transmission request for the same copy is made. Once receiving the retransmission data packets, the receiver tries to decode the retransmission combining the first version. An ACK (acknowledge) message is sent to the eNB if the decoding is successful, otherwise, another retransmission request is sent [17]. This procedure is repeated until the packets are decoded successfully with cumulated information. While the single loop automatic repeat request (ARQ) in Wi-Fi networks simply discards the packets with error and request for retransmission until the transmission is successful or a maximum retransmission number (6 in 802.11 ac [25]) has been reached [26, 27]. Clearly, ARQ is less effective than HARQ because no cumulated information is used for the decoding. HARQ outperforms ARQ in retransmission, especially in poor radio link quality scenarios.

The above differences demonstrate the strengths and potentials of deploying LTE in the unlicensed spectrum while leaving the design of coexistence mechanisms a huge challenge. Research also showed that without properly designed coexistence mechanisms, Wi-Fi performance experiences significantly degradation [28][29][30][31].

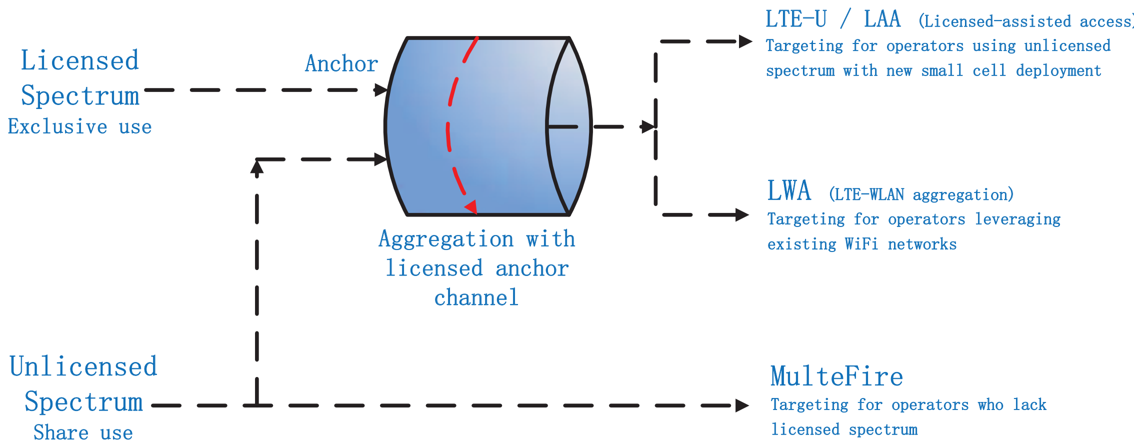

Fig. 2.3 Various access schemes exploiting the unlicensed spectrum

2.2 Literature Review

In Fig. 2.3, various of coexistence mechanisms proposed to suit different deployment scenarios and regional regulations are summarized as follows:

- **Licensed-assisted access (LAA)**: As a key feature in 3GPP Rel. 13, it combines licensed primary component carriers (PCCs) and one or multiple unlicensed secondary component carriers (SCCs) by using carrier aggregation for the downlink in LTE. Listen-before-talk (LBT) scheme, which is regulated in Europe and Japan to access the ISM spectrum, is considered in the design of the LAA scheme. Although modifications are required in LTE air interface to apply LBT scheme, LAA is still considered as the most promising global solution for exploiting 5 GHz spectrum in LTE [32]. LAA can be applied in both the collated and non-collocated scenarios. Enhanced LAA (eLAA) standardized in 3GPP Rel. 14 allows uplink transmission in the unlicensed spectrum [31].

- **LTE-U**: LTE-U is proposed in countries without mandatory LBT requirements for accessing the unlicensed spectrums, such as U.S., China, and Korea. LTE is able to exploit the unlicensed spectrums based on the version given in 3GPP Rel. 10-12, which means that no changes in LTE air interface have to be made. Therefore, LTE-U is expected to be the first commercial version of deploying LTE on the unlicensed spectrum. LTE-U can also be applied in both collated and non-collocated scenarios.

- **LWA**: LTE-WLAN aggregation (LWA) is also included in 3GPP Rel. 13, which is suitable for areas with Wi-Fi infrastructure deployed by operators. LTE SCBS has the control of Wi-Fi APs and can control the load balancing on the LTE and Wi-Fi links by offloading UEs or traffic from the licensed spectrums to the unlicensed spectrums. Protocol (PDCP) aggregation is performed on UE to combine packets transmitted via LTE and Wi-Fi links. No modifications are required on either cellular infrastructure and UE hardware. LWA can be applied in collocated and requires a X_w link in non-collocated scenarios [33, 34].

- **MulteFire**: MulteFire scheme proposed by Qualcomm is expected to be applied in scenarios where licensed spectrum coverage is not available, i.e., stand-alone. It is solely operated in the unlicensed spectrum without licensed anchor based on 3GPP standards. From December 2015, MulteFire Alliance formed by Qualcomm and Nokia is dedicated to developing a global deployment of MulteFire [35].

2.2.1 Access schemes with LBT

In Europe and Japan, LBT scheme is mandated to access the 5 GHz unlicensed spectrum. With LBT, an equipment is required to perform clear channel assessment (CCA) based on energy detection to detect the availability of the channel. If the energy detection level is above a pre-defined threshold (generally -60 dBm for 20 MHz spectrum), the channel would be considered as occupied and can not be accessed. LBT is designed for a fair share of the unlicensed spectrum and is a key feature for LAA as a global deployment of LTE on the unlicensed spectrum.

LBT schemes are standardized by the European Telecommunications Standards Institute (ETSI) and load-based equipment (LBE) and frame-based equipment (FBE) are two major types [36].

[1] LBE-based LAA

LBE-based LAA (Fig. 2.4) is a traffic-driven contention-based medium access mechanism and requires an equipment detect the availability of a channel. If a clear channel is identified by the equipment during a CCA slot ($\geqslant 20\mu s$), it transmits immediately. Otherwise, LBE-based LAA enters extended CCA (ECCA) stage 0 with initial contention window (CW) size $CW_0 = 16$. The channel energy level is observed for a duration of an integer N multiplied by the duration of a single ECCA slot ($\geqslant 20\mu s$). N is random number chosen from $[1, 2, \ldots, CW_0]$. The counter number N is decremented by one if the channel is sensed to be idle during an ECCA slot and freezes if the channel is busy.

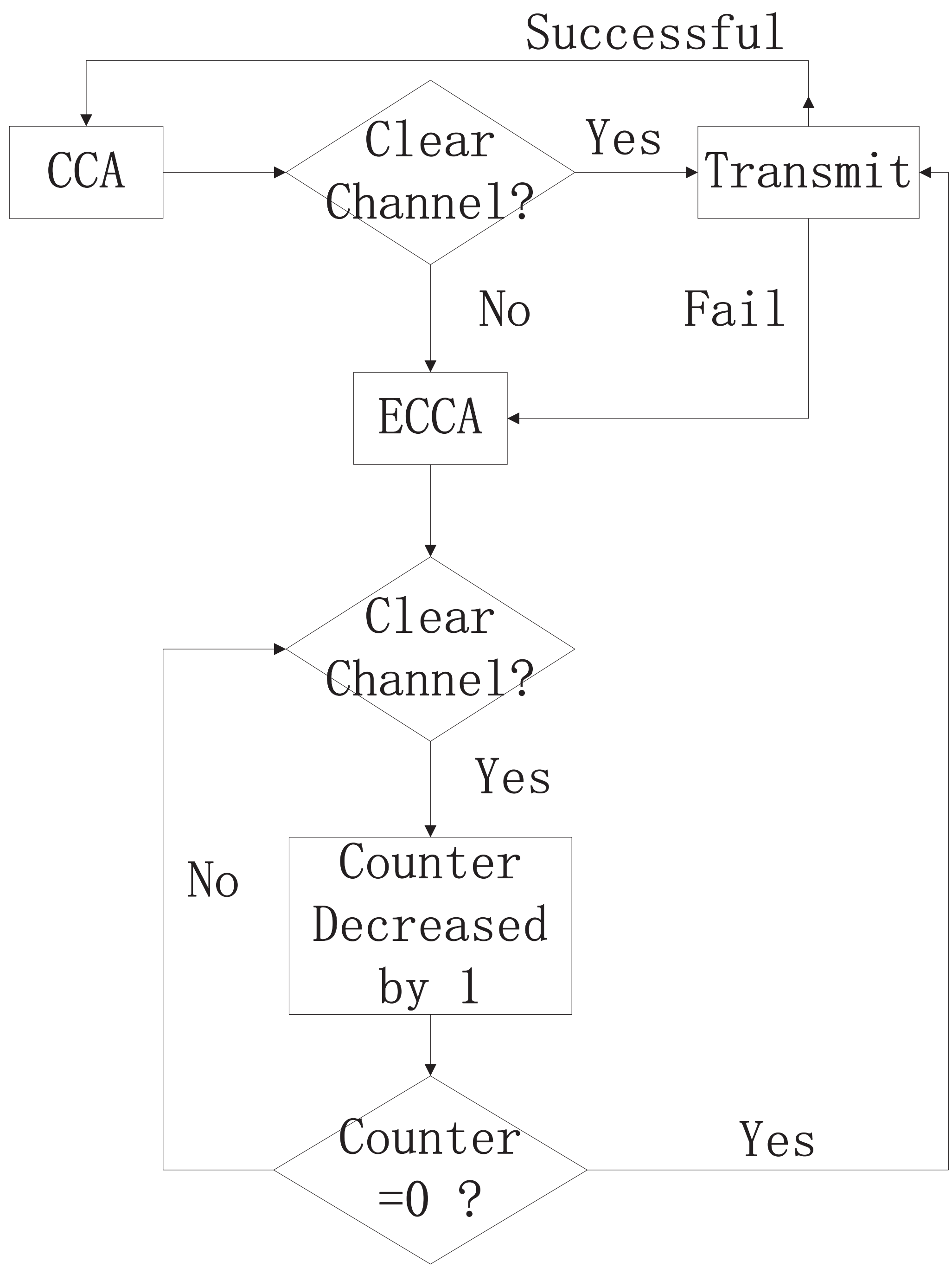

Fig. 2.4 LBE-based Coexistence Scheme

When the counter reaches zero, the equipment transmits and occupies the channel for a maximum amount of time of $N * (12/32)$ ms. If the transmission is successful, the equipment enters an idle state and will perform CCA when the next packet arrives; otherwise, the equipment enters the backoff procedure. There are two types of LBE-based LAA, which differ in backoff procedure:

- **Category (Cat) 4**: If a transmission is failed, the ECCA stage increases by 1 (up to 6) and the CW size doubles (up to the maximum CW size of 1024). If an eNB fails to deliver a packet when reaching the maximum ECCA stage, the ECCA stage and CW size will be reset to their initial values (ECCA stage 0 and CW size of 16).
- **Cat 3**: Different from Cat 4, in Cat 3 LBE-LAA scheme the CW size is fixed and there is only one ECCA stage.

[2] FBE-based LAA (Cat 2)

Different from LBE, FBE is not traffic-driven. In FBE, a fixed frame period (duration of 10 ms) is applied, which consists of a channel occupancy time (COT) and an idle period. Prior to transmissions, the FBE equipment performs a CCA check lasting at least 20 μs. If the channel is sensed to be idle, the equipment can transmit immediately during the COT, which is between 1 ms to 10 ms, along with an idle slot lasting at least 5 % of COT. Otherwise, the equipment is muted during the next fixed frame period.

[3] A comparison

LBE-based LAA and FBE-based LAA are compared in the following aspects:

- **Modification effect**: Compared with LBE-based LAA, fewer modification changes are required in FBE-based LAA.
- **Measurement and Coordination**: Measurement and coordination, such as synchronization, can be easily performed in FBE-based LAA.
- **Channel access chance**: Coexisting with Wi-Fi users or LBE-based equipment, FBE-based LAA will be muted for the whole fixed frame period if a CCA fails, which means less chance to access the unlicensed spectrum.
- **Resource efficiency and delay**: A lower resource efficiency and larger delay are expected because the arriving traffic is often blocked for the whole frame period if the channel is sensed to be busy during the CCA period.
- **Power Consumption of UEs**: After a failed CCA/ECCA check, FBE will wait for the whole long fixed frame period, while LBE may sense the channel multi-

ple times to access the channel, resulting in a higher power consumption in LBE compared with FBE.

[4] Related Works

Analysis and performance enhancement of LAA access schemes have attracted worldwide attention and research mainly focuses on two primary aspects.

1) Control of the CCA/ECCA procedure: The frame structure in FBE fixed frame and the backoff procedure in Cat 3 and 4 are critical factors in the coexistence between LAA and Wi-Fi networks. A FBE-based algorithm applying back-off and ECCA strategy is proposed in [37], LBT with synchronous frame structure performs poorer than that with asynchronous LBT due to the increase interference imposed on Wi-Fi due to reservation signal and overhead. In [38], a FBE-based scheme is proposed to enhance Wi-Fi performance at the expense of a slight degradation of coexisting LAA performance by adjusting the DL & UL frame numbers based on LTE TDD. However, the numeric results are obtained via simulation results. An enhanced LAA scheme based on Cat 3 LBT is proposed to enable fair coexistence between LAA and Wi-Fi by adjusting CW size. The proposed approach reduced Wi-Fi latency and enhanced Wi-Fi throughput while sacrificing a little LAA performance. However, the computational complexity of finding the optimal CW size is not analyzed [39]. In [2], Markov chain models are developed to evaluate the coexistence of Wi-Fi and Cat 4-based LAA-LTE, showing that by applying the LBT-based scheme Wi-Fi performance is enhanced. However, the developed Markov chain models are too simplified and Wi-Fi performance gain in p-resence of LBT is much lower than the LAA performance degradation. In [3], a Cat 4-based LAA-LTE is adapted in terms of CCA threshold and CW size to enable fair coexistence with Wi-Fi, however, the numeric results are obtained by simulation results. A four-state Markovian model is developed to capture the transmission process of an LAA-BS applying Cat 3 and Cat 4 LBT and closed-form of effective system capacity is derived. The expression of capacity is proved to be concave and the optimal capacity is obtained, which has enhanced the system capacity and energy efficiency significantly [4]. It also revealed that Cat 3 outperforms Cat 4 in networks with less number of LAA users and stations. However, the computational complexity of obtaining the maximum system capacity is not analyzed, which may affect the practical application of the proposed framework.

2) Control of the CCA Sensing Algorithm: The CCA sensing threshold should be carefully considered to enable fair coexistence between LAA and Wi-Fi. If a higher CCA threshold is adopted in LAA, Wi-Fi performance is less protected because ongoing Wi-

Fi transmission will not be detected if the received Wi-Fi transmission power is lower. LAA transmission will be scheduled, which may lead to a higher probability of collision. However, if the CCA threshold is lower, the channel accessing probability of LAA [3]. A tradeoff between frequency and interference avoidance is observed by changing the CCA energy detection threshold of LBE-based LAA scheme and an adaptive LBT scheme is developed to enhance LAA performance while guaranteeing Wi-Fi performance by adjusting CCA energy detection threshold [40].

Novel frameworks are introduced into the wireless networks control and scheduling, machine learning is one of them with great potential. An RL approach is developed in [41] to find the optimal duty cycle period to enable fair coexistence. However, the complexity analysis of the proposed scheme is missing, which makes whether this scheme can be practically efficient in doubt. In [42], a multi-agent RL learning framework is developed to enable Cat 4 LAA eNBs by tuning the minimum CW response to maximize sum LAA throughput and guaranteeing Wi-Fi throughput. However, the learning process of the proposed algorithm is not analyzed and the number of iterations to obtain converge Q-table is not presented, which is a limitation of this paper.

2.2.2 Access schemes without LBT

Duty cycle-based LTE-U scheme is proposed in markets without LBT requirements to enable resource sharing and fair coexistence with Wi-Fi networks. In Fig. 2.5, a 3-step mechanism centralized by carrier sense adaptive transmission (CSAT) is proposed by Qualcomm as shown [43]. The first step is channel selection, in which LTE-U implements a scanning procedure on the conditions of different unlicensed spectrums based on energy detection. If one or several clear channels is observed, the clearest channel to avoid the potential interference to and from Wi-Fi or other LTE-U transmissions. If LTE-U detects interference above a predefined threshold, it will switch to another clear channel it detects one. Channel selection enables fair coexistence between Wi-Fi and LTE-U networks, however, in a dense deployment scenario, where no clear channel can be observed, CSAT is proposed. The primary mechanism of CSAT is duty-cycle, which access the unlicensed spectrums based on a ON/OFF manner. LTE-U BSs stations fist sense the channel for a longer time, generally 10s of msec to 200 msec, than that of LBT or CSMA. Based on the observation of medium occupancy, an ON/OFF cycle is set. The BSs transmit on a high power level during the ON period, and transmit on a lower power level or even being muted during the OFF period so as to avoid interference to Wi-Fi transmission. Opportunistic supplement downlink (OSDL) is utilized based on demand. If the demand of the small cell is high and there are active users

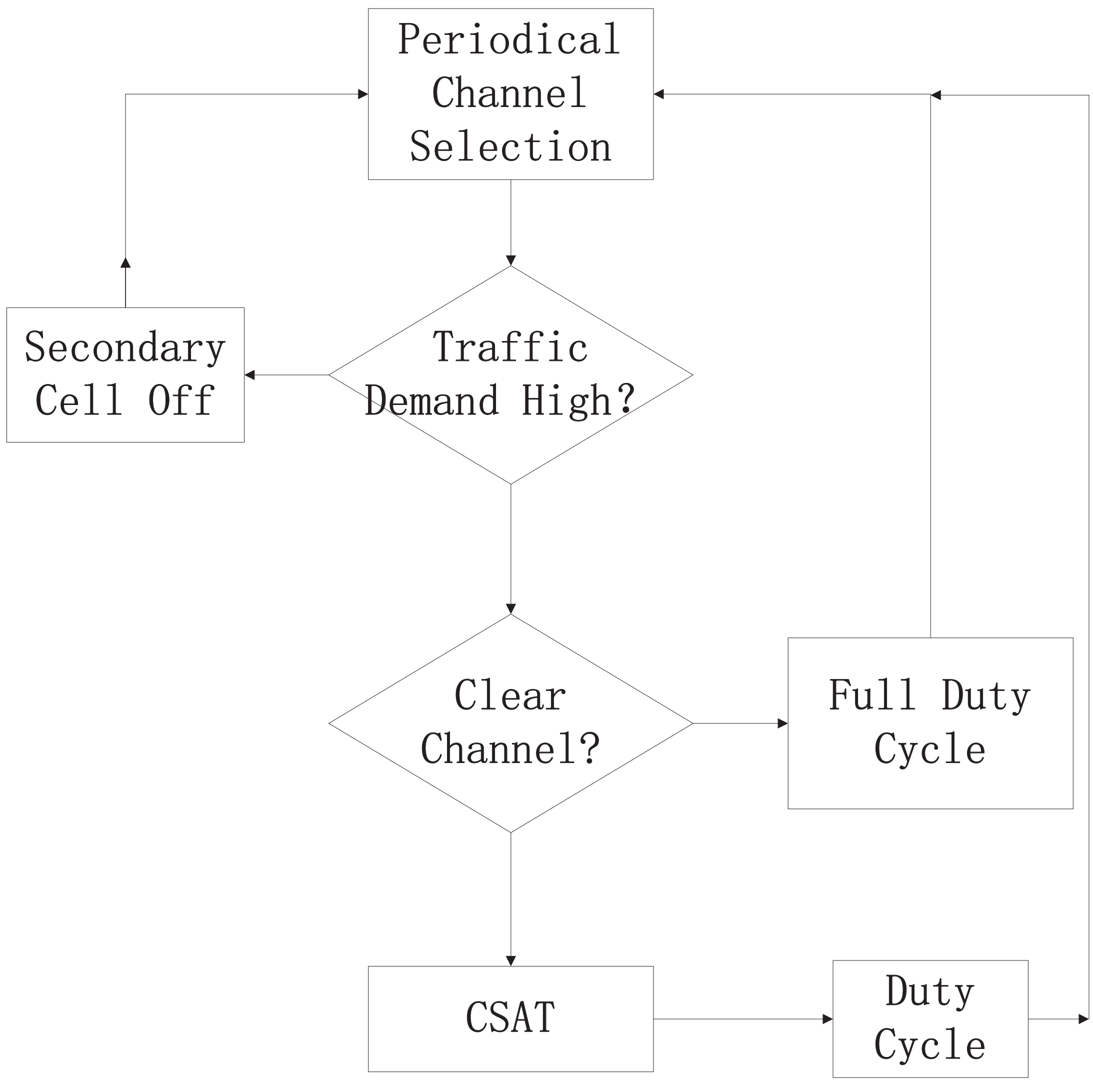

Fig. 2.5 Coexistence Scheme Centralized by CSAT

accessing the unlicensed spectrum, SDL transmission is turned on for higher throughput. If the demand of the small cell is low, or there are no active unlicensed spectrum users, the SDL transmission is turned off to avoid co-channel interference to Wi-Fi and other LTE-U users.

Almost blank sub-frame (ABS) scheme, which is similar to CSAT, can also be used for LTE-U by muting LTE-U transmissions on some sub-frames to avoid accessing the same channel at the same time with Wi-Fi. The concept of ABS was organically proposed in 3GPP Rel. 10 as part of eICIC for cross-tier interference management [20, 44]. To be specific, MBS transmissions are muted during the blank sub-frames so that the small cell or picocell edge users can be served better with much lower interference from MBS. Similarly, in a coexistence scenario, ABS-based LTE-U will be muted for several sub-frames, during which Wi-Fi devices can access the channel without interference from LTE-U [45].

CSAT scheme is more adaptive than the ABS scheme but requires coordination between different access technologies. In scenarios where coordination cannot be performed among devices from different operators, ABS is simpler to implement. ABS is also more flexible to exploit the channel during Wi-Fi backoff period in a competition-intense situation [46, 47].

[1] Related Works

Researches on LTE-U focused on the following aspects:

1) Duration and Ratio of ON/OFF period: Clearly, the duration of a duty cycle and the ratio of ON/OFF period has a significant impact on the performance of Wi-Fi and LTE-U. The duration of a duty cycle, being the summation of an ON and OFF period, strikes a trade-off between LTE-U and Wi-Fi performance. There is still no authoritative specifications that set the limit of duration of duty cycle ON and OFF period. LTE-U forum requires the ON and OFF period to be less than 50 ms [48], while the duration of a duty cycle is proposed to be great than 200 ms to enable a measurement for the shared medium [49]. A longer duration effectively enhances LTE-U performance with less overhead [50], while a shorter duration makes Wi-Fi transmissions suffer from a smaller latency [1].

2) Resource Allocation: Resource allocation problem in LTE-U is defined as the allocation of the unlicensed channels and/or licensed channels to CUs and WUs to maximize or minimize an objective function. Such optimization problem is generally NP-hard to obtain global optimal solutions. Various novel algorithms have been proposed to solve the resource allocation problems with reduced computational complexity. Game theory-based frameworks have been applied in resource allocation problems by considering UEs or BSs as the players choosing strategies to maximize their own inter-

est, such as throughput [51–53]. However, an agent (such as a UE or BS) needs the actions of other agents to make its own decisions in game theory, which requires information exchange between agents, which limits its distribution applications [54]. To overcome these limitations, matching theory has been applied to solve future wireless resource allocation problems. To maximize the sum system rate in a full duplex OFDMA network, UL and DL user pairing and sub-channel allocations are modeled as a three-sided one-to-one matching [5]. In [6], an uplink-downlink user decoupled association problem in multi-tier full-duplex cellular networks is formulated as a two-sided many-to-one matching. A near optimum solution of this problem is obtained by using a stable marriage-based algorithm with much lower complexity than that of a conventional coupled user decoupled association approach. To solve a resource allocation problem for device-to-device (D2D) communications underlying cellular networks, a two-sided many-to-many matching scheme with externalities is proposed to find the sub-optimality [7]. The student-project model is used to study the resource allocation problem in an LTE-U scenario, in which students (cellular users) apply for projects (unlicensed bands), and the decisions are made by lectures (base stations) to achieve maximal system (both LTE-U and Wi-Fi) throughput [55]. Based on this framework, the same optimization problem with user mobility is studied in [56].

3) Adaptivity of ON/OFF ratio: The ON/OFF ratio should be adaptive according to channel utilization conditions so as to optimize LTE-U performance and guarantee Wi-Fi performance. The adjustment of ON/OFF ratio could be done based on the measurement carried out at UEs and BSs [12, 57]. Also, collision is more likely to occur where the ABS ON frames are not adjacent as Wi-Fi transmissions are buffered during these periods [44]. Such problem can be solved by coordination between LTE-U and Wi-Fi networks so that Wi-Fi transmissions are confined in the ABS OFF period [1]. A coordination scheme is proposed to solve the information exchange on CSAT-based scheme between LTE-U and Wi-Fi networks [58], but the procedure consists of 7 steps, which is quite complicated and is not always piratical in every scenario especially LTE-U and Wi-Fi BSs belong to different operators. As the network topologies (number of UEs) and conditions (traffic load of each UE) varies from time to time, the ON/OFF ratio and resource allocation scheme is expected to change accordingly for maximum spectrum efficiency and UE QoS.

2.3 Motivation

Based on the above research we identify the following research challenges in respect to LAA and LTE-U, respectively.

2.3.1 Research Challenges for LAA

Based on the above research, 3 research challenges have been identified:

- **Performance Evaluation**: Many researches have been done to evaluate the coexistence of Wi-Fi and LAA, however, in most of the above works, performance analysis is based only on simulation results and focuses only on Wi-Fi performance. The coexistence performance of LAA and Wi-Fi should be evaluated for both Wi-Fi and LAA performance. Moreever, Markov chain model is applied to model Wi-Fi distributed coordination function (DCF) performance in [59], which showed a great effectiveness of modeling DCF scheme with great tractability. Markov chain has also been developed to analyze the performance between LAA and Wi-Fi in [2], however, the model is too simplified to capture LAA backoff procedure and the accuracy of numeric results is limited.

- **Performance Optimization**: Previous studies on DCF scheme showed that it is not always optimal. Modified DCF models under unsaturated traffic [60, 61], non-ideal channel conditions [62] and retry limits [63] have been developed for Wi-Fi systems. Various improvements of DCF have been proposed through the optimization of contention window (CW) [64–66]. The coexistence between Cat 3 (Cat 4) LAA and Wi-Fi faces unfairness in terms of resource utilization [67]. Such unfairness has been mitigated by changing the signal/energy threshold applied by LAA-LBT nodes [68], and by adaptively changing the CW size of LAA-LBT schemes [69–71]. However, all the above works focus on the change on adaptive LAA-LBT schemes while keeping Wi-Fi unchanged. Moreover, in [69], performance evaluation was based only on numeric results. In [70, 71], optimization problems, which were formulated as several integer linear programming (ILP) problems with different objectives (e.g. minimal collision probability, minimal required unlicensed spectrum), are NP-hard.

- **Learning Approach**: Reinforcement learning has been attractive in wireless communications to solve real-time resource allocation and scheduling problems in a self-organizing manner, enabling SCBSs or UEs choose the optimal action based on the wireless environment. It has been applied to optimize the performance of LAA coexisting with Wi-Fi [41, 42], however, the computational complexity of training the above learning-based algorithms are not analyzed, which leaves a gap from theory to reality.

2.3.2 Research Challenges for LTE-U

Based on the above research, 2 research challenges have been identified:

- **Fairness in Unlicensed Bands Allocation**: Fair coexistence in an LTE-U and Wi-Fi coexisting scenario is defined as that the deployment of the LTE-U system should not affect the performance of the Wi-Fi system more than another Wi-Fi system does [1, 72, 73]. Max-min fairness is another fairness definition to protect the user which is allocated the least resource by maximizing the minimum resource allocation. α-fairness is also used by evaluation the resource allocation fairness by developing α-fair utility functions. Both of max-min fairness and α-fairness are used to study throughput fairness in [74], where time division access and channel sharing between Wi-Fi and LTE-U proposed along with a criterion choosing one of the two schemes according to different network scenarios. Recently, the idea of quality of experience (QoE) has attracted increasing interest in wireless communications and QoE fairness has been proposed to quantify fairness by means of QoE of each end user [75].

- **Unlicensed & Licensed Bands Allocation**: How to efficiently allocate CUs and traffic across the licensed and unlicensed spectrums has attracted a lot of research interest. In [76], a centralized user association and resource allocation scheme across the licensed and unlicensed bands with different RATs was developed to minimize the average packet delay of all queues in the network. As the low flexibility of the centralized scheme, a distributed resource allocation scheme was proposed for software-defined cellular networks to maximize the total utility of all the CUs accessing both the licensed and unlicensed spectrums in [77]. In [78], a learning-based downlink traffic balancing scheme was proposed to maximize the energy efficiency of a small cell while guaranteeing its fair coexistence with Wi-Fi networks. In [79], a joint band selection across the unlicensed and licensed bands algorithm was proposed to minimize the sum interference that both cellular and Wi-Fi networks suffer from D2D communications. In [8], duty-cycle based spectrum sharing between CUs and Wi-Fi users (WUs) was developed to maximize the minimum throughput of CUs by offloading CUs to the unlicensed spectrums. In [9], a self-organized user association and resource allocation scheme was proposed to maximize the sum throughput of CUs and Wi-Fi users using an echo state-based learning approach. We note that most of the above works mainly focused on the optimization of overall system performance, such as sum throughput, average packet delay, etc., ignoring the fairness among CUs.

It has been shown that pricing strategies are effective in traffic-load balancing among base stations [10]. However, pricing strategies have not been sufficiently studied for traffic balancing between different radio access technologies. Operators may use pricing strategies to set various prices for CUs accessing the licensed and unlicensed spectrums because operators paid higher price for using the licensed spectrum. We study the traffic offloading ratio from the licensed spectrum to unlicensed spectrum by setting different prices for accessing the unlicensed bands and licensed bands and evaluate the traffic offloading ratio.

2.4 Methodology

In this section, Markov chain model and matching theory are introduced briefly. In Chapter 3, Markov chain is quite powerful to capture the performance of the procedure of DCF in Wi-Fi and LAA scheme in LAA, including traffic buffer, transmission success and failure, backoff counter, etc. Closed-form expression of transmission success and failure probability can be easily obtained based on the models and be used to calculate KPIs, such as throughput and transmission delay to evaluate the performance of Wi-Fi and LAA in coexistence scenarios. In Chapter 4 and 5, matching-based frameworks are developed to solve resource allocation problems between Wi-Fi and LTE-U, which are generally NP-hard to solve. The resource allocation obtained by using the matching approach are proved to be stable and Pareto optimal.

2.4.1 Markov Chain

Markov Chain is a stochastic model describing a sequence of states and the state transition probability, which satisfy Markov property: the transition probability from current state to another depends only on the current state [80]. The transition probability from one state to another is defined as the event. An example is shown in Fig. 2.6. The transition of the market state is listed as follows:

- The probability that the market keeps in the bull market;

  $P(bull|bull) = 0.9$

- The probability that the market transits from the bull market into the bear market; $P(bear|bull) = 0.075$
- The probability that the market transits from the bull market into the stagnant market; $P(stagnant|bull) = 0.025$
- The probability that the market keeps in the bear market; $P(bear|bear) = 0.8$
- The probability that the market transits from the bear market into the bull market; $P(bull|bear) = 0.15$
- The probability that the market transits from the bear market into the bull market; $P(stagnant|bear) = 0.05$
- The probability that the market keeps in the stagnant market; $P(stagnant|stagnant) = 0.5$
- The probability that the market transits from the stagnant market into the bull market; $P(bull|stagnant) = 0.25$
- The probability that the market transits from the stagnant market into the bear market; $P(bear|stagnant) = 0.25$

We obtain the following relation equations in steady state:

$$\begin{cases} p_{bull} = 0.9p_{bull} + 0.15p_{bear} + 0.25p_{stagnant} \\ p_{bear} = 0.075p_{bull} + 0.8p_{bear} + 0.025p_{stagnant} \\ p_{stagnant} = 0.025p_{bull} + 0.05p_{bear} + 0.5p_{stagnant} \\ Normalization\,condition : p_{bull} + p_{bear} + p_{stganant} = 1 \end{cases} \tag{2.1}$$

By mathematical calculation, it is quite easy to obtain a closed-form solution for this Markov chain, to get the probability of each state in steady state:

$$\begin{cases} p_{bull} = 0.625 \\ p_{bear} = 0.3125 \\ p_{stagnant} = 0.0625 \end{cases} \tag{2.2}$$

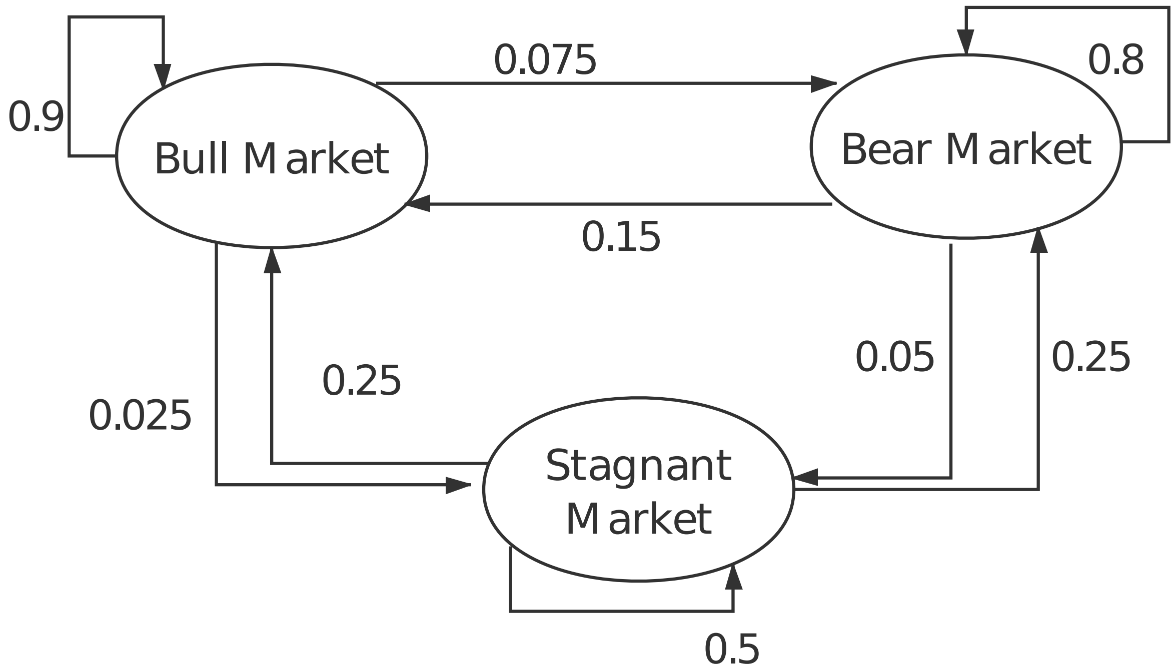

Fig. 2.6 Markov Chain model: stock market

The expected revenue in the stock market can be calculated accordingly.

Similarly, DCF in Wi-Fi and LBT scheme in LAA can be modelled by Markov Chain, which could be used to calculate the transmission probability of a Wi-Fi AP or an LAA eNB in a given scenario with easy mathematical calculation. The detail of Markov Chain models and corresponding calculations are expressed in Chapter 3.

2.4.2 Matching Theory

The matching theory was first used in economics to study a mutually beneficial relation between two disjoint sets [81]. The stable marriage (SM) problem is a typical one-to-one matching problem and is stated as follows: given same number of men and women, where each person has a preference list containing all the opposite sex in order of preference. One member of the two sex groups form a pair and the pair is deemed stable if there are no two people of the opposite sex who would both have each other rather than their current partners. Gale Shapley (GS) algorithm (also known as the deferred-acceptance algorithm) was proposed and proved to solve such SM problem [82]. GS algorithm for SM problem is stated as follows:

It has been proved that the matching μ_1 is stable and Pareto efficient by using GS algorithm.

Algorithm 2.1 GS algorithm

Input: $Men, Women, PL^{men}, PL^{women}$
Output: Matching μ_1
Stage 1: Proposing:
  All free *Men* propose their favourite women in their preference lists, and remove the women from the list.
Stage 2: Accepting/rejecting:
  Women accepts the most preferred man based on her preference list, the rest are rejected.
Termination Criterion:
  If all the men and women are paired.
  Otherwise, **Stage 1** and **Stage 2** are performed again.

SM problem can be extended to a many-to-one problem, such as the student project allocation (SPA) probelm. Each student has a preference list of the projects that they can choose from, while the lecturers have a preference list of students for each project or a preference list for student-project pairs. The maximum number of students that can be assigned to each particular project is limited and is denoted as the quota [83]. The GS algorithm for SPA problem is stated as follows:

Algorithm 2.2 SPA Matching

Input: $Student, Project, PL^{student}, PL^{project}, n$
Output: Matching μ_2
Stage 1: Proposing:
  All free *Student* propose their favourite project in their preference lists, and remove project from the list.
Stage 2: Accepting/rejecting:
  Each *project* accepts the most preferred n proposers based on its preference list, the rest are rejected.
Termination Criterion:
  If every *Student* is allocated with a project, this algorithm terminates with an output μ.
  Otherwise, **Stage 1** and **Stage 2** are performed again.

It has been proved that the matching μ_2 is stable and Pareto efficient by using the GS algorithm.

Inspired by the SPA problem, resource allocation problem in cellular networks can be transferred into a many-to-one matching problem.

- Matching theory can model the interactions between two distinct sets of players with different or even conflicting interests (Matching theory for future wireless networks:

fundamentals and applications,). For example, in an LTE uplink network, UE aims to achieve its QoS (mainly throughput) with minimal energy consumption while the objectives of small cell base stations (SCBSs) are serving users with certain QoS requirements and maximizing its capacity.

- Compared with game theory, a UE does not need other UEs' actions to make decisions. A preference list in terms of performance matrix, such as throughput and EE, is set up based on the local information including channel conditions. UEs made proposals according to this list. The only global information required from a centralized agent is the rejection/acceptance decision of each UE's proposal and blocking pair.

However, our resource allocation matching game differs from the SPA game in the following aspects:

- **Maximum throughput as the 'quota'**: The 'quota' or the maximum number of CUs can be served is limited by the capacity of a UB. The capacity of a UB is the maximum achievable throughput the UB can provide for CUs after reserving necessary resources to meet the minimum required WU throughput in TDD mode.

- **Incompleteness of preference lists**: The SCBSs sense the availabilities of UBs and keep the CUs updated. Any UB that is not able to fulfill a CU's minimal throughput requirement will be deleted from the preference list of the CU and the CU will also be removed from the preference list of that UB. Only a subset of UBs (CUs) are in the preference list of a CU (UB), i.e., the preference lists are incomplete.

The GS algorithm is modified according the the above differences and similarities in Chapter 4 and 5.

Chapter 3

Coexistence Between LAA Networks and Wi-Fi Systems: Performance Evaluations and Optimization

3.1 Introduction

Remind in Chapter 2.2.1 and 2.3.1, as the first global deployment LTE in the unlicensed spectrum, LAA is a key feature in 3GPP Rel. 13 and its performance has attracted world-wide interest. In this chapter, we study 3 topics on LAA.

The performance evaluation of LAA and Wi-Fi in a coexisting scenario has been studied by using analytical models, and Markov Chain models is one of the most popular ones. Markov chain models capture the back-off procedure and collision avoidance mechanism with great tractability to calculate the performance of LAA and Wi-Fi, such as throughput [2]. However, exiting Markov chain models neglect important factors of the LBT scheme in LAA [2] and DCF in Wi-Fi systems [59], which affects the accuracy of the performance evaluation results. Also, existing works mainly focus on Wi-Fi performance evaluation rather than LAA performance or overall performance. To overcome the above limitations, in section 3.2, We developed comprehensive Markov chain models for Wi-Fi DCF, Cat 3 and Cat 4 LBT-LAA to overcome the limitations of Markov models in [2, 59]. We evaluated throughput and mean transmission delay of coexisting LAA networks and Wi-Fi systems, respectively, which gives insights on the coexistence of LAA and Wi-Fi. This work has been published in our paper [67].

DCF applied in Wi-Fi has been proved to be inefficient in channel usage and multiple modifications have been proposed to enhance Wi-Fi performance by reducing channel idle period and collision probability [64–66]. Similar collodion avoidance scheme and back-off procedure in DCF is applied in LBT, the inefficiency problem also exists in LBT schemes. Such problems tend to affect the coexistence of LAA and Wi-Fi and spectral efficiency of the unlicensed spectrum. In section 3.3, we aim to maximize LAA system throughput while guaranteeing minimum Wi-Fi system throughput by tuning Wi-Fi and LAA CW sizes and it is formulated as an NP-hard nonlinear optimization problem (NLP). To solve the optimization problem with reduced complexity we propose a joint CW optimization scheme based on the mathematical derivations of the relationships between Wi-Fi (LAA) throughput and Wi-Fi & LAA initial CW sizes, which has not been achieved by any existing works. The performance of the proposed algorithm in terms of LAA throughput and computational complexity is evaluated through simulation compared with an exhaustive-search based algorithm. This work has been published in our work [84]

Reinforcement learning is a promising framework to solve real-time CW optimization problem concerning ever-changing and unpredictable Wi-Fi throughput requirements. Although reinforcement learning-based algorithms have been applied in Wi-Fi and LAA coexisting problems [41, 42], their computational complexity is not analyzed. In section 3.4, we develop a reinforcement learning based algorithm to find the optimal CW combination of LAA and Wi-Fi to solve the same problem in section 3.3. We analyze the computational complexity of this approach and overcome the limitation in [84], which based on the assumption being solid in dense networks only. The performance of the proposed algorithm is evaluated through simulations and comparisons between an exhaustive-search based algorithm.

3.2 Performance Evaluation

In this section, we evaluate the performance of both LAA networks and Wi-Fi systems in coexisting scenarios by using Markov chain-based models. We develop Wi-Fi model following Wi-Fi DCF, two LAA models following LAA Cat 3 and Cat 4 scheme, respectively. We calculate the transmission probabilities of Wi-Fi systems and LAA networks in coexisting scenarios, which is a key to the performance matrixes we evaluate, performance and transmission delay. We apply the definition of fairness between LAA networks and Wi-Fi systems coexistence as an LAA network should not affect a Wi-Fi system more than another Wi-Fi network [72, 85, 86]. Therefore, we also evaluate the performance of a Wi-Fi-only scenario as a comparison. Our models overcome the limitation of over-simplified models in [2, 59] and our results demonstrate a trade-off between Wi-Fi protection and LAA-Wi-Fi system performance enhancement.

3.2.1 System Model

Carrier sense mechanisms and corresponding thresholds are different for Wi-Fi and LAA-LBT. Wi-Fi devices can detect a minimum -82 dBm energy level for Wi-Fi signal with 20 MHz bandwidth and a minimum of -62 dBm energy level for a non-Wi-Fi signal with the same bandwidth. LAA-LBT energy detection threshold is -60 dBm with 20 MHz bandwidth for both Wi-Fi and non-Wi-Fi signals [36]. Recent research has shown that applying the same carrier sense threshold in Wi-Fi and LAA-LBT networks, and enabling Wi-Fi preamble detection in LAA-LBT would enhance Wi-Fi performance in coexistence scenarios [87, 88]. Therefore, also for analytical tractability, we apply the same carrier sense threshold settings in our system model. We consider a local network with a limited number of Wi-Fi APs and LAA eNBs sharing the same unlicensed bands, and all the nodes in the coexistence scenario can detect the signal from any one of the other nodes above the carrier sense threshold.

3.2.2 Cat 4 LBT-LAA

With Cat 4 LBT scheme, upon a new transmission buffered at an idle LAA eNB, it performs a clear channel assessment (CCA) to detect the availability of a an unlicensed band. If the band is sensed to be idle, the LAA eNB transmits immediately. If CCA fails to detect an idle band, LAA-LBT enters the extended-CCA (ECCA) stage 0 with an initial CW size of 16 with a back-off counter. Every time an unsuccessful transmission occurs, the ECCA stage increases by 1 and the CW size doubles (up to the maximum ECCA stage of 6 and the maximum CW size of 1024, respectively). The counter value is an integer randomly chosen from the range $(0, CW_m - 1)$ related to ECCA stage m . The counter is decremented by 1 if the band is sensed to be idle for the whole time slot, and freezes if the band is busy. When the counter reaches 0 the eNB starts transmission. If an eNB fails to deliver a packet when reaching the maximum ECCA stage, the ECCA stage will be reset to stage 0 and CW size to the initial CW size. The eNB enters idle state after the transmission is completed successfully and ECCA and CW will be reset to their initial values, respectively.

The above Cat 4 LBT LAA mechanism is formulated as Markov chains model as follows. The state of an LAA eNB is represented by a 2-tuple stochastic process $(s(t), z(t))$, where (-1, 0) denotes the state after a successful CCA. $s(t) \in (0, 1 \cdots m-1, m)$ denotes the ECCA stage and $z(t)$ denotes the counter value in the corresponding back-off stage. CW size of stage $s(t)$ is calculated as $CW_{s(t)} = CW_{min} 2^{s(t)}$. Under unified transmission failure probability p_f, the channel busy probability p_b and packet arrival rate q, state transition probabilities in the Cat 4 LBT Markov chains model in Fig. 3.1 are as follows:

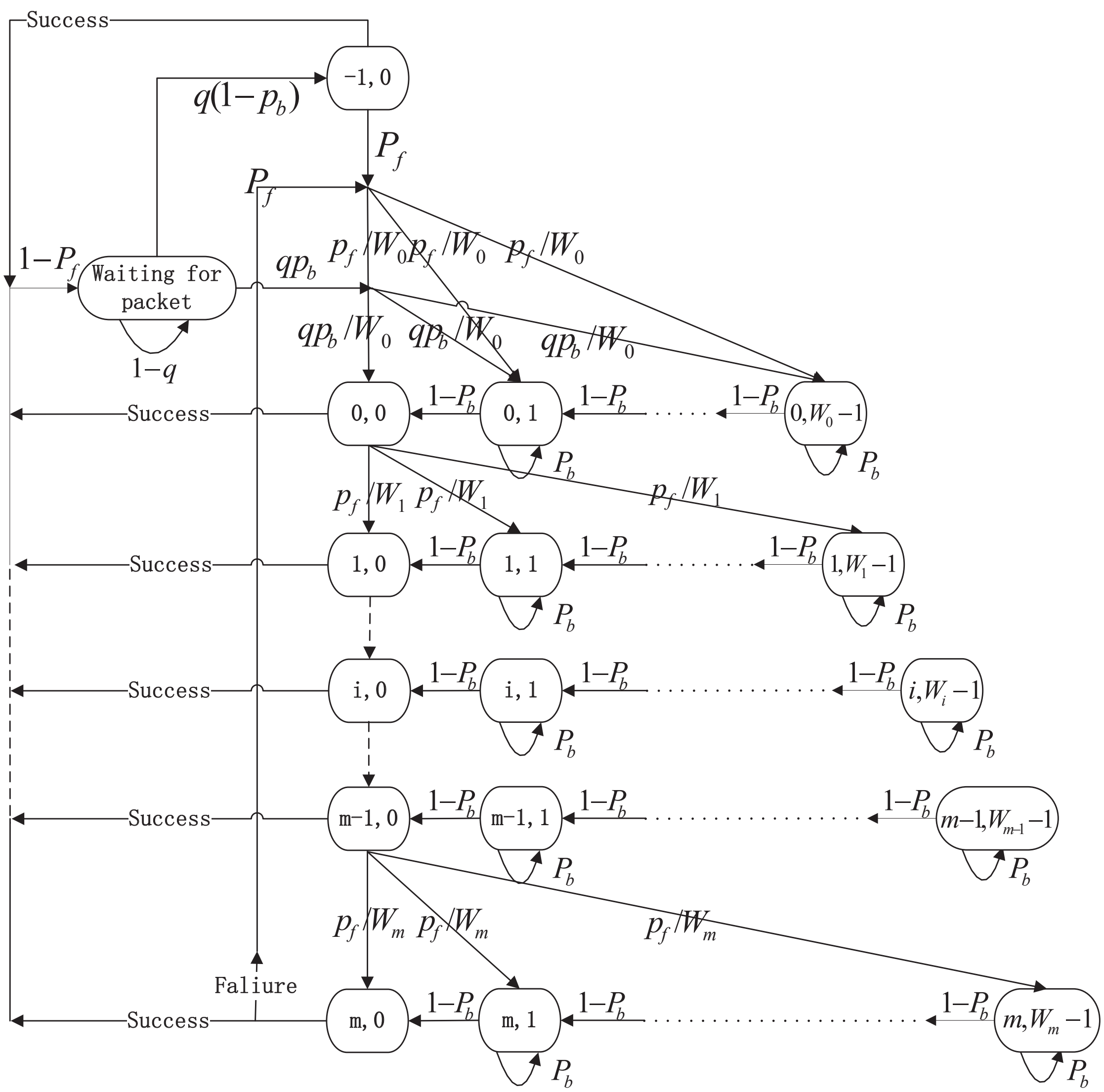

Fig. 3.1 Cat 4 LBT LAA Backoff Mechanism Modelling

- The probability that an eNB is idle, i.e, no pending transmission, is:

  $P(wait|wait) = 1 - q$

- The probability that an eNB transits from the idle state to (-1,0) state with a successful CCA is: $P(-1,0|wait) = (1 - p_b)q$

- The probability that an eNB enters ECCA stage from (-1,0) state after a failed transmission is:

  $P(0,k|-1,0) = p_f/W_0, k \in (0, W_0 - 1)$ where W_0 is the initial CW size, i.e. 16.

- The probability that an eNB enters backoff stage from the idle state with a unsuccessful CCA is : $P(0,k|wait) = qp_b/W_0, k \in (0, W_0 - 1)$

- The probability that the non-zero counter is decremented by 1 after the channel is sensed to be idle for a time slot is:

  $P(i,k-1|i,k) = 1 - p_b, i \in (0,m)\, and\, \in (1, W_i - 1)$

- The probability that the counter freezes because the channel is sensed to be busy is:

  $P(i,k|i,k) = p_b, i \in (0,m)\, and\, k \in (1, W_i - 1)$

- The probability that the ECCA stage increases by 1 due to transmission failure is:

  $P(i,k|i-1,0) = p_f/W_i, i \in (1,m) \cup k \in (0, W_i - 1)$

- The probability that the backoff stage reaches m and is reset after a transmission failure is:

  $P(0,k|m,0) = p_f/W_0, k \in (0, W_0 - 1)$

- The probability that an eNB returns to idle state after a successful transmission is:

  $P(w|i,0) = 1 - p_f, i \in (-1,m)$

We consider the stationary distribution of the Markov model $b_{i,k} = \lim_{t\to\infty} P(s(t) = i, b(t) = k)$, $i \in (-1,m)$ and $k \in (0, W_i - 1)$. We obtain the following relation equations in steady state:

$$\begin{cases} b_{wait} = (1-q)b_{wait} + (1-p_f)\sum\limits_{i=-1}^{m} b_{i,0}, i \in (-1,m) \\ b_{-1,0} = q(1-p_b)b_{wait} \\ b_{0,W_0-1} = \frac{q}{W_0}p_b b_w + \frac{p_f}{W_0}(b_{-1,0}+b_{m,0}) + p_b b_{0,W_0-1} \\ b_{0,j} = \frac{q}{W_0}p_b b_{wait} + \frac{p_f}{W_0}(b_{-1,0}+b_{m,0}) + p_b b_{0,j} + (1-p_b)b_{0,j+1}, j \in (1,W_0-1) \\ b_{0,0} = \frac{q}{W_0}p_b b_w ait + \frac{p_f}{W_0}(b_{-1,0}+b_{m,0}) + (1-p_b)b_{0,1} \\ b_{i,W_i-1} = \frac{p_f}{W_i}b_{i-1,0} + p_b b_{i,W_i-1}, i \in (1,m-1) \\ b_{i,j} = \frac{p_f}{W_i}b_{i-1,0} + p_b b_{i,j} + (1-p_b)b_{i,j+1}, i \in (1,m-1), j \in (1,W_i-2) \\ b_{i,0} = \frac{p_f}{W_i}b_{i-1,0} + (1-p_b)b_{i,1}, i \in (1,m-1) \\ b_{m,W_m-1} = \frac{p_f}{W_m}(b_{m-1,0}) + p_b b_{m,W_m-1} \\ b_{m,j} = \frac{p_f}{W_m}(b_{m-1,0}+b_{m,0}) + p_b b_{m,j} + (1-p_b)b_{m,j+1}, j \in (1,W_m-2) \\ b_{m,0} = \frac{p_f}{W_m}b_{m-1,0} + (1-p_b)b_{m,1} \\ Normalization\,condition: b_{wait} + \sum\limits_{i=-1}^{m}\sum\limits_{j=0}^{W_i} b_{i,j} = 1 \end{cases} \tag{3.1}$$

Where b_{wait} is the probability of a Cat 4 LBT LAA eNB being idle, and normalization condition means that the probabilities of all the states add up to 1.

By solving (3.1), we get the probability that a Cat 4 LBT LAA eNB transmits in a randomly chosen slot time as follows:

$$P_{tr}^{Cat4} = \sum_{i=-1}^{m} b_{i,0} = \frac{2q(1-p_b)(1-2p_f)R}{Q+q[W_0P(1-p_f)(1-(2p_f)^{m+1})+PR(1-2p_b)(1-2p_f)+2R(1-p_b)^2(1-p_f)(1-2p_f)]} \tag{3.2}$$

where $Q = 2(1-p_b)(1-p_f)(1-2p_f)$, $P = (p_b + p_f - p_b p_f)$ and $R = (1-p_f{}^{m+1})$.

3.2.3 Cat 3 LBT LAA

As shown in Fig. 3.2, Cat 3 LBT scheme is similar to Cat 4 LBT scheme except for the fixed CW size in Cat 3 LBT scheme. Similarly to that of Cat 4 LBT scheme, we obtain the following relation equations in steady state for Cat 3 LBT scheme:

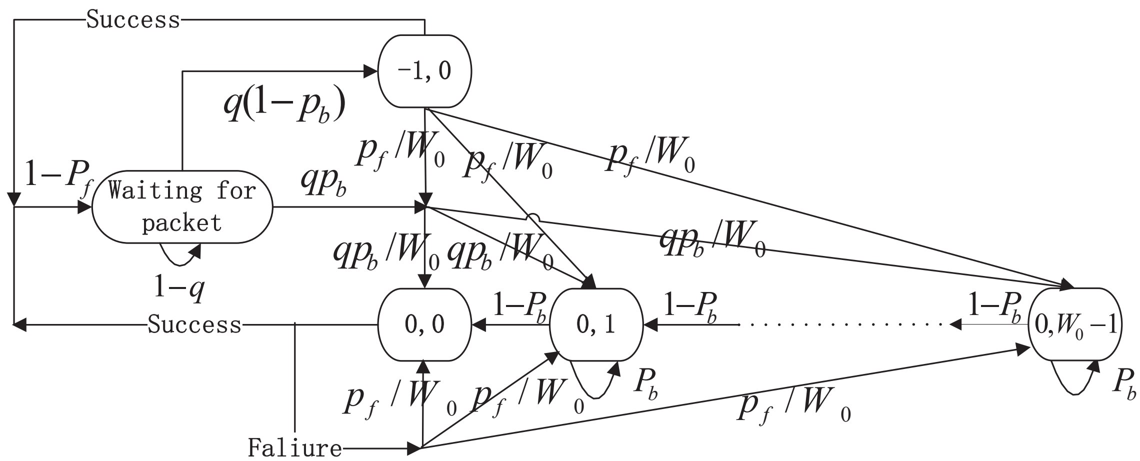

Fig. 3.2 Cat 3 LBT LAA Backoff Mechanism Modelling

$$\begin{cases} b_{wait} = (1-q)b_{wait} + (1-p_f)\sum\limits_{i=-1}^{0} b_{i,0}, i \in (-1,0) \\ b_{-1,0} = q(1-p_b)b_{wait} \\ b_{0,W_0-1} = \frac{q}{W_0}p_b b_{wait} + \frac{p_f}{W_0}(b_{-1,0}+b_{0,0}) + p_b b_{0,W_0-1} \\ b_{0,j} = \frac{q}{W_0}p_b b_{wait} + \frac{p_f}{W_0}(b_{-1,0}+b_{0,0}) + p_b b_{0,j} + (1-p_b)b_{0,j+1}, j \in (1, W_0-2) \\ b_{0,0} = \frac{q}{W_0}p_b b_{wait} + \frac{p_f}{W_0}(b_{-1,0}+b_{0,0}) + (1-p_b)b_{0,1} \\ Normalization\,condition: b_{wait} + \sum\limits_{i=-1}^{0}\sum\limits_{j=0}^{W_i} b_{i,j} = 1 \end{cases} \tag{3.3}$$

Where b_{wait} is the probability of a Cat 3 LBT LAA eNB being idle, and normalization condition means that the probabilities of all the states add up to 1.

By solving (3.3), we get the probability that a Cat 3 LBT LAA eNB transmits in a randomly chosen slot time as follows:

$$P_{tr}^{Cat3} = \sum_{i=-1}^{0} b_{i,o} = \frac{2q(1-p_b)}{(1-p_b)(1-p_f)+q[(1-p_b)^2(1-p_f)+(W_0+1)(p_f+p_b-p_b p_f)]} \tag{3.4}$$

3.2.4 Wi-Fi DCF

Different from the above two LAA LBT schemes, there is no $(-1, 0)$ state in Wi-Fi DCF, and an AP at the highest backoff stage that fails to deliver a packet will remain at that stage. The Markov chain model for Wi-Fi DCF is shown in Fig. 3.3.

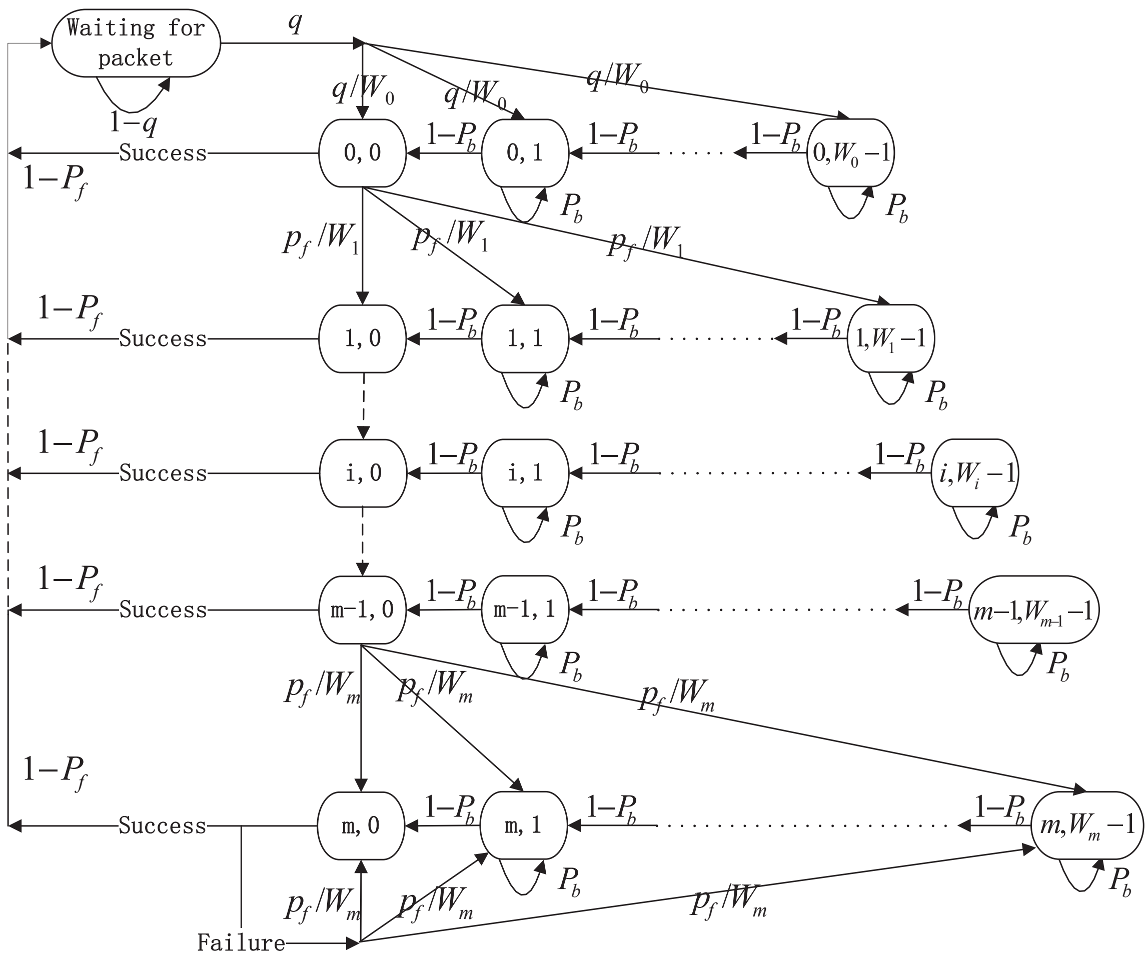

Fig. 3.3 Wi-Fi DCF

Accordingly, we obtain the following relation equations in steady state:

$$\begin{cases} b_{wait} = (1-q)b_{wait} + (1-p_f)\sum_{i=0}^{m} b_{i,0}, i \in (0,m) \\ b_{0,W_0-1} = \frac{q}{W_0}b_{wait} + p_b b_{0,W_0-1} \\ b_{0,j} = \frac{q}{W_0}b_{wait} + p_b b_{0,j} + (1-p_b)b_{0,j+1}, j \in (1, W_0-1) \\ b_{0,0} = \frac{q}{W_0}b_{wait}(1-p_b)b_{0,1} \\ b_{i,W_i-1} = \frac{p_f}{W_i}b_{i-1,0} + p_b b_{i,W_i-1}, i \in (1, m-1) \\ b_{i,j} = \frac{p_f}{W_i}b_{i-1,0} + p_b b_{i,j} + (1-p_b)b_{i,j+1}, \\ i \in (1, m-1), j \in (1, W_i-2) \\ b_{i,0} = \frac{p_f}{W_i}b_{i-1,0} + (1-p_b)b_{i,1}, i \in (1, m-1) \\ b_{m,W_m-1} = \frac{p_f}{W_m}(b_{m-1,0} + b_{m,0}) + p_b b_{m,W_m-1} \\ b_{m,j} = \frac{p_f}{W_m}(b_{m-1,0} + b_{m,0}) + p_b b_{m,j} + (1-p_b)b_{m,j+1}, j \in (1, W_m-2) \\ b_{m,0} = \frac{p_f}{W_m}(b_{m-1,0} + b_{m,0}) + (1-p_b)b_{m,1} \\ Normalization\, condition : b_{wait} + \sum_{i=0}^{m}\sum_{j=0}^{W_i} b_{i,j} = 1 \end{cases} \tag{3.5}$$

By solving (3.5), we get the probability that an AP transmits in a randomly chosen slot time as follows:

$$P_{tr}^{Wi-Fi} = \sum_{i=0}^{m} b_{i,0} = \frac{2q(1-p_b)(1-2p_f)}{2(1-p_b)(1-p_f)(1-2p_f)+q[W_0 p_f(1-(2p_f)^m)+(1+W_0-2p_b)(1-2p_f)]} \tag{3.6}$$

3.2.5 Transmission Probability

We consider 3 scenarios: Wi-Fi-AP only, the coexistence of Wi-Fi APs and Cat 4 LBT eNBs, and the coexistence of Wi-Fi APs and Cat 3 LBT eNBs.

- Wi-Fi-AP only System For a Wi-Fi AP in a Wi-Fi-AP only system (with n APs), if the channel is occupied by transmission(s) from other AP(s), the channel is sensed either to be busy or a collision occurs. Thus, the probability P_b^W that the channel is sensed to be busy and transmission failure probability P_b^W are identical for a Wi-Fi AP because all APs experience the same channel condition. Thus, we have:

$$P_b^W = P_f^W = 1-(1-P_{tr}^{Wi-Fi})^{n-1} \tag{3.7}$$

We get the transmission probability of a Wi-Fi AP in a Wi-Fi-AP only network by solving (3.6), (3.7) numerically.

- Wi-Fi & Cat 4 LBT scheme LAA Assuming that channel busy probability and transmission failure probability is identical for all APs and all eNBs, respectively. For a hybrid-RAT network with i Wi-Fi APs and j LAA eNBs we have:

$$\begin{cases} P_b^{W\dagger} = P_f^{W\dagger} = 1-(1-P_{tr}^{Wi-Fi})^{i-1}(1-P_{tr}^{Cat4})^{j} \\ P_b^{L\dagger} = P_f^{L\dagger} = 1-(1-P_{tr}^{Wi-Fi})^{i}(1-P_{tr}^{Cat4})^{j-1} \end{cases} \tag{3.8}$$

By solving (3.2), (3.6) and (3.8) numerically, we get the transmission probability of a Wi-Fi AP and Cat 4 LBT eNB in a coexistence network.

- Wi-Fi & Cat 3 LBT scheme LAA Similar to the calculation for Wi-Fi & Cat 4 LBT system, the transmission probability of a single AP and Cat 3 LBT eNB can be obtained by solving (3.4), (3.6) and (3.8) numerically.

Intuitively, the transmission probability of an LAA Cat 3 LBT eNB is the highest due to its fixed backoff stage, while that of a Wi-Fi AP is the lowest. It should be noted that the transmission failure probabilities and channel busy probabilities in (3.7) for a Wi-Fi AP or LBT, (3.8) are different from those of a system perspective. The system busy probability and transmission failure probability will be defined in section III to calculate system throughput and transmission delay.

3.2.6 System Throughput Analysis

The system throughput can be calculated as the expected transmitted packet size over the expected transmission time [59]:

$$S = \frac{E[P]P_s}{E[T]} \tag{3.9}$$

where $E[P]$ is the average packet size, P_s denotes the successful transmission probability in a random slot time, and $E[T]$ is the average length of a time slot.

Wi-Fi-AP only System

For a Wi-Fi system with n APs,

$$E[T] = (1-P_b)\delta + P_s^W \overline{T_s^W} + P_c^W \overline{T_c^W} \tag{3.10}$$

where

$P_s^W = nP_{tr}^{Wi-Fi}(1-P_{tr}^{Wi-Fi})^{n-1}$

$P_c^W = 1-(1-P_{tr}^{Wi-Fi})^n - P_s^W$

and the $\overline{T_s^W}$ is the average time that the channel is occupied due to a successful transmission and $\overline{T_c^W}$ is the average time that the channel is busy due to transmission collision [59]:

$$\begin{cases} T_s^W = \frac{(H+E[P])}{R_{Wi-Fi}} + \delta + SIFS + \frac{(ACK)}{R_{Wi-Fi}} + DIFS + \delta \\ T_c^W = \frac{(H+E[P])}{R_{Wi-Fi}} + \delta + DIFS + \frac{(ACK)}{R_{Wi-Fi}} + DIFS + \delta \end{cases} \tag{3.11}$$

where, $SIFS$ is the short interframe space (SIFS), $DIFS$ is the DCF interframe space (DIFS), δ is a slot time, H is the size of MAC and PHY header, $E[P]$ is packet size, ACK is the size of an acknowledgment frame and R_{LAA} is the bit rate of Wi-Fi.

Thus, the system throughput is given by:

$$S_W = \frac{P_s^W \overline{E(P_W)}}{(1-P_b)\delta + P_s^W \overline{T_s^W} + P_c^W \overline{T_c^W}} \tag{3.12}$$

Wi-Fi and LAA Coexistence

For a system with i Wi-Fi APs and j LAA eNBs, the system throughput for Wi-Fi and LAA can also be calculated by (3.9), respectively. However, $E[\mathrm{T}]$ is different from that in a Wi-Fi-AP only system, and contains the following events:

- the probability that the channel is idle is $1-P_b$, where $P_b = 1-(1-P_{tr}^{Wi-Fi})^i(1-P_{tr}^{LBT})^j$, and the corresponding time in a time slot is δ,
- the probability that the channel is occupied by a successful transmission of a Wi-Fi AP is $P_s^W = iP_{tr}^{Wi-Fi}(1-P_{tr}^{Wi-Fi})^{i-1}(1-P_{tr}^{LBT})^j$, and the corresponding time in a time slot is $\overline{T_s^W}$,
- the probability that the channel is occupied by a successful transmission of an LAA eNB is $P_s^L = (1-P_{tr}^{Wi-Fi})^i jP_{tr}^{LBT}(1-P_{tr}^{LBT})^{j-1}$, and the corresponding time in a time slot is $\overline{T_s^L}$,
- the probability that the channel is occupied by a collision between Wi-Fi transmissions is $P_c^W = (1-P_{tr}^{LBT})^j(1-(1-P_{tr}^{Wi-Fi})^i - iP_{tr}^{Wi-Fi}(1-P_{tr}^{Wi-Fi})^{i-1})$, and the corresponding time in a time slot is $\overline{T_c^W}$,

- the probability that the channel is occupied by a collision between LAA transmissions is $P_c^L = (1-P_{tr}^{Wi-Fi})^i(1-(1-P_{tr}^{LBT})^j - jP_{tr}^{LBT}(1-P_{tr}^{LBT})^{j-1})$, and the corresponding time in a time slot is $\overline{T_c^L}$,
- the probability that the channel is occupied by a collision between LAA and Wi-Fi transmissions is $P_c^{WL} = 1-P_b-P_s^W-P_c^W-P_s^L-P_c^L$, and the corresponding time in a time slot is $\max(\overline{T_c^W},\overline{T_c^L})$;

Thus, Wi-Fi and LAA throughput are calculated as:

$$\begin{cases} S_{Wi-Fi} = \\ \frac{P_s^{Wi-Fi}\overline{E(P_{Wi-Fi})}}{(1-P_b)\delta+P_s^W\overline{T_s^W}+P_s^L\overline{T_s^L}+P_c^W\overline{T_c^W}+P_c^L\overline{T_c^L}+P_c^{WL}\max(\overline{T_c^W},\overline{T_c^L})} \\ S_{LAA} = \\ \frac{P_s^{LAA}\overline{E(P_{LAA})}}{(1-P_b)\delta+P_s^W\overline{T_s^W}+P_s^L\overline{T_s^L}+P_c^W\overline{T_c^W}+P_c^L\overline{T_c^L}+P_c^{WL}\max(\overline{T_c^W},\overline{T_c^L})} \end{cases} \tag{3.13}$$

For simplicity, assuming that the LBT LAA scheme employs the same frame structure as Wi-Fi DCF scheme does, except for the ACK frame, which is transmitted immediately after the destination node receives the packet in the LBT LAA scheme [36]. Thus, we have

$$\begin{cases} T_s^L = \frac{(H+E[P])}{R_{LAA}} + \delta + \frac{ACK}{R_{LAA}} + DIFS + \delta \\ T_c^L = \frac{(H+E[P])}{R_{LAA}} + \delta + DIFS + \frac{ACK}{R_{LAA}} + DIFS + \delta \end{cases} \tag{3.14}$$

where, R_{LAA} is the bit rate of LAA, T_s^W and T_c^W are given in (3.11).

3.2.7 Transmission Delay

Transmission delay is another important indicator for the network performance and is defined as the time spanning from the beginning of an available packet until it is successfully received by its destination node. In a queuing system, according to the Little's law [89], the average number of customers (N) in a system in a long-term period is equal to the corresponding departure rate (λ) multiplied by the average transmission delay (W) that a customer spends in the system, i.e. $N = \lambda W$. In our analytical models in Section 3.2.1, no retry limit is considered, i.e. all the packets are ultimately successfully transmitted. The average number of a packet waiting in a Wi-Fi system is nq_W, or iq_W for Wi-Fi and jq_L for LAA in Wi-Fi-LAA networks. The departure rate is equivalent to the average number of packets being delivered per unit time, i.e., $\lambda_W = \overline{S_W}/E(p)$ in a Wi-Fi system, and as $\lambda_W = \overline{S_W}/E(p)$, $\lambda_L = \overline{S_L}/E(p)$ for Wi-Fi and LAA, respectively. Thus, for unlimited retry number, the transmission delay is expressed according to the Little's law [89]:

$$D = \frac{nq_W}{S_W/\overline{E(p)}} \tag{3.15}$$

for a Wi-Fi system, and

$$\begin{cases} D_W = \frac{iq_W}{S_W/\overline{E(p)}} \\ D_L = \frac{jq_L}{S_L/\overline{E(p)}} \end{cases} \tag{3.16}$$

for Wi-Fi and LAA nodes in a coexistence system, respectively.

3.2.8 Numeric Results

In this section, we evaluate the system performance for three systems.

- Wi-Fi only system: 3 or 6 Wi-Fi APs;
- Wi-Fi & Cat 4 LBT LAA coexistence: 3 Wi-Fi APs and 3 LAA eNBs with dynamic CW LBT;
- Wi-Fi & Cat 3 LBT LAA coexistence: 3 Wi-Fi APs and 3 LAA eNBs with fixed CW LBT.

The parameters used in the evaluations are listed in Table I. MAC header, PHY header and ACK frame length are defined in 802.11 standard [90]. The maximum transmission rate of 802.11ac is 96.3 Mbit/s [90], in the simulation the transmission rate of Wi-Fi and LAA is set to be 50 Mbit/s [2], half of the maximum value for a general case. CW_{min}, CW_{max}, Slot Time, SIFS, DIFS and packet size are defined in 802.11 standard [90].

Fig. 3.4 shows the system throughput of the four networks. The Wi-Fi system with 3 APs offers a slightly higher system throughput than the one with 6 APs, which agrees with the results in [59]. This is because of the heavier contention among the increasing number of APs. Wi-Fi throughput experiences a higher degradation in coexistence with Cat 3 LBT LAA than with Cat 4 LBT LAA, which implies that LAA with dynamic LBT CW size is a better neighbour to Wi-Fi than with fixed LBT CW size. This is consistent with the simulation results provided in [91]. Compared with Wi-Fi systems, the overall throughput of Wi-Fi & LAA coexistence systems is much higher at the expense of Wi-Fi throughput degradation. Between the two Wi-Fi-LAA coexistence systems, Wi-Fi-LAA system with Cat 3 LBT LAA eNBs provides higher throughput than that with Cat 4 LBT scheme LAA eNBs. Although Wi-Fi throughput in Wi-Fi-LAA system with Cat 3 LBT LAA eNBs is smaller than that in Wi-Fi-LAA system with Cat 4 LBT scheme LAA eNBs. This implies

Table 3.1 Wi-Fi system and LAA system parameters

Packet Size	12800 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
Wi-Fi Bit Rate	40 Mbit/s
LAA Bit Rate	75 Mbit/s
q_w	1
q_l	1
Slot Time	9 μs
SIFS	16 μs
DIFS	34 μs

that Cat 3 LBT LAA occupies the unlicensed bands more efficient than Cat 3 LBT LAA and Wi-Fi is degraded more coexisting with Cat 3 LBT LAA than with Cat 4 LBT LAA. As a result, Wi-Fi APs coexisting with Cat 3 LBT LAA eNBs suffer more reduction in throughput.

The average throughput provided by each Wi-Fi AP or LAA eNB is shown in Fig. 3.5. The 3-AP Wi-Fi system provides the highest throughput per-AP, followed by the 6-AP Wi-Fi, Wi-Fi APs coexisting with Cat 3 LBT LAA eNBs have the lowest throughput per AP. This implies that LAA eNBs with LBT fixed CW size degrades the performance of coexisting Wi-Fi APs more than the same number of LAA eNBs with dynamic LBT CW size or the same number of Wi-Fi APs. Either Cat 3 LBT LAA eNBs or Cat 4 LBT LAA eNBs affect Wi-Fi throughput more than the same number of Wi-Fi APs, implying that fair coexistence can not be guaranteed by using baseline Cat 3 LBT LAA scheme or Cat 4 LBT LAA scheme. Cat 3 LBT eNBs achieve the highest throughput per node among all nodes in all scenarios. The per-node throughput of Cat 4 LBT LAA LAA eNBs is slightly lower than that of Wi-Fi APs in the 3-AP Wi-Fi system but much higher than that of Wi-Fi APs in all the other scenarios. This implies that, among the 3 access schemes, Cat 3 LBT LAA eNBs make the most efficient use of the unlicensed spectrum and Wi-Fi occupy the unlicensed spectrum least efficiently.

Fig. 3.6 shows the transmission delays of Wi-Fi and LAA in different networks. We can see that the 3-AP Wi-Fi system has the lowest transmission delay among all Wi-Fi systems,

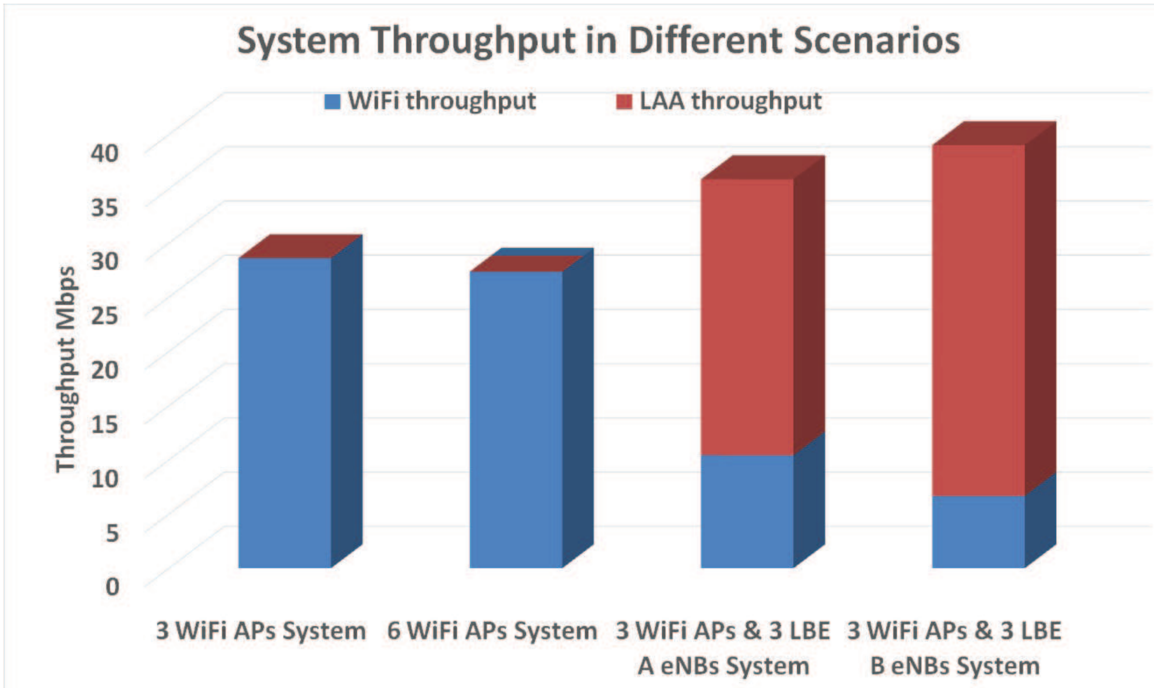

Fig. 3.4 System throughput in different scenarios

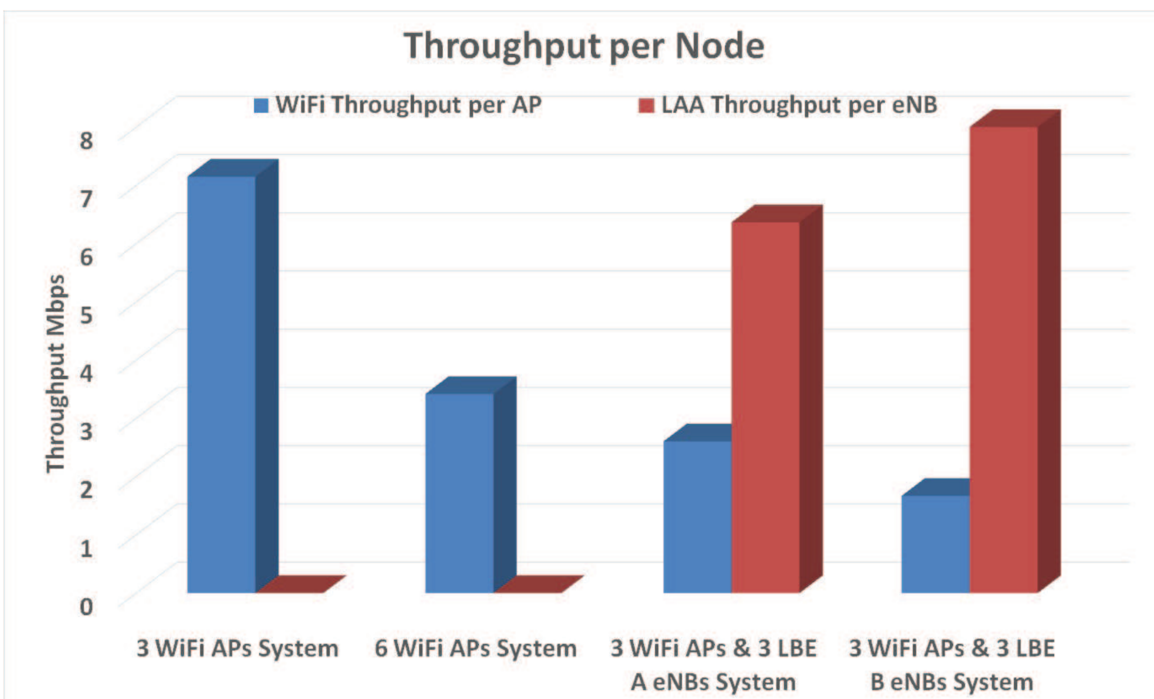

Fig. 3.5 Throughput per node in different scenarios

while the delay is more than doubled in the 6-AP Wi-Fi system. Wi-Fi APs experience the highest transmission delay in coexistence with Cat 3 LBT LAA eNBs. Cat 4 LBT LAA experience slightly lower delay than Cat 3 LBT LAA eNBs, while the latter has slightly larger delay than the 3-AP Wi-Fi system. Either Cat 3 LBT LAA eNBs or Cat 4 LBT LAA eNBs affect Wi-Fi transmission delay more than the same number of Wi-Fi APs, implying that fair coexistence can not be guaranteed by using baseline Cat 3 LBT LAA scheme or Cat 4 LBT LAA scheme.

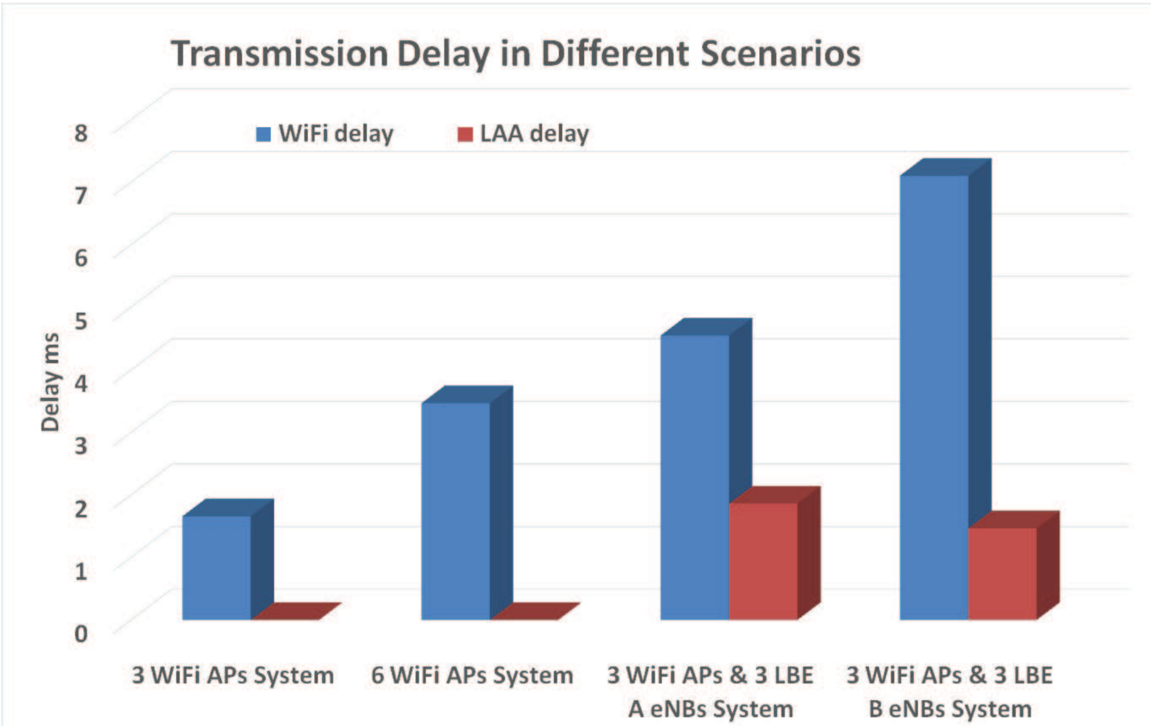

Fig. 3.6 Transmission delay in different scenarios

From Figs. 3.4-3.6 we can see that Cat 4 LBT LAA eNBs provide better protection of Wi-Fi performance (in terms of both throughput and transmission delay). Regarding LAA system performance, LAA LBT with fixed CW size outperforms LAA LBT with dynamic CW size in terms of both throughput and delay. This implies that there is a trade-off between Wi-Fi protection and LAA system performance in the design or choice of LAA LBT mechanism.

The backoff procedure is quite critical in terms of throughput and LAA, compared with Cat 4 and Cat 3, more backoff stages are designed in Cat 4 scheme which results in a less aggressive channel access manner. There two ways to change the channel access probability: 1) the number of backoff stage and 2) backoff CW size. By increasing either one of the number of backoff stage or backoff CW size, the channel access probability decreases and Wi-Fi performance is less affected in a coexistence scenario.

3.2.9 Conclusion

In this section, we have analyzed the downlink performance of LAA and Wi-Fi coexisting in the unlicensed spectrum. We have established Markov chain models to calculate the throughput and delay of Wi-Fi networks and Wi-Fi-LAA networks. Regarding 2 LAA LBT schemes, numerical results indicate that LAA LBT with fixed CW size outperforms LAA LBT with dynamic CW size while degrades Wi-Fi performance more.

Our analytical results demonstrate the trade-off between Wi-Fi performance protection and LAA performance enhancement. If we hold the definition of fairness as LAA networks that affect a Wi-Fi system no more than another Wi-Fi system, spectral efficiency is sacrificed. We consider other criteria to measure fairness, especially on Wi-Fi's side: fair coexistence between LAA networks and Wi-Fi systems should ensure minimum Wi-Fi performance, such as throughput. From the next section, we will use this definition in our optimization problem as constraints to ensure fair coexistence.

3.3 Contention Window Based Optimization

In this section, we analyze a Wi-Fi and LAA coexisting scenario, in which we aim to find the optimal combination of LAA and Wi-Fi CWs to maximize LAA throughput while guaranteeing Wi-Fi throughput above a certain threshold. This optimization problem is NP-hard.

We derive the explicit expressions for the relationships between Wi-Fi (LAA) throughput and Wi-Fi & LAA initial CW sizes, which have not been achieved by any existing works. Based on the derived relationships, we proposed a joint optimization scheme to find the optimal combination of Wi-Fi and LAA initial CW to maximize LAA throughput and guarantee Wi-Fi throughput above a pre-defined threshold. The proposed scheme has much lower complexity (P-hard) than solving ILP.

The accuracy and efficiency of our proposed joint optimization scheme are verified by comparing it with an exhaustive search scheme. The proposed scheme offers a significant LAA (system) throughput gain up to 100% (40%) over the coexisting Wi-Fi and LAA with fixed initial CW sizes. Especially, the effectiveness of the proposed scheme in dense scenarios is also revealed.

3.3.1 System Model

To analyze the throughput of n Wi-Fi and m LAA in a coexistence scenario, we apply the same system framework as in section 3.2.1, which is also presented in (12) in [67]. Assume the average packet size for Wi-Fi and LAA are the same and denote as $\overline{E(p)}$, we have the i-th LAA and the j-th Wi-Fi throughput:

$$\begin{cases} S_i^L = \frac{\overline{E(p)} P_{s,i}^L}{P_I \delta + \overline{T_s} + \overline{T_c}} \\ S_j^W = \frac{\overline{E(p)} P_{s,j}^W}{P_I \delta + \overline{T_s} + \overline{T_c}} \end{cases} \tag{3.17}$$

where: $P_{s,i}^L$ and $P_{s,j}^W$ are the successful transmission probability of the i-th LAA eNB and the j-th Wi-Fi AP, respectively. P_I is the probability that channel being idle, and δ is the slot time (9μs) of 802.11.

$\overline{T_s}$ is the expected time consumed by a successful transmission (either LAA or Wi-Fi):

$$\overline{T_s} = P_s^L T_s^L + P_s^W T_s^W \tag{3.18}$$

Where P_s^L and P_s^W are the successful transmission probability of any LAA eNB and Wi-Fi AP. T_s^L and T_s^W are the average time consumed by a successful transmission of LAA and Wi-Fi, respectively.

$$\begin{cases} T_s^L = \frac{H+\overline{E(p)}}{R_L} + \delta + \frac{ACK}{R_L} + DIFS + \delta \\ T_s^W = \frac{H+\overline{E(p)}}{R_W} + \delta + \frac{ACK}{R_W} + DIFS + \delta \end{cases} \tag{3.19}$$

where, R_L and R_W are the transmission rate of LAA and Wi-Fi, respectively. H is the size of a packet head, ACK is the size of an ACK frame. $DIFS$ is the DCF inter-frame space defined in 802.11.

$\overline{T_c}$ is the average time duration for a collision and is given by:

$$\overline{T_c} = P_c^L T_c^L + P_c^W T_c^W + P_c^{LW} max(T_c^L, T_c^W) \tag{3.20}$$

Collision arises due to more than one simultaneously transmissions in the same time slot. There are three types of collisions: collision between Wi-Fi transmissions (with probability P_c^W), collision between LAA transmissions (with probability P_c^L), and collision between Wi-Fi and LAA transmissions (with probability P_c^{LW}).

The average time consumed by the first and second type of collision is T_c^L and T_c^W:

$$\begin{cases} T_c^L = \frac{H+\overline{E(p)}}{R_L} + \delta + DIFS + \frac{ACK}{R_L} + DIFS + \delta \\ T_c^W = \frac{H+\overline{E(p)}}{R_W} + \delta + DIFS + \frac{ACK}{R_W} + DIFS + \delta \end{cases} \tag{3.21}$$

3.3.2 Problem Formulation

We consider a scenario where n Wi-Fi APs and m LAA eNBs coexisting and contending for the same unlicensed spectrum. We formulate our optimization problem as maximizing LAA throughput while guaranteeing Wi-Fi performance above a predefined throughput:

$$\textbf{Max} \qquad \sum_{i=1}^{m} S_i^L \tag{3.22}$$

s.t. :

$$S_j^W \geq Threshold, \forall CW^L, CW^W \in [CW_{Min}, CW_{Max}], j \in [1,n] \tag{3.23}$$

and (3.18) - (3.21).

In a Wi-Fi-LAA coexistence scenario, n Wi-Fi APs and m LAA eNBs compete for the same medium resource. We denote the transmission probability of a Wi-Fi AP and an LAA eNB as p' and p, respectively. We applied the same expression in terms of transmission successful probability and collision probability in [67].

$$\begin{cases} P_I = \prod_{j=1}^{n}(1-p'_j)\prod_{i=1}^{m}(1-p_i) \\ P_{s,j}^W = p'_j \prod_{k\neq j}^{n}(1-p'_k)\prod_{i=1}^{m}(1-p_i) \\ P_s^W = \sum_{j=1}^{n} P_{s,j}^W \\ P_{s,i}^L = \prod_{k=1}^{n}(1-p'_k)p_i\prod_{k\neq i}^{m}(1-p_i) \\ P_s^L = \sum_{i=1}^{m} P_{s,i}^L \\ P_c^W = \prod_{i=1}^{m}(1-p_i) - P_I - P_s^W \\ P_c^L = \prod_{j=1}^{n}(1-p'_i) - P_I - P_s^L \\ P_c^{LW} = 1 - P_I - P_s^W - P_s^L - P_c^W - P_c^L \end{cases} \tag{3.24}$$

The transmission probabilities of LAA and Wi-Fi is p and p' which take the following expressions for simplicity [64, 92]:

$$\begin{cases} p_i = \frac{2}{1+CW_i^L} \\ p'_j = \frac{2}{1+CW_j^W} \end{cases} \tag{3.25}$$

3.3.3 Analysis of Throughput in Coexistence Scenario

In this section, we propose a joint optimization algorithm based on mathematical derivation to solve the optimization problem 3.22 formulated in the previous section.

We assume that all Wi-Fi APs share the same wireless conditions and so do all the LAA eNBs, which is widely accepted [64, 66]. For simplicity, we assume that the transmission rate of Wi-Fi APs and LAA eNBs to be the same, i.e. $R_W = R_L$. Thus we have:

$$\begin{cases} T_s = T_s^W = T_s^L \\ T_c = T_c^W = T_c^L \end{cases} \tag{3.26}$$

The expressions of LAA and Wi-Fi throughput are simplified as follows:

$$\begin{cases} S_L = \frac{\overline{E(p)}P_s^L}{P_I\delta+(P_s^L+P_s^W)T_s+(P_c^L+P_c^W+P_c^{LW})T_c} \\ S_W = \frac{\overline{E(p)}P_s^W}{P_I\delta+(P_s^L+P_s^W)T_s+(P_c^L+P_c^W+P_c^{LW})T_c} \end{cases} \tag{3.27}$$

In a Wi-Fi-LAA coexistence scenario with n Wi-Fi APs and m LAA eNBs competing for the same unlicensed band.

According to the relations between transmission probability and CW in (3.25), to find the optimal combination of LAA and Wi-Fi CWs is equivalent to finding the optimal transmission probabilities of LAA and Wi-Fi.

Taking the first derivative of the LAA throughput against p and p', we have:

$$\begin{aligned} \frac{\partial S_L}{\partial p} = (1-mp)x' + (1-p')^{n-1}(1-p)^m * \\ [np'(1-x) - (1-p')(x'-x)] \end{aligned} \tag{3.28}$$

$$\frac{\partial S_L}{\partial p'} = (1-p')^{n-1}(1-p)^m(1-x) - x' \tag{3.29}$$

where according to (3.19) and (3.21), $x' = \frac{\delta}{T_s}(\to 0)$ and $x = \frac{T_c}{T_s}(> 1)$.

Then we take the first derivative of the Wi-Fi throughput against p and p':

$$\begin{aligned} \frac{\partial S_W}{\partial p'} = (1-np')x' + (1-p')^n(1-p)^{m-1} * \\ [mp(1-x) - (1-p)(x'-x)] \end{aligned} \tag{3.30}$$

$$\frac{\partial S_W}{\partial p} = (1-p')^n(1-p)^{m-1}(1-x) - x' \tag{3.31}$$

Let us first consider (3.29) and (3.31), as $x > 1$, we have:

$$\begin{cases} \frac{\partial S_L}{\partial p'} < 0 \\ \frac{\partial S_W}{\partial p} < 0 \end{cases} \tag{3.32}$$

Theorem 3.1. *The LAA throughput is monotonically decreasing with the transmission probability of Wi-Fi, and the Wi-Fi throughput is monotonically decreasing with the transmission probability of LAA.*

To find the maximum LAA throughput against LAA transmission probability, we let (3.28) be 0.

For simplicity, we assume$(1-p)^m \approx 1-mp$ in (3.28), and because $x' << x$ we have:

$$\begin{cases} p_1 = \frac{1}{m-1} \\ p_2 = \frac{x}{xm-m+x} \end{cases} \tag{3.33}$$

Converting transmission probabilities to CWs by using the expression (3.25), we have:

$$\begin{cases} CW_1^L = 2m-3 \\ CW_2^L = 2m(1-\frac{1}{x})+1 \end{cases} \tag{3.34}$$

If $n <= 2$, then $CW_1^L < CW_2^L$. In the interval $[CW_1^L, CW_2^L]$, LAA throughput increases with LAA CW; in the interval $[CW_2^L, \infty]$, LAA throughput decreases with LAA CW. As $CW_2^L - 1 \approx 0$, in the interval $[CW_{Min}, CW_{MAx}]$, LAA throughput decreases with CW. For $n > 2$, $CW_1^L > CW_2^L$. In the interval $[CW_2^L, CW_1^L]$, LAA throughput is increasing against LAA CW; in the interval $[CW_1^L, \infty]$, LAA throughput decreases with LAA CW. Thus for the interval $[CW_{Min}, CW_1^{LAA}]$, LAA throughput is increasing; for the searching interval $[CW_1^L, CW_{Max}]$, LAA throughput is decreasing. Thus, for a proper chosen CW range, LAA throughput decreases with LAA CW size, e.g. CW interval [8, 64] for 4 LAA eNBs.

Solving (3.30), we obtain the similar insights for the change of Wi-Fi throughput with Wi-Fi CW.

$$\begin{cases} p'_1 = \frac{1}{n-1} \\ p'_2 = \frac{x}{xn-n+x} \end{cases} \tag{3.35}$$

Thus, for proper choosing of CW range, LAA throughput is monotone decreasing against the CW of LAA, and Wi-Fi throughput is monotone decreasing against the CW of Wi-Fi.

3.3.4 Joint CW Optimization Algorithm

A joint CW optimization algorithm proposed in [84] is used as a comparison. Algorithm 3.1 is used to find the solution space **S** that satisfies the Wi-Fi throughput threshold condition based on Theorem 3.1 in [84].

Algorithm 3.1 Joint CW Optimization Algorithm: Finding Solution Space [84]

1: **for** $CW_{Wi-Fi} \leftarrow CW_{Min} : 1 : CW_{Max}$ **do**
2:     $Initialize \quad CW_{Min}, CW_{Max}$
3:     $CW_L^{Upper} \leftarrow CW_{Max}$
4:     $CW_L^{Lower} \leftarrow CW_{Min}$
5:     $(S_1^W, S_1^L) \leftarrow TH(CW_W, CW_L^{Upper})$
6:     $(S_2^W, S_2^L) \leftarrow TH(CW_W, CW_L^{Lower})$
7:     *loop:*
8:     **if** $S_1^W > 0$ **then**
9:         **while** $CW_L^{Upper} - CW_L^{Lower} > 1$ **do**
10:             **if** $S_2^W > 0$ **then**
11:                 $CW_L^{Upper} \leftarrow 1/2(CW_L^{Upper} + CW_L^{Lower})$
12:                 $(S_2^W, S_2^L) \leftarrow TH(CW_W, CW_L^{Upper})$
13:             **end if**
14:             **if** $S_2^W < 0$ **then**
15:                 $CW_L^{Lower} \leftarrow 1/2(CW_L^{Upper} + CW_L^{Lower})$
16:                 $(S_2^W, S_2^L) \leftarrow TH(CW_W, CW_L^{Lower})$
17:             **end if**
18:         **end while**
19:         $CW_0 \leftarrow CW_{Max}$
20:         $Save \quad CW_W, \quad corresponding \quad CW_0, \quad S_2^W,$
21:         $and \quad S_2^L in \quad$ **S**
22:     **end if**
23: **end for**

It is quite simple to find the maximum LAA throughput in the output of Algorithm 3.1 **S** by using the ranking function in Matlab.

The complexity of Algorithm 3.1 is $O(Dlog_2(D))$, which is the number of iterations. Each iteration corresponds to the whole while loop (line 9-18) in Algorithm 3.1.

3.3.5 Exhaustive Search

The exhaustive search is also applied as a benchmark to evaluate the accuracy and efficiency of the proposed optimization algorithm. Exhaustive search follows the same two-step procedure in the proposed optimization scheme, i.e. 1) to generate a solution space that meets Wi-Fi minimal throughput criterion; 2) to find the maximum LAA throughput along with its corresponding CW combination.

For simplicity, exhaustive search has certain searching direction in terms of choosing CW combination, i.e. searching begins with the minimal Wi-Fi and LAA CW sizes. In each iteration, Wi-Fi throughput at the current CW combination is calculated and compared with the predefined Wi-Fi throughput threshold. If Wi-Fi throughput is smaller than the threshold, then LAA CW size increases by 1, and the iteration is performed again, until Wi-Fi throughput is just above the threshold. CW combination and corresponding throughput are then saved in the first row of a matrix **S**'. Wi-Fi CW then increases by 1 up to the maximal Wi-Fi CW, and the above calculation and comparison is performed again. In the matrix **S**', optimal CW combination and corresponding throughput can be obtained easily.

3.3.6 Comparisons With Exhaustive Search

In this section, the optimization scheme is compared with the exhaustive search based numeric results.

We assume the throughput threshold for each Wi-Fi AP is 1, 2, or 4 Mbps, we consider n Wi-Fi APs and m LAA coexisting together to compete for unlicensed spectrum resource ($n,m \subseteq [2,3,4]$). Other parameters used in the evaluations are listed in Table 3.2. MAC header, PHY header and ACK frame length are defined in 802.11 standard [90]. The maximum transmission rate of 802.11ac is 96.3 Mbit/s [90], in the simulation the transmission rate of Wi-Fi and LAA is set to be 50 Mbit/s [2], half of the maximum value for a general case. CW_{min}, CW_{max}, Slot Time, SIFS, DIFS and packet size are defined in 802.11 standard [90].

As shown in Fig. 3.7,3.8,3.9, apart from a few scenarios (4 Wi-Fi APs & 4 LAA eNBs, and 4 Wi-Fi APs & 3 LAA eNBs in Fig. 3.7), optimization algorithm provides exactly the same results as the exhaustive search does.

In scenarios with the same number of Wi-Fi APs and LAA eNBs, a higher Wi-Fi throughput threshold leads to larger LAA CW size. This is in accordance with Theorem. 3.1, which means we have to sacrifice LAA throughput for Wi-Fi throughput protection.

In a scenario with a constant number of Wi-Fi APs and the same Wi-Fi throughput threshold, by decreasing the number of LAA eNBs, smaller LAA CW size can guarantee Wi-

Table 3.2 Wi-Fi System and LAA System Parameters

Packet Size	12800 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
Wi-Fi & LAA Bit Rate	50 Mbit/s
CW_{min}	8
CW_{max}	64
Slot Time	9 μs
SIFS	16 μs
DIFS	34 μs

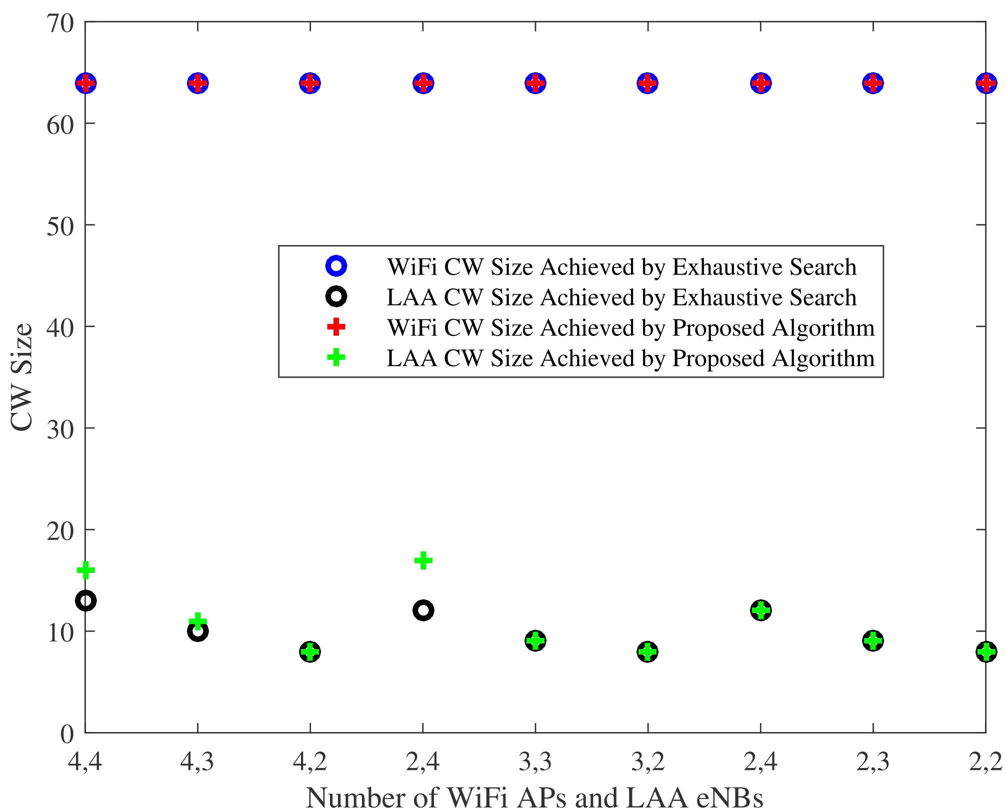

Fig. 3.7 Optimal combination of Wi-Fi & LAA CWs achieved by exhaustive search and proposed algorithm under 1 Mbps/AP throughput threshold

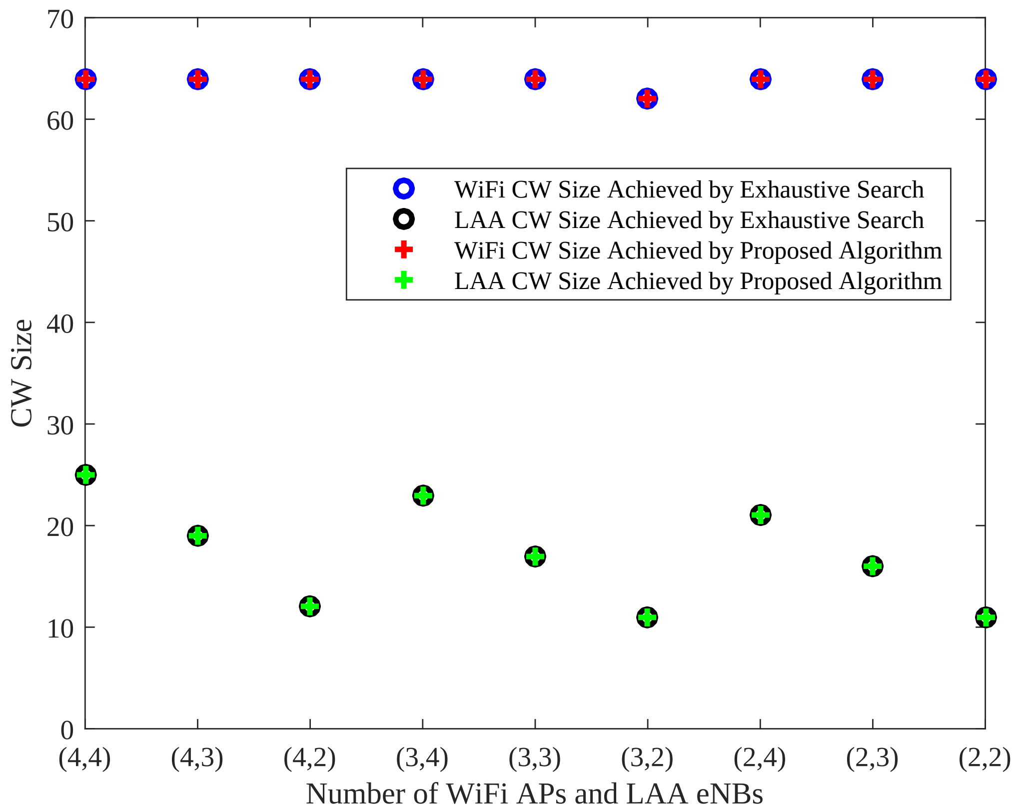

Fig. 3.8 Optimal combination of Wi-Fi & LAA CWs achieved by exhaustive search and proposed algorithm under 2 Mbps/AP throughput threshold

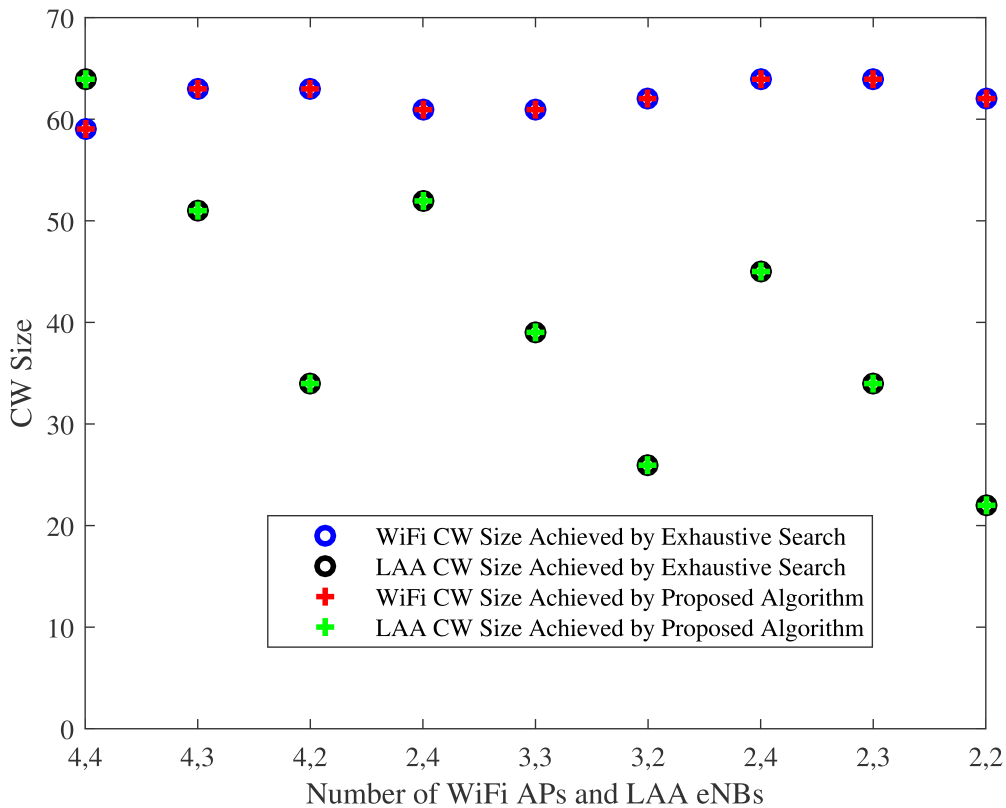

Fig. 3.9 Optimal combination of Wi-Fi & LAA CWs achieved by exhaustive search and proposed algorithm under 4 Mbps/AP throughput threshold

Fi throughput above the threshold. Besides, optimal LAA throughput is higher in scenarios with less LAA eNBs.

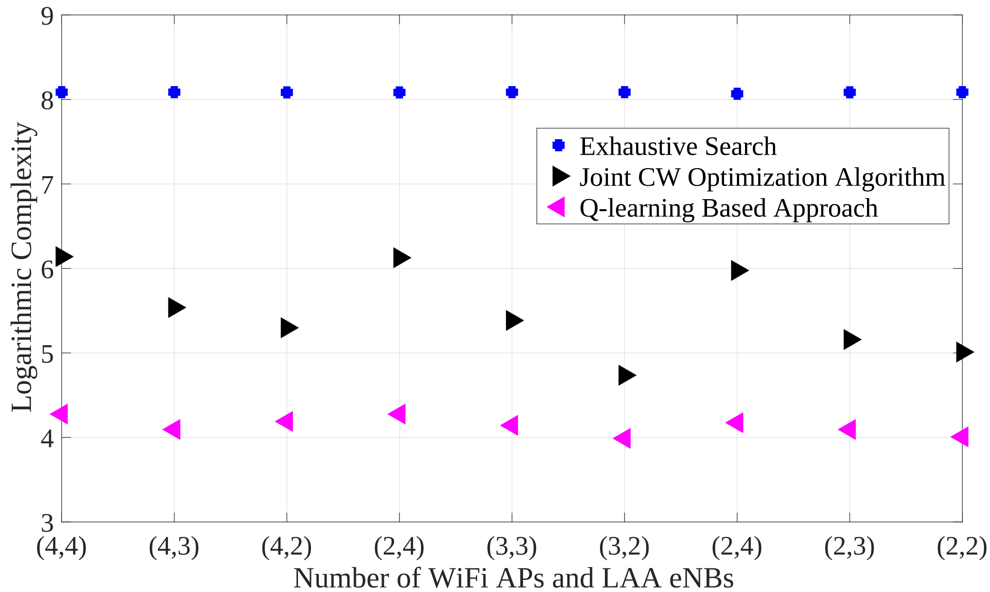

Fig. 3.10 Comparison between optimization algorithm and exhaustive search in terms of complexity

The complexity of the optimization algorithm and the exhaustive search are compared in Fig. 3.10. Each iteration contains three parts: 1) the calculation of Wi-Fi and LAA throughput for given number of Wi-Fi APs and LAA eNBs, 2) the judgment whether Wi-Fi throughput is greater than the predefined threshold and 3) the change of CW, which is increased by 1 in the exhaustive search scheme and is line 15 in Algorithm 3.1 in the proposed algorithm. Although each iteration in the exhaustive search scheme and proposed scheme are not the same in part 3), the time consumed in this part can be approximated the same because both are algebra calculation. The number of iterations used in the optimization algorithm is much less (approximately 90% to 95%) than those used by exhaustive search to achieve the same results. The number of iterations is equivalent to the complexity of the algorithm: the complexity of exhaustive search algorithm is $O(D^2)$, while the complexity of proposed search algorithm is $O(Dlog_2(D))$ (D is the difference between the minimal CW and maximum CW).

3.3.7 Throughput Gain By Using Proposed Scheme

Fig. 3.11 shows the total throughput achieved with optimization scheme under various Wi-Fi throughput thresholds, and fixed CW sizes. In general, total throughput increases by decreasing the number of Wi-Fi APs and (or) LAA eNBs. Total throughput shows the most significant increase by applying fixed initial CW sizes, while optimization scheme applied to achieve Wi-Fi throughput above 4 Mps/AP provides the least throughput gain.

In dense scenario (where 4 Wi-Fi APs and 4 LAA eNBs coexist), the optimization scheme achieves much higher spectral efficiency gain (up to 40%), than applying default CW sizes. While in a less dense scenario with only 2 Wi-Fi APs and 2 LAA eNBs, the throughput gain achieved by optimization scheme drops by 2%-7%. This shows that the proposed optimization scheme is more effective in dense scenarios than in sparse scenarios in terms of throughput increase. In scenario with 2 Wi-Fi APs and 3 LAA eNBs, the overall throughput obtained by using the proposed algorithm given Wi-Fi throughput threshold of 1 Mbps is slightly lower than the throughput achieved under default CW size. This is due to the heavy contention.

A fluctuation is observed in LAA throughput with initial CW in Fig. 3.12, as the total throughput increases with the decreasing number of Wi-Fi APs and LAA eNbs as shown in Fig. 3.11. LAA throughput can be divided into three groups according to scenarios: 1) the number of LAA eNBs being greater than that of Wi-Fi APs, 2) the same number of LAA eNBs and Wi-Fi APs and 3) the number of LAA eNBs being smaller than that of Wi-Fi APs. LAA throughput in scenario 1) is the largest while that in scenario 3) is the smallest. This is due the fact that the channel access probability of LAA eNBs is positively related to the number of LAA eNBs, a larger number of LAA eNBs coexisting with the same number of Wi-Fi APs provides higher LAA throughput. With the same number of LAA eNBs, LAA throughput is larger in scenario with smaller number of Wi-Fi APs because the channel access probability of Wi-Fi APs is smaller. In scenario with the same number of Wi-Fi APs and LAA eNBs, smaller number of Wi-Fi APs and LAA eNBs provide higher total throughput and LAA throughput because the probability of contention is lower.

Under various Wi-Fi throughput thresholds, the LAA throughput achieved with optimization scheme and fixed CW sizes are shown in Fig. 3.12. In general, by using fixed initial CWs at Wi-Fi APs and LAA eNBs, LAA throughput achieved is the lowest. The highest LAA throughput gain (60%-100%) is achieved by the proposed optimization scheme under a low Wi-Fi throughput threshold, i.e. 1 or 2 Mbps/AP. The smallest LAA throughout gain, 10%-30%, is achieved under higher Wi-Fi throughput threshold (4 Mbps/AP). This

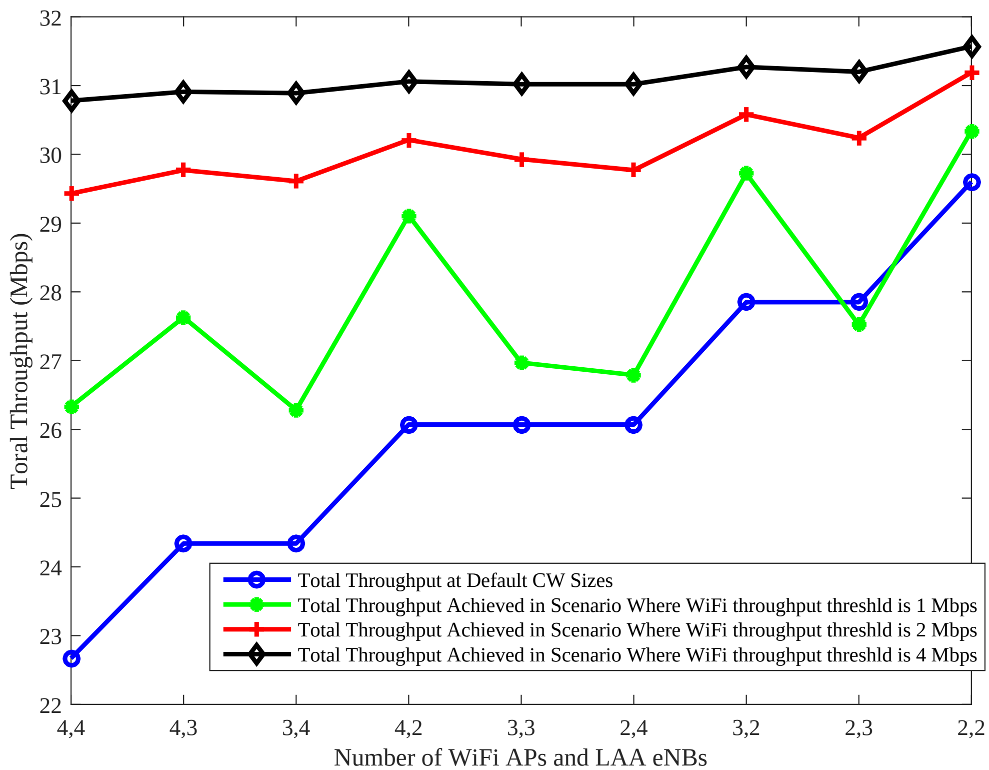

Fig. 3.11 Total throughput achieved in different scenarios with optimization scheme or at fixed initial CW sizes

is because the total achievable throughput is limited if more resource is allocated to Wi-Fi (higher Wi-Fi throughput threshold), lower throughput can be achieved by LAA.

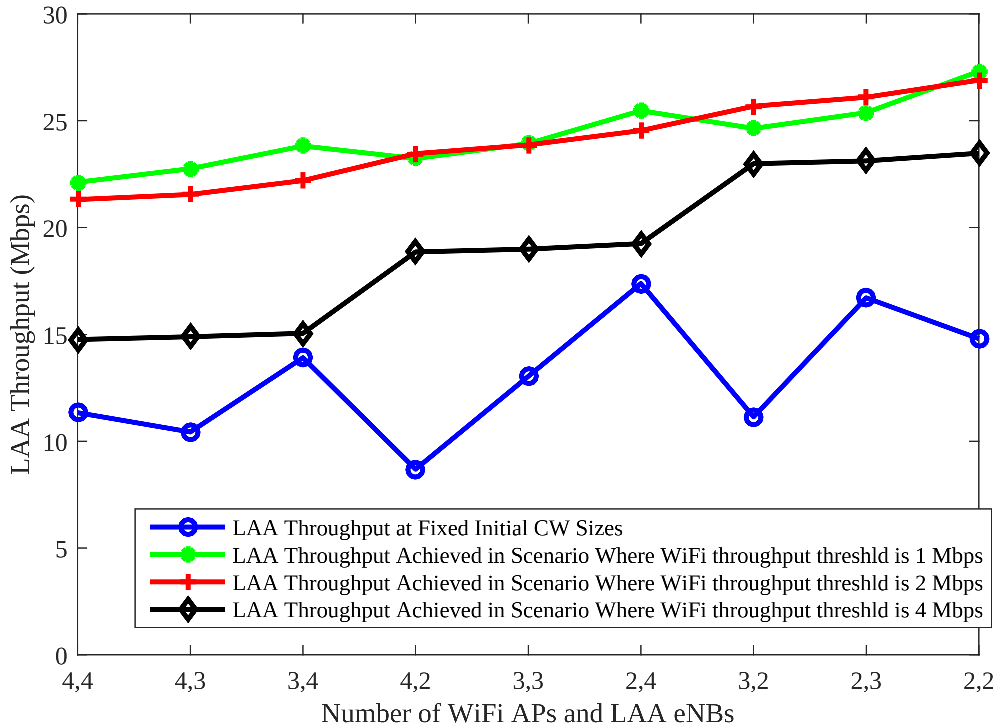

Fig. 3.12 LAA throughput achieved in different scenarios with optimization scheme or at fixed initial CW sizes

3.3.8 Conclusion

In this section, we analyzed LAA and Wi-Fi throughput in coexistence scenarios competing for the same unlicensed spectrum. By mathematical derivation, we established the relations between Wi-Fi, LAA throughput and CW combination. Then we developed an optimization algorithm to find the CW combination that achieves maximum LAA throughput and guarantees Wi-Fi throughput above the predefined threshold.

The accuracy of the proposed optimization algorithm is validated by comparing with exhaustive search. The proposed algorithm can achieve good fairness and spectral efficiency with much lower complexity than the exhaustive search algorithm. The proposed optimization scheme is also shown to be more effective in dense scenarios, in which both higher LAA throughput and total throughput gains are achieved. The trade-off between Wi-Fi and

LAA throughput is revealed due to the fact that the total achievable system throughput is limited.

3.4 Learning-Based Contention Window Optimization

In this section, we study the coexistence problem by using reinforcement learning (RL). We use RL to dynamically configure the initial CW sizes of both LAA and Wi-Fi to maximize LAA throughput while guaranteeing Wi-Fi throughput based on the learning from the environment. To the best of our knowledge, we are the first to use RL in CW optimization. Our work can be applied in other contention-based MAC radio access technology for performance optimization easily.

We develop a modified ε-greedy Q-learning approach to ensure the learning process works effectively and accurately by carefully selecting parameters including learning rate, discount rate, and ε.

The accuracy and efficiency of the Q-learning based CW optimization algorithm is verified by comparing with existing works. With a reasonable number of learning iterations, the output of the algorithm is the same as exhaustive search with a much lower number of iterations. The numeric results also show that the algorithm outperforms the existing scheme in terms of output and complexity.

In this section, we propose a Q-learning based CW optimization algorithm to solve the optimization problem 3.22. The proposed approach can maximize LAA throughput while guaranteeing minimal Wi-Fi throughput.

3.4.1 Q-Learning Approach

When formulating the Q-learning based approach, we consider N Wi-Fi APs and M LAA eNBs as two palyers/agents. The states of Wi-Fi APs are feasible initial CW size of Wi-Fi, denoted as $\{CW_1^W,...CW_J^W\}$, while those of LAA eNBs are feasible initial CW size of LAA, denoted as $\{CW_{min}^1,...CW_{max}^I\}$. The combinational states is a two-dimensional matrix denoted as $S_{i,j}$=$\{CW_1^W,...CW_J^W;\ CW_1^L,...CW_I^L\}$. The action set of the controller is $A_k = \{a_1, ...a_{|A_k|}\}$. In the Q-learning, the central controller keeps a Q-table with Q-values $Q_{i,j}(S_{i,j}, a_k)$ for each state $S_{i,j}$ and each action a_k. This Q-value provides an estimation for future reward if action a_k is taken in state $S_{i,j}$.

The system in state $S_{i,j}$ deploys action a_k, LAA eNBs and Wi-Fi APs obtain rewards in terms of throughput, respectively. The controller learns the outcome of taking action a_k in state $S_{i,j}$. If Wi-Fi throughput is lower than the threshold, the Q-value $Q_{i,j}(S_{i,j}, a_k)$ of performing performing action a_k in state $S_{i,j}$ is set to be a negative number to avoid system choosing action a_k in state $S_{i,j}$. We denote the state after deploying action a_k in state $S_{i,j}$ as $S_{i',j'}$, the Q-value $Q_{i,j}(S_{i,j}, a_k)$ is updated as follows:

$$Q_{i,j}(S_{i,j}, a_k) \leftarrow (1-\alpha)Q_{i,j}(S_{i,j}, a_k) + \alpha[S^L_{i,j} + \gamma max(Q_{i',j'})] \tag{3.36}$$

where α and γ are the learning rate and discount factor respectively. A new Q-value $Q_{i,j}(S_{i,j}, a_k)$ is calculated based on the current $Q_{i,j}(S_{i,j}, a_k)$, achievable LAA throughput $S^L_{i,j}$ and the maximum Q-value of next state $Q_{i',j'}$.

The learning rate α $(0 \leq \alpha \leq 1)$ determines how fast the learning process can occur, if α is too small, i.e., close to 0, the learning would not be effective, if it is very big, the learning process may not converge. The discount factor γ $(0 \leq \gamma \leq 1)$ controls the weight on current reward and future reward. On one hand, system with a small γ will consider immediate throughput; on the other hand, learning will count on future throughput heavily.

Algorithm 3.2 Q-Learning Based Approach Implementation

1: **Initialization:**
2: Initialize $Q_{i,j}(S_{i,j}, a_k)$, $i \in \{1, ...I\}$, $j \in \{1, ...j\}$, $a_k \in \{a_1, ...a_{|A_k|}\}$.
3: Choose a random starting state $S_{i,j}$
4: **Learning:**
5: Generate a random number $r \in U(0,1)$
6: **if** $r < \varepsilon$ **then**
7:     Select a random feasible action
8: **else**
9:     Select action a'_k given by $argmax_{a'_k} Q_{i',j'}(S_{i',j'}, a'_k)$
10: **end if**
11: Update the Q-table in expression of 3.36.
12: Execute action a'_k and update state to $S_{i',j'}$.
13: Terminate until reaching maximum iteration number

3.4.2 Implementation of Q-Learning Based Approach

The main loop of the learning process can be found in Algorithm. 3.2, line 5 - 10, in which exploiting the optimal action or exploring a random action is performed based on ε-greedy policy.

Once an action a_k is performed in state $S_{i,j}$, the next state becomes $S_{i',j'}$, and the next action a'_k is selected based on ε-greedy policy, in which, a random value $r \in U(0,1)$ is generated and is compared to ε. If r is smaller than ε, the next action a'_k will be selected randomly. Otherwise, the action with the maximum Q-value $a'_k = argmax_{a'_k} Q_{i',j'}(S_{i',j'}, a'_k)$ is selected in state $S_{i',j'}$. The ε-greedy parameter ensures that all state/action will be explored as the number of trails goes to a relatively large number. The detail of modified Q-learning algorithm can be found in Algorithm 3.2.

To ensure the effectiveness and accuracy of the learning process, the learning rate α, discount factor γ and ε should be selected carefully. One on hand, the learning process should converge in a reasonable number of iterations. On the other hand, all the Q value $Q_{i,j}(S_{i,j}, a_k)$ related to state $S_{i,j}$ and action a_k will be explored.

Different from the usual Q-learning approach, we integrate the constraints of (3.23) into our learning process. If the state $S_{i,j}$ fails to satisfy Wi-Fi minimal throughput requirement, reward $S^L_{i,j}$ is set to be a negative value (e.g., -100), so that the algorithm can be trained to avoid entering such state in action selection stage. Also, the action that makes CW of LAA or Wi-Fi exceeds its feasible range will set a negative value to avoid it to be selected.

Once the learning process finished, the number of iterations required to obtain the optimal CW combination from a random starting state $S_{i,j}$ is $O(D)$, where D is the difference between the minimal CW and maximum CW.

3.4.3 Simulation Results

In this section, the optimization scheme is compared with the joint CW optimization scheme and exhaustive search [84].

We assume the throughput threshold for each Wi-Fi AP is 1, 2, or 3 Mbps, we consider N Wi-Fi APs and M LAA coexisting together to compete for unlicensed spectrum resource ($n, m \subseteq [2,3,4]$).

Without any loss of generality, we consider that the state, action and state transition in the proposed Q-leaning based algorithm as follows

- **State:**

  $S_{i,j} = (CW^W_i, CW^L_j), CW^W_i \in \{CW^W_1, \ldots, CW^W_I\}; CW^L_j \in \{CW^L_1, \ldots, CW^L_J\}$.

- **Action:**

  $a_k \in \{a_1, a_2, a_3, a_4\}$

- **State Transition:**

Table 3.3 Wi-Fi System and LAA System Parameters

Packet Size	12800 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
Wi-Fi & LAA Bit Rate	50 Mbit/s
CW_{min}	8
CW_{max}	64
Slot Time	9 μs
SIFS	16 μs
DIFS	34 μs
α	0.5
γ	0.5
ε	0.05

$$S_{i+1,j} \leftarrow S_{i,j}, a_1$$
$$S_{i-1,j} \leftarrow S_{i,j}, a_2$$
$$S_{i,j+1} \leftarrow S_{i,j}, a_3$$
$$S_{i,j-1} \leftarrow S_{i,j}, a_4$$

Other parameters used in the evaluations are listed in Table 2.3, which is adopted in IEEE 802.11 ac standard [90]. MAC header, PHY header and ACK frame length are defined in 802.11 standard [90]. The maximum transmission rate of 802.11ac is 96.3 Mbit/s [90], in the simulation the transmission rate of Wi-Fi and LAA is set to be 50 Mbit/s [2], half of the maximum value for a general case. CW_{min}, CW_{max}, Slot Time, SIFS and DIFS are defined in 802.11 standard [90]. α and γ are set to be 0.5 to achieve balance between learning and experience. ε is set to be 0.05 to make sure all the possible state-action are explored and a fast convergence is achieved.

First we evaluate how effective the learning process of learning Q-learning based algorithm is, we train the algorithm 15000 and 30000 times, in essence, update Q-table those times. The results of the q-learning based algorithm with different number of training iterations are displayed in Fig. 3.13 and 3.14, with those of exhaustive search being benchmark.

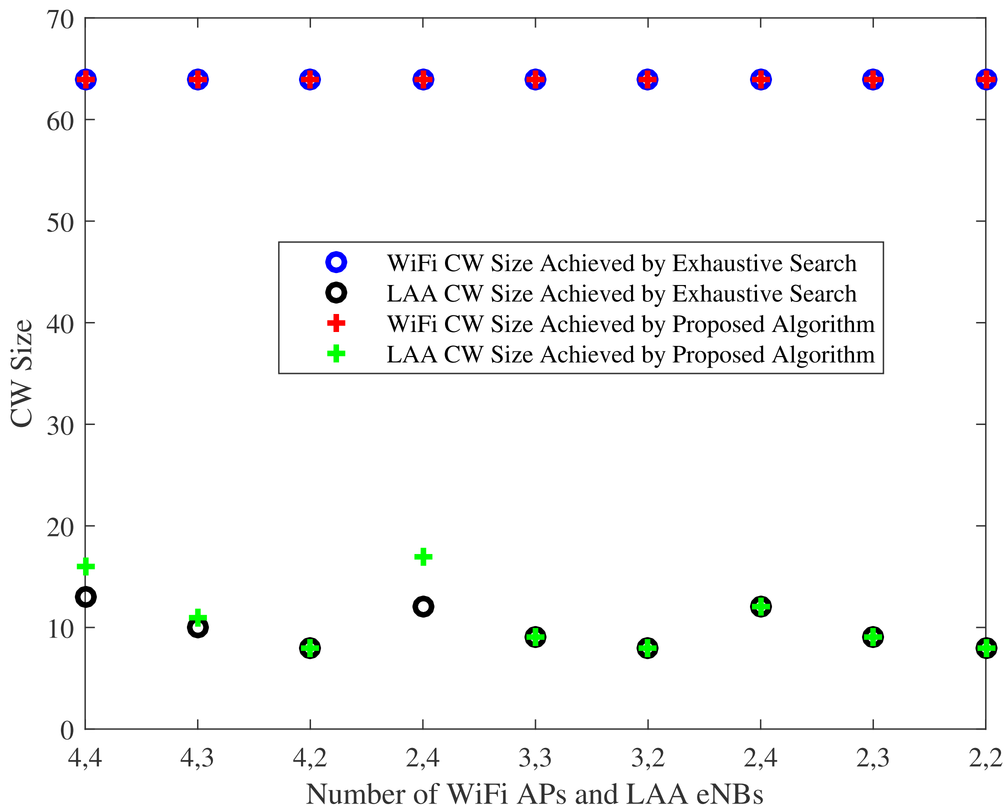

Fig. 3.13 Optimal combination of Wi-Fi & LAA CWs achieved by exhaustive search and Q-learning based approach with different learning iterations under 1 Mbps/AP throughput threshold

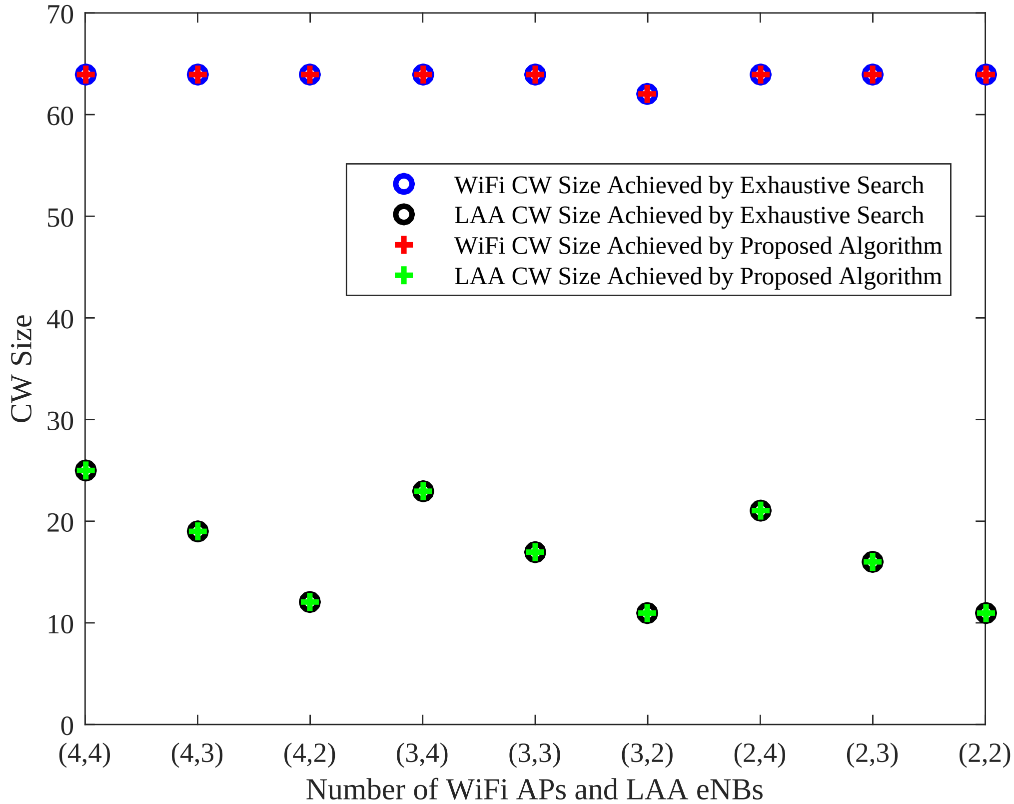

Fig. 3.14 Optimal combination of Wi-Fi & LAA CWs achieved by exhaustive search and Q-learning based approach with different learning iterations under 2 Mbps/AP throughput threshold

The proposed algorithm is evaluated in different Wi-Fi and LAA scenarios with 1 Mbps and 2 Mbps throughput requirement.

After training of 15000 iterations, our proposed algorithm can provide CW combination close to that obtained by using exhaustive search. If we train the algorithm 30000 times, learning approach and exhaustive search give exactly the same optimal CW combination in all the scenarios we study, which means that the learning approach converges at 30000 iterations.

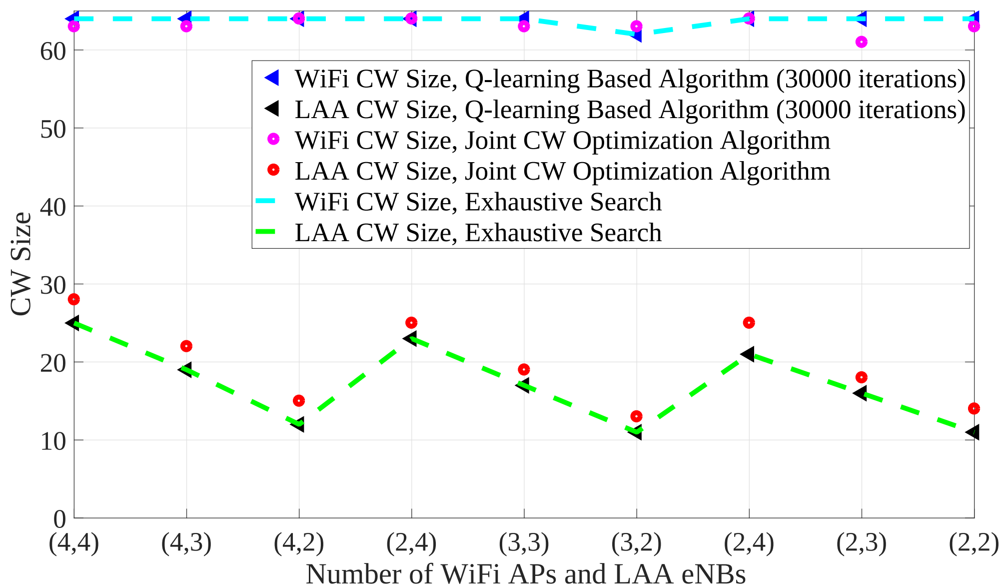

Fig. 3.15 Optimal combination of Wi-Fi & LAA CWs achieved by exhaustive search, Q-learning based approach and joint CW optimization algorithm under 2 Mbps/AP throughput threshold

If we increase the throughput requirement of Wi-Fi in the same scenario, we found that LAA CW size is increased. A larger CW size of LAA means that LAA has lower channel access probability, as a result, Wi-Fi has more chances to occupy the unlicensed bands, leading to a higher throughput.

Comparisons are made between Q-learning approach and joint CW optimization algorithm in Fig. 3.15 and 3.16. Q-learning approach outperforms joint CW algorithm in many scenarios including 4 Wi-Fi APs, 4 LAA eNBs with 1 Mbps throughput requirement of Wi-Fi.

The logarithmic complexity of Q-learning based algorithm, exhaustive search and are compared in Fig. 3.17. The number of iterations used in Q-learning based algorithm is much less (approximately 66% to 85%) than those used by joint CW optimization. The number

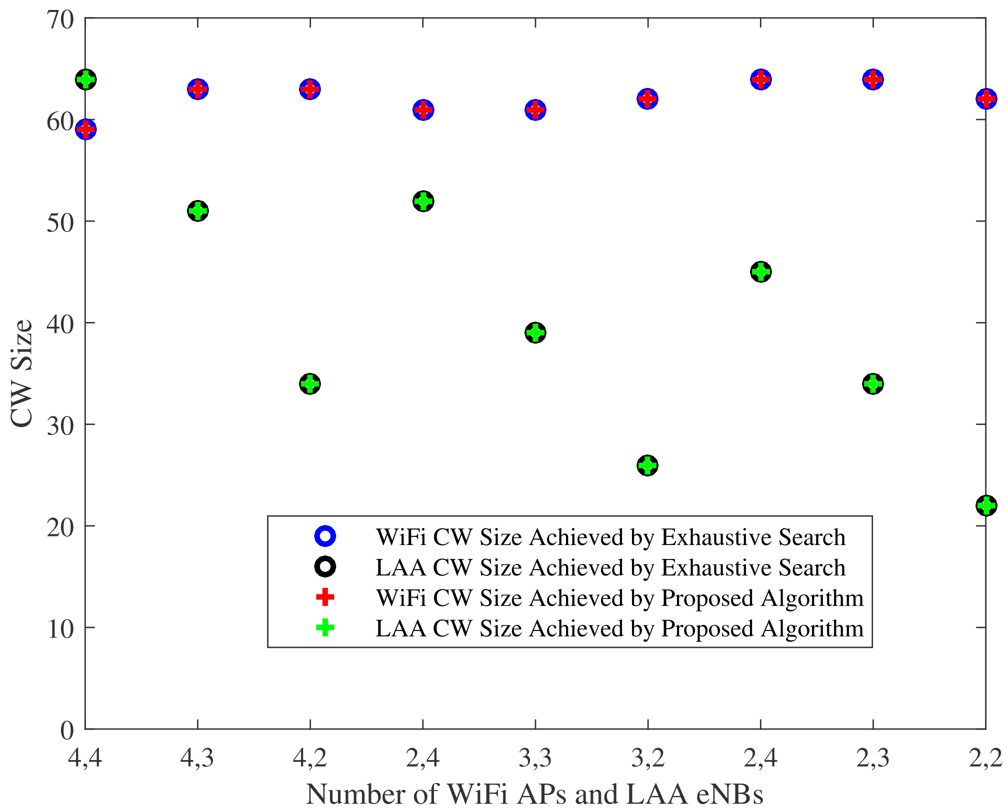

Fig. 3.16 Optimal combination of Wi-Fi & LAA CWs achieved by exhaustive search, Q-learning based approach and joint CW optimization algorithm under 4 Mbps/AP throughput threshold

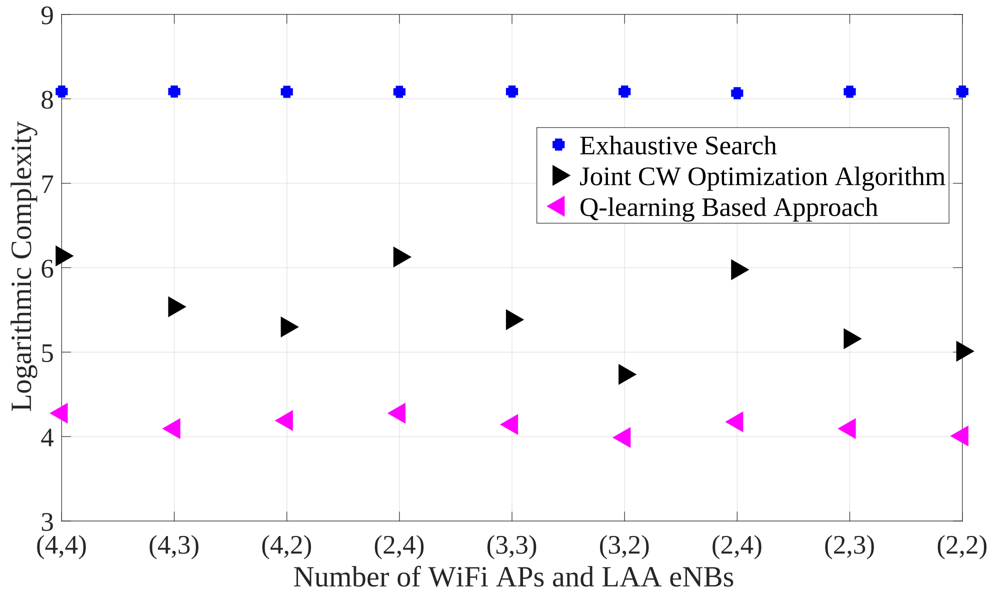

Fig. 3.17 Complexity of proposed optimization algorithm, exhaustive search and joint CW optimization algorithm

of iterations used in Q-learning based algorithm is only 2% of those by using exhaustive search. These results are equivalent to the complexity of these algorithms, which are $O(D)$, $O(Dlog_2(D))$ and $O(D^2)$.

From the numerical results, the design of the Q-learning based algorithm is quite effective to optimize the CW combination of LAA and Wi-Fi with relatively reasonable number of training iterations. The station only need to communicate with the other stations to get the number of Wi-Fi APs and LAA eNBs. Then, the training process is carried out in an off-line manner. This implies that the algorithm is promising to be applied in real world resource allocation.

3.4.4 Conclusion

In this section, we study LAA and Wi-Fi coexistence sharing unlicensed bands. We maximize LAA throughput while guaranteeing Wi-Fi minimal throughput, which is formulated as a nonlinear integer optimization problem. To solve the problem with reduced complexity and without assumptions in [84], we develop Q-learning based optimization approach.

The proposed Q-learning algorithm is trained with a different number of iterations, and the numeric results show that it can provide exactly the same CW combination as the exhaustive search does within a reasonable number of learning iterations. The accuracy of the

Q-learning based optimization algorithm is validated by comparing with exhaustive search. The proposed algorithm outperforms joint CW optimization scheme in terms of accuracy and computational complexity. The proposed algorithm can achieve good fairness and spectral efficiency with much lower complexity than the joint CW optimization algorithm and exhaustive search algorithm.

3.5 Conclusions

In this chapter, we first developed comprehensive Markov Chain models considering the backoff stage of Cat 3, Cat 4 LAA and Wi-Fi in section 3.2. We obtain mathematical expressions for transmission probability of an LAA eNB using Cat 3, 4 LBT and Wi-Fi AP in a coexistence scenario. Further, we evaluate the LAA and Wi-Fi throughput and transmission delay and observe that an LAA (Cat 3 or Cat 4) network affects a Wi-Fi network more than another Wi-Fi network. There is a trade-off between Wi-Fi throughput protection and total throughput enhancement. In section 3.3, we aim to maximize LAA throughput while guaranteeing Wi-Fi minimal throughput and it is formulated as a nonlinear optimization problem which is NP-hard. To reduce the computational complexity, we develop a joint CW optimization algorithm based on the derivation of the relationship between LAA (Wi-Fi) throughput against LAA (Wi-Fi) CW size. The proposed algorithm gives the same results as the exhaustive search algorithm does with much less iteration number. In section 3.4, we develop a reinforcement-learning based algorithm to tune the combination of LAA and Wi-Fi CW in response to the traffic demand of LAA and Wi-Fi system. We evaluate the RL-based algorithm in terms of LAA throughput and computational complexity, which outperforms a joint CW optimization algorithm and exhaustive algorithm.

Chapter 4

Matching-based Unlicensed Spectrum Allocation Algorithm

In this chapter, and as it is in our paper [93], different from existing works, which typically consider only the fairness problem or overall EE in an LTE-U network and WiFi system co-existing networks, we study the unlicensed bands allocation problem in the context and aim to optimize uplink EE of each CU while guaranteeing the minimal throughput of each WU and CU. This optimization problem is formulated as a *multi-objective optimization problem*, in which typically a set of Pareto efficient solutions can be achieved. We utilize the weighted sum method to transform the multi-objective optimization problem into a *single-objective optimization problem*, which is NP-hard. To solve the single-objective optimization problem with reduced computational complexity, it is modeled as a many-to-one matching game with partial information. Here *partial information* means *incomplete preference lists*, which is due to the fact that some UBs fail to fulfill a user's minimal throughput requirement and are not acceptable to that user. Such a problem has not yet been considered in a resource allocation context.

We propose a semi-distributed two-step matching-based algorithm to obtain a near-optimal solution of the problem. The first step aims to solve the externalities problem by extending the Gale-Sharply algorithm [94] to a many-to-one matching. Step 2 is designed to reallocate the unmatched CUs obtained in step 1, aiming to maximize the number of CUs served. The stability, Pareto efficiency, and convergence of each step are proved. The proposed algorithm is evaluated through simulations and outperforms greedy band allocation scheme with relatively smaller computational complexity.

4.1 System Model

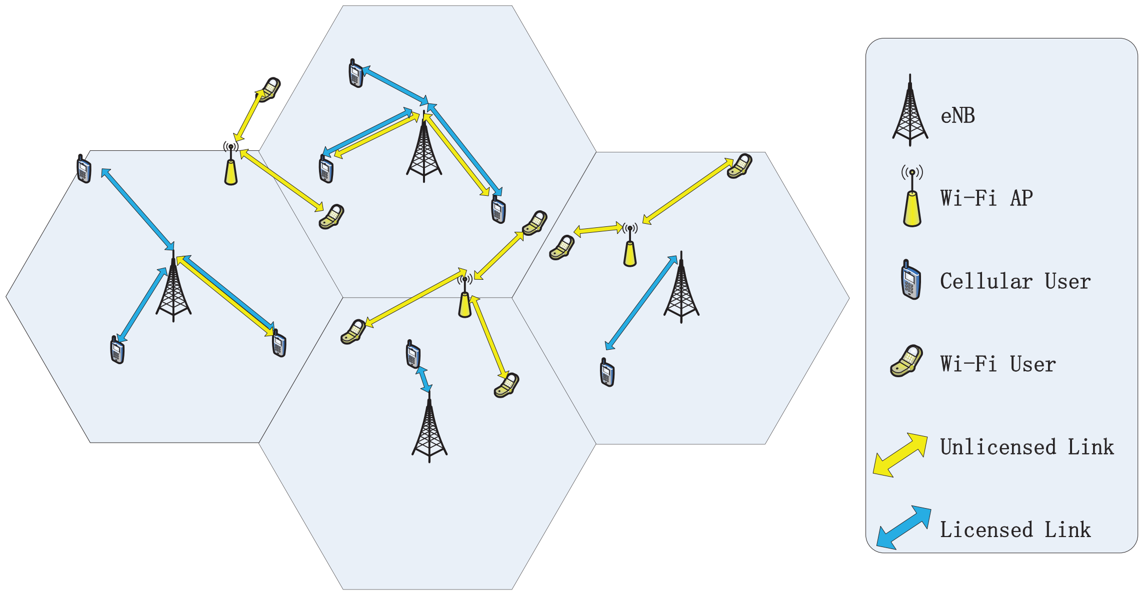

Fig. 4.1 System architecture of a LTE-U and Wi-Fi system

As shown in Fig. 4.1, we consider an LTE-U network sharing ISM bands (e.g. 5.8 GHz) with a Wi-Fi network. In this scenario, M small-cell base stations (SCBSs) and N Wi-Fi access points (APs) distribute independently and uniformly. SCBSs (deployed by the same cellular network operator) are denoted as $SCBS = \{SCBS_1, \ldots SCBS_m, \ldots SCBS_M\}$ and APs are denoted as $AP = \{AP_1, \ldots AP_n, \ldots AP_N\}$, respectively. SCBSs serve K cellular users (CUs), denoted as $CU = \{CU_1, \ldots CU_k, \ldots CU_K\}$ while APs serve N' Wi-Fi users (WU), denoted $WU = \{WU_1, \ldots WU_{n'}, \ldots WU_{N'}\}$. CUs and WUs are independently and uniformly distributed in the area of interest.

As shown in Fig. 4.2, the whole unlicensed spectrum is divided into U orthogonal unlicensed bands (UBs) in frequency domain and slots in the time domain. The duration of a slot is T, consisting of 10 subframes. The duration of a subframe ($T/10$) is smaller than the coherence time of the signal channel, which means that during each subframe, the transmission power attenuation caused by Rayleigh fading in each link can be regarded as a fixed parameter. Moreover, each sub-frame is considered strictly independent.

Unlicensed bands are used to serve WUs by APs with carrier sense multiple access with collision avoidance (CSMA/CA) scheme. CUs are served by SCBSs by using a licensed band for both uplink and downlink transmission, while they seek to aggregate unlicensed bands for enhanced data rate. Unlicensed bands are shared between WUs and CUs using

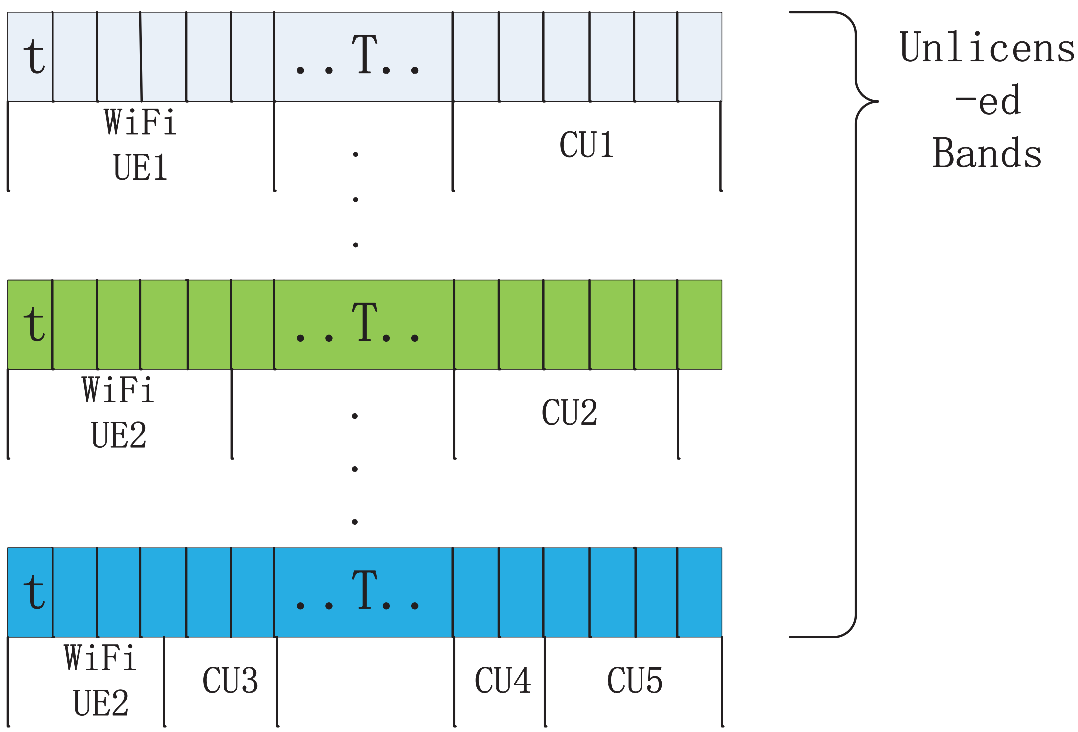

Fig. 4.2 TDD sharing of unlicensed bands between Wi-Fi and LTE-U users

the duty cycle scheme in the time domain. By using this duty cycle method, CUs access UBs in an almost blank subframe (ABS) pattern [95] to guarantee Wi-Fi QoS by muting l_u sub-frames for each unlicensed band UB_u. The number l_u is adaptively adjusted based on the Wi-Fi data requirement. Here, we consider the static synchronous muting pattern.

The notations used in this chapter can be found in Table 4.1.

4.1.1 LTE-U Throughput

We denote the average uplink throughput during a slot of the k-th CU CU_k associating with $SCBS_m$ on unlicensed band UB_u as $R^{CU}_{k,m,u}$. Thus, the uplink throughput on UB_u is given by:

$$R^{CU}_{k,m,u} = (I_{k,m,u}/10)\sum_{i=1}^{I_{k,m,u}} C^{CU}_{k,m,u,i}, \tag{4.1}$$

where $I_{k,m,u}$ is the number of sub-frames in UB_U allocated to CU_k served by $SCBS_m$. $C_{k,m,u,i}$ is the achievable data rate of CU_k served by $SCBS_m$ on the i-th sub-frame of UB_u, which is given by Shannon equation [96]:

$$C^{CU}_{k,m,u,i} = B(1+SINR) = B_u log_2(1+\frac{\chi_{k,m,u}P^{CU}_{k,m}g_{k,m,u}}{\sigma_N^2+\sum_{j\neq k}^{K}\sum_m^M \rho_{j,m,u}P^{CU}_{j,m}g_{j,m,u}}) \tag{4.2}$$

where, $\chi_{k,m,u}$ is an indicator function, defined as:

$$\chi_{k,m,u} = \begin{cases} 1, \text{ if } CU_k \text{ is served by } SCBS_m \text{ using } UB_u, \\ 0, \text{ otherwise.} \end{cases} \tag{4.3}$$

$P^{CU}_{k,m}$ represents the transmission power from CU_k to $SCBS_m$. $g_{k,m,u}$ is the channel power gain between CU_k and $SCBS_m$ on UB_u, and $g_{j,m,u}$ is the channel gain between CU_j and $SCBS_m$ on UB_u. σ_N^2 is the thermal noise.

4.1.2 Wi-Fi Throughput

Each WU $WU_{n'}$ access one of the unlicensed bands with equal probability. We consider all the WUs sharing the same UB as one 'WU', the interactions between co-channel CUs and WUs can be simplified to the interactions between co-channel CUs and a 'WU' [55, 56]. The 'WU' that occupies UB_u is denoted as WU_u. The throughput of WU_u is the same as (3.9) in Chapter 3 of this thesis:

Table 4.1 General Notation

$SCBS_m$	the m-th small cell base station
AP_n	the n-th access point
CU_k	the k-th cellular user
UB_u	the u-th unlicensed band
T	slot time
t	sub-frame time
l_u	the fraction of time LTE-U is muting on UB_u
$C^C_{k,m,u}$	the uplink capacity CU_k associating with $SCBS_m$ on unlicensed band UB_u
$I_{k,m,u}$	the number of sub-frames in UB_U allocated to CU_k served by $SCBS_m$
$C_{k,m,u,i}$	the achievable data rate of CU_k served by$SCBS_m$
$\chi_{k,m,u}$	equals 1 if CU_k is served by $SCBS_m$ using UB_u
$P^{CU}_{k,m}$	transmission power from CU_k to $SCBS_m$
$g_{k,m,u}$	channel power gain between CU_k and $SCBS_m$ on UB_u
$R_{k,m,u}$	the uplink throughput of CU_k served by $SCBS_m$ on UB_u
σ^2_N	the thermal noise
WU_u	Wi-Fi users on UB_U
R^W_u	throughput requirement of WU_u
PE^{CU}_k	energy efficiency of CU_k
R^L_k	Throughput requirement of CU_k

$$Th_u = \frac{\overline{E(p)}P_{tr}^u P_s^u}{(1-P_{tr}^u)\delta + P_{tr}^u P_s^u T_s + P_{tr}^u(1-P_s^u)T_c}, \tag{4.4}$$

where $\overline{E(p)}$ is the average packet size of a Wi-Fi transmission, P_{tr}^u is the probability that UB_u is occupied, and P_s^u is the successful transmission probability in UB_u. δ is the slot time defined in 802.11. T_s and T_c are the average time consumed by a successful transmission and a collision in UB_u, respectively.

Based on the ABS scheme, l_u sub-frames of UB_u are allocated to WU_u to guarantee throughput requirement R_u^W of WU_u. l_u is calculated as:

$$Th_u l_u T \geq R_u^W, l_u \in integer \tag{4.5}$$

4.2 Problem Formulation

The EE of CU_k is the throughput of CU_k achieved per unit power consumption with the unit of '$bits - per_Joule$' [97], which is defined as follows:

$$PE_k^{CU} = \frac{\sum_m^M \sum_u^U \chi_{k,m,u} R_{k,m,u}}{\sum_m^M \sum_u^U \chi_{k,m,u} I_{k,m,u} P_{k,m}^{CU}} \tag{4.6}$$

We formulated the following EE maximization problem for each CU as a multi-objective optimization problem:

$$min(-PE_1^{CU}, \ldots, -PE_K^{CU}), \tag{4.7}$$

$$s.t$$

$$\sum_k^K \sum_u^U \chi_{k,m,u} \leq 1, m \in \{1, \ldots, M\}, \tag{4.7a}$$

$$\sum_m^M \sum_u^U \chi_{k,m,u} I_{k,m,u} t \leq T l_u, \;\; k \in \{1, \ldots, K\}, \tag{4.7b}$$

$$\chi_{k,m,u} \in \{0,1\}, k \in \{1, \ldots, K\}, m \in \{1, \ldots, M\}, \quad u \in \{1, \ldots, U\}, \tag{4.7c}$$

$$P_{k,m}^{CU} \leq P_{max}, k \in \{1, \ldots, K\}, m \in \{1, \ldots, M\}, \tag{4.7d}$$

$$Th_u(l_u)T \geq R_u^W, u \in \{1, \ldots, U\}, \tag{4.7e}$$

$$\sum_m^M \sum_u^U \chi_{k,m,u} R_{k,m,u} \geq R_k^L, k \in \{1, \ldots, K\}. \tag{4.7f}$$

where, constraint (4.7a) indicates that a CU can access to 1 UB at a time. (4.7b) is the limitation of the available subframes in UB_u for CUs. Constraint (4.7c) is defined in (4.3). (4.7d) defines the transmission power limit of each CU. (4.7e) and (4.7f) set the minimum throughput requirement for each WU and CU, respectively.

The multi-objective optimization is solved by using a weighted-sum or scalarization method to transform a multi-objective optimization problem into a single-objective optimization problem [98] as:

$$min(-\sum_{k=1}^{K}\gamma_k PE_k^{CU}), \tag{4.8}$$

$$s.t$$

$$\sum_{k=1}^{K}\gamma_k = K, \tag{4.8a}$$

$$\sum_{k}^{K}\sum_{u}^{U}\chi_{k,m,u} \leq 1,\, m \in \{1,\dots,M\}, \tag{4.8b}$$

$$\sum_{m}^{M}\sum_{u}^{U}\chi_{k,m,u} I_{k,m,u} t \leq T l_u,\;\; k \in \{1,\dots,K\}, \tag{4.8c}$$

$$\chi_{k,m,u} \in \{0,1\},\, k \in \{1,\dots,K\}, m \in \{1,\dots,M\}, \\ u \in \{1,\dots,U\}, \tag{4.8d}$$

$$P_{k,m}^{CU} \leq P_{max},\, k \in \{1,\dots,K\}, m \in \{1,\dots,M\}, \tag{4.8e}$$

$$Th_u(l_u)T \geq R_u^W,\, u \in \{1,\dots,U\}, \tag{4.8f}$$

$$\sum_{m}^{M}\sum_{u}^{U}\chi_{k,m,u} R_{k,m,u} \geq R_k^L,\, k \in \{1,\dots,K\}. \tag{4.8g}$$

The effectiveness of the transformations is defined in *Lemma* 4.1 [98] as follows:

Lemma 4.1. *The single-objective minimizer is an effective solution for the original multi-objective problem and is a strict Pareto optimum if the weight vector γ is strictly greater than zero.*

where strict Pareto optimum is defined as:

Definition 4.1. *Strict Pareto Optimum: A solution Matrix **M** is said to be a strict Pareto optimum or a strict efficient solution for the multi-objective problem (4.7) if and only if there is no $m \subseteq S$ such that $PE_k^{CU}(m) \leq PE_k^{CU}(m')$ for all $k \in 1,\dots,K$, with at least one strict inequality. S is the constraints (4.7a-4.7f).*

We consider all the CUs have the same level of priority of accessing UBs, i.e.,

$$\gamma_k = 1, k \in \{1, \ldots, K\}. \tag{4.9}$$

The EE optimization is finally transformed into:

$$min(-\sum_{k=1}^{K} PE_k^{CU}), \tag{4.10}$$

$$s.t$$

$$\sum_{k}^{K}\sum_{u}^{U} \chi_{k,m,u} \leq 1, m \in \{1, \ldots, M\}, \tag{4.10a}$$

$$\sum_{m}^{M}\sum_{u}^{U} \chi_{k,m,u} I_{k,m,u} t \leq Tl_u, \ \ k \in \{1, \ldots, K\}, \tag{4.10b}$$

$$\chi_{k,m,u} \in \{0,1\}, k \in \{1, \ldots, K\}, m \in \{1, \ldots, M\}, \\ u \in \{1, \ldots, U\}, \tag{4.10c}$$

$$P_{k,m}^{CU} \leq P_{max}, k \in \{1, \ldots, K\}, m \in \{1, \ldots, M\}, \tag{4.10d}$$

$$Th_u(l_u)T \geq R_u^W, u \in \{1, \ldots, U\}, \tag{4.10e}$$

$$\sum_{m}^{M}\sum_{u}^{U} \chi_{k,m,u} R_{k,m,u} \geq R_k^L, k \in \{1, \ldots, K\}. \tag{4.10f}$$

We denote the solution for optimization problem (4.10) as Matrix $\boldsymbol{M}$, which, according to Lemma. 4.1, is an strict Pareto optimum for the multi-objective optimization problem (4.7).

The objective function (4.10) is a mixed integer nonlinear programming (MINLP) problem because it is a summation of $PE_k^{CU}, k \in \{1, \ldots, K\}$. PE_k^{CU} is nonlinear as in (4.6), in which $I_{k,m,u}$ and $\chi_{k,m,u}$ are integers, $R_{k,m,u}$ and $P_{k,m}^{CU}$ are continuous variables. To solve this NP-hard MINLP problem with reduced computation complexities, we developed a matching-based solution, which will be in next section.

4.3 Matching with Incomplete Preference Lists

4.3.1 Introduction to Matching Theory

Student project allocation (SPA) is a many-to-one matching model, in which each student has a preference list of the projects that they can choose from, while the lecturers have a preference list of students for each project or a preference list for student-project pairs. The maximum number of students that can be assigned to each particular project is limited and is denoted as the quota [83].

Inspired by the SPA problem, we model the resource allocation problem in (4.10) as a many-to-one resource allocation matching game, where the CUs, UBs and SCBSs are considered equivalent to students, projects and lecturers, respectively. In this model, SCBSs offer the set of available UBs and maintain a preference list for each UB, and each CU has a preference list of UBs that they can use for uplink transmission. SCBSs allocate UBs to CUs based on the achievable EE on UBs. However, our resource allocation matching game differs from the SPA game in the following aspects:

- **Maximum throughput as the ’quota’**: The ’quota’ or the maximum number of CUs can be served is limited by the capacity of a UB. The capacity of a UB is the maximum achievable throughput the UB can provide for CUs after reserving necessary resources to meet the minimum required WU throughput in TDD mode.

- **Incompleteness of preference lists**: The SCBSs sense the availabilities of UBs and keep the CUs updated. Any UB that is not able to fulfill a CU’s minimal throughput requirement will be deleted from the preference list of the CU and the CU will also be removed from the preference list of that UB. Only a subset of UBs (CUs) are in the preference list of a CU (UB), i.e., the preference lists are incomplete.

The many-to-one resource allocation matching is defined as follows:

Definition 4.2. *Let μ denote the many-to-one resource allocation matching game between two disjoint sets **CU** and **UB**.*

- $\mu(CU_k) = UB_u$ *indicates that the k-th CU is matched to the u-th UB*
- $\mu(UB_u) = \{CU_k, \ldots, CU_{k'}\}$ *indicates that the u-th UB is matched to* $\{CU_k, \ldots, CU_{k'}\}$
- $\mu(CU_k) = CU_k$ *indicates that the k-th CU is not really matched to any UB.*

Out of the individual rationality of each player, two CUs may swap their matched UBs to increase their EE in a matching. Such matching is unstable and undesirable, and should coverage into a stable matching, which implies the robustness of the matching against deviations. The definition of stability of the many-to-one matching is given as follows:

Definition 4.3. *Stability of the many-to-one resource allocation matching game. A two-sided many-to-one resource allocation matching game μ is stable, only if it is not blocked by any blocking pair or blocking individual.*

A blocking pair of a matching μ in the many-to-one resource allocation matching game is defined as:

Definition 4.4. *Blocking Pair. A pair* (CU_k, UB_u) *is a blocking pair of a matching* μ *if all the following 3 conditions are satisfied:*

(1) $\mu(CU_k) \neq UB_u$ *and* $pri(CU_k, UB_u) > pri(CU_k, \mu(CU_k))$*;*

(2) $\mu(UB_u) \neq CU_k$ *and* $pri(UB_u, CU_k) > pri(UB_u, \mu(UB_u))$*;*

(3) There is still enough spectrum resource in UB_u *after resource allocation in matching of a matching* μ *to meet the minimum throughput requirement of* CU_k*.*

A blocking individual of a matching μ in the many-to-one resource allocation matching game is defined as:

Definition 4.5. *Blocking Individual. A CU is a blocking individual of a matching* μ *if it prefers being unmatched rather than being matched to any available UB.*

4.3.2 Preference Lists of CUs Over UBs

We assume that the preference of CU_k over UB_u is based on EE $PE^{CU}_{k,m,u}$ achieved by CU_k served by $SCBS_m$ using UB_u to guarantee its QoS threshold, which is written as follows:

$$PE^{CU}_{k,m,u} = \frac{\sum_m^M \sum_u^U \chi_{k,m,u} R_{k,m,u}}{\sum_m^M \sum_u^U \chi_{k,m,u} P^{CU}_{k,m} I_{k,m,u} t} \tag{4.11}$$

If both UB_u and $UB_{u'}$ can fulfill the minimum throughput requirement of CU_k, and CU_k can achieve higher EE using UB_u than $UB_{u'}$, CU_k prefers UB_u over $UB_{u'}$, which is stated mathematically as follows:

$$pri(CU_k, UB_u) > pri(CU_k, UB_{u'}) \Leftrightarrow PE^{CU}_{k,m,u} > PE^{CU}_{k,m,u'} \tag{4.12}$$

The preference lists of each CU are set up based on local channel sensing information and unlicensed band availability alone in a distributed manner. Based on the preference lists information, the resource allocation is performed at SCBSs centrally. Thus, the resource allocation matching scheme is semi-distributed.

4.3.3 Preference Lists of SCBS Over (CU_k, UB_u) Pair

The preference list of $SCBS_m$ over user-band pair (CU_k, UB_u) is based on the EE achieved on UB_u by CU_k to fulfil the QoS threshold of CU_k. $SCBS_m$ prefers CU_k over $CU_{k'}$ to occupy

UB_u if CU_k can achieve higher EE than $CU_{k'}$ by using UB_u, which is stated as follows:

$$pri(UB_u, CU_k) > pri(UB_u, CU_{k'}) \Leftrightarrow PE^{CU}_{k,m,u} > PE^{CU}_{k',m,u} \tag{4.13}$$

4.3.4 Matching-Based Algorithms

The above resource allocation matching game is solved in two steps and for each step an algorithm is developed.

Step 1: Modified GS Algorithm for Many-to-One Resource Allocation Matching Game

For the first step, an extension of the GS algorithm is developed to solve the many-to-one matching with incomplete preference lists. An iteration begins with every unmatched CU making a proposal to their favourite UB (i.e., the first UB) on their current preference lists. The UB that has been proposed will be removed from its proposer CU's preference list. For each UB_u, SCBSs decide whether to accept or reject the proposals to UB_u based on SCBSs' preference lists over (CU_k, UB_u) pairs. SCBSs choose to keep the most preferred CUs as long as these CUs do not occupy more resources than the UB could offer and the remaining CUs are rejected. Such a procedure runs until every CU is either matched or its preference list is empty. The implementation detail of Step 1 of the algorithm is stated in 4.1 as follows:

Algorithm 4.1 Many-to-One Matching

1: **Input:** CU, UB, PL^{CU}, PL^{UB}
2: **Output:** Matching μ_1
3: **Stage 1:** Proposing:
4: All free CU_k propose their favourite UB_u in their preference lists, and remove UB_u from the list.
5: **Stage 2:** Accepting/rejecting:
6: UB_u accepts the most preferred n proposers based on its preference list, the rest are rejected. The sum of the slot time of the accepted proposers does not exceed its available resource time.
7: None of the accepted proposers are free.
8: All the rejected proposers are free.
9: **Termination Criterion:**
10: If every CU is either allocated with a UB or its preference list is empty, this algorithm terminates with an output μ_1.
11: Otherwise, **Stage 1** and **Stage 2** are performed again.

Theorem 4.1. *Stability of μ_1. In any instance of a many-to-one matching, Algorithm 4.1 terminates with a stable matching μ_1.*

Proof. We prove this theorem by contradiction and assume that for an instance of a many-to-one matching, Algorithm 4.1 terminates with an unstable matching μ_1, i.e., there exists at least one blocking pair (CU_k, UB_u) or one blocking individual CU_k in matching μ_1.

If there exists one blocking pair (CU_k, UB_u) in μ_1:

- Case 1: In μ_1, UB_u is unmatched and CU_k is matched with UB'_u.

  If UB_u is not on the preference list of CU_k, there is no incentive for CU_k to match with UB_u; If $pri(CU_k,UB_{u'}) > pri(CU_k,UB_u)$, and CU_k is matched with UB'_u in μ, then there is no incentive for CU_k to match with UB_u; If $pri(CU_k,UB_u) > pri(CU_k,UB_{u'})$, then CU_k proposes to UB_u before $UB_{u'}$. CU_k is rejected during the proposal stage or is first accepted by UB_u, then is rejected in later stages because UB_u prefers other proposer. In conclusion, in any situation in which CU_k is matched and UB_u is unmatched, a blocking pair does not exist.

- Case 2: In μ_1, both UB_u and CU_k are unmatched.

  UB_u is unmatched means that it receives no proposal from CU, including CU_k. This means that UB_u is not on $CU_k{}'s$ preference list, then there is no incentive for CU_k to match with UB_u. In conclusion, in any situation in which both CU_k and UB_u are unmatched, blocking pair does not exist.

- Case 3: In μ_1, UB_u being matched with CU'_k and CU_k unmatched.

  CU_k is unmatched means that either UB_u is not in its preference list, or all its proposals have been rejected. For the former, there is no incentive for CU_k to match with UB_u. For the latter, UB_u rejects CU_k because it prefers other proposer(s). Thus, there is no incentive for UB_u to match with CU_k. In conclusion, in any situation in which both CU_k is unmatched and UB_u is matched, a blocking pair does not exist.

- Case 4: In μ_1, UB_u is matched with CU'_k and CU_k with UB'_u.

  UB_u must be on CU'_ks preference list, and vice versa, otherwise, there is no incentive to form the (CU_k, UB_u) pair. If $pri(CU_k,UB_{u'}) > pri(CU_k,UB_u)$, then, CU_k does not have an incentive to match with UB_u if it is matching with $UB_{u'}$. If $pri(CU_k,UB_u) > pri(CU_k,UB_{u'})$, then, CU_k proposes to UB_u first and gets rejected, because UB_u prefers CU'_k to CU_k, then there is no incentive for UB_u to match with CU'_k. In conclusion, in any situation in which both CU_k and UB_u are matched, a blocking pair does not exist.

The above analysis leads to contradictions, as (CU_k, UB_u) is any pair, we could prove that there is no blocking pair in matching μ_1.

If one blocking individual CU_k or UB_u exists in μ_1:
for blocking individual CU_k:

- Case 1: In μ_1, CU_k is matched with UB_u, i.e., UB_u is on CU_k's preference list, as such CU_k does not have incentive be unmatched. In conclusion, in any situation in which CU_k is matched, blocking individual CU_k does not exist.

- Case 2: In μ_1, CU_k is unmatched. There are 2 possible reasons. The first is that the preference list of CU_k is empty. The second is all CU_k' proposals are rejected or first accepted than gets rejected at a later stage. For these two cases, no UB_u has an incentive to match CU_k.

In conclusion, in any situation in which CU_k is unmatched, blocking individual CU_k does not exist.

for blocking individual UB_u:

- Case 1: In μ_1, UB_u is matched with CU_k, i.e., CU_k is on UB_u's preference list, as such UB_u does not have incentive be unmatched. In conclusion, in any situation in which UB_u is matched, blocking individual UB_u does not exist.

- Case 2: In μ_1, UB_u is unmatched. There 2 possible reasons. The first is that the preference list of UB_u is empty. The second is all CUs are matched to UBs, which has a higher level of preference than UB_u. For these two cases, no UB_u has an incentive to unmatched, because it is already unmatched.

In conclusion, in any situation in which CU_k is unmatched, blocking individual CU_k does not exist.

As the above blocking pair (CU_k, UB_u), blocking individuals CU_k or UB_u can be any pair or individual, thus, we prove that there is no blocking pair or blocking individual in matching μ_1. ☐

Theorem 4.2. *Praeto optimality of μ_1.*

In any instance of a many-to-one matching, stable matching μ_1 achieved by 4.1 is Praeto optimal, i.e., no player(s) can be better off, without reducing the other players' EE.

Proof. In stable matching μ_1:

- Case 1: There exists an unmatched CU_k, which can be matched to UB_u to increase the achievable EE of both CU_k and UB_u, meaning that (CU_k, UB_u) is the blocking pair of matching μ_1, contradicting **Theorem 4.1**.

- Case 2: There exists a (CU_k, UB_u) pair. Obviously, CU_k does not have an incentive to be unmatched; CU_k has the incentive to change partner from UB_u to $UB_{u'}$ to increase its achievable EE, meaning that $(CU_k, UB_{u'})$ is a blocking pair of matching μ_1, contradicting **Theorem 4.1**.

It is impossible to increase the EE of some CUs' without decreasing that of the remaining of the CUs. The state stands for UB, which can be proven similarly as above. □

We define the computational complexity of Algorithm 4.1 as the number of accepting/rejecting decisions required to output a stable matching μ_1. The complexity of Algorithm 4.1, i.e., the convergence of Algorithm 4.1 is given in **Theorem 4.3**.

Theorem 4.3. *Complexity of Algorithm 4.1 (Convergence of Algorithm 4.1). In any many-to-one resource allocation matching game, a matching μ_1 can be obtained by using Algorithm 4.1 within $\mathcal{O}(KU)$ iterations.*

Proof. In each iteration, a CU proposes to its most favourite UB in its current preference list, and SCBS accepts/rejects the proposal. The maximum number of elements in the preference list of CU_k equals the number of UBs, i.e., U. Thus, stable matching μ_1 can be obtained in $\mathcal{O}(KU)$ overall time, where K is the number of CUs and U is the number of UBs. □

Step 2: EE Optimization

As proven above, stability and Pareto optimality have been guaranteed by using Algorithm 4.1, meaning that there are no incentives for any CUs and UBs to form a new matching. If the preference lists of CUs are incomplete, some CUs may be unmatched [99], [100].

To further maximize the system's EE, Algorithm 4.2 is developed in step 2 by increasing the number of CUs matched. An iteration of Algorithm 4.2 begins with a unmatched CU_k proposing to its most favourite UB_u, and this UB_u would be deleted from the preference list of CU_k. An SCBS would consider this proposal as profitable if the following criteria are fulfilled:

- After deleting several non-favourite or all CUs matched with UB_u in μ_1 obtained via Algorithm 4.1, the minimal throughput of CU_k can be achieved by using UB_u
- All the deleted CUs could be served by other UBs to fulfill their minimal throughput requirement.
- The EE of the new matching μ_k is greater than that of the previous matching μ_1.

Such matching μ_k would be considered as a profitable reallocation, and would be updated as the new matching, if there is only one profitable reallocation. Should there be multiple profitable reallocations, the one that enhances the overall EE the most would be the new matching. Algorithm 4.2 would run until every CU is either allocated with a UB or its preference list is empty. The detail of Algorithm 4.2 is described as follows:

Algorithm 4.2 System EE Maximization & Unmatched CUs Reallocation

Input: CU, UB, PL^{CU}, PL^{UB}, μ_1
Output: Matching μ_2
Step 1: Proposing:
  Every free CU_k proposes to their favourite UB_u in their preference lists, and removes UB_u from the list.
Step 2: Reallocation:
  Each CU_k is accommodated in UB_u by deleting its least favorite partners in μ_2, to ensure that the occupying slot time does not exceed the available slot time.
  All the deleted CUs can be accommodated by other UBs. A matching μ_k is formed.
  EE increases from matching μ_1 to μ_k.
  μ_k is stored if all the above three criteria are fulfilled, or discarded otherwise. **Step 2** is performed until all free CUs have gone through **Step 2**.
Step 3: Accepting/rejecting:
  The μ_k that increases the system's EE most is updated; CU_k is set to be served. The rest $\mu_{k'}$ are rejected, and $CU_{k'}$ are rejected and set to be free.
Termination Criterion:
  Each CUs is either allocated with a UB or its preference list is empty, this algorithm is terminated with an output μ_2.
  Otherwise, **step 1**, **step 2** and **step 3** are performed again.

Theorem 4.4. *Stability of μ_2. In any instance of many-to-one matching, stability is achieved by using Algorithm 4.2 in μ_2.*

Proof. We prove this theorem by contradiction and assume that for an instance of many-to-one matching, Algorithm 4.2 terminates with an instable matching μ_2, i.e., there exists at least one blocking pair (CU_k, UB_u) or one blocking individual CU_k or UB_u.

If there exists one blocking pair (CU_k, UB_u) in μ_2:

- Case 1: In μ_2, UB_u is unmatched and CU_k is matched with UB'_u. If UB_u is not on the preference list of CU_k, then, CU_k does not have an incentive to match with UB_u; If $pri(CU_k, UB_{u'}) > pri(CU_k, UB_u)$, and CU_k is matched with UB'_u in μ_2, then CU_k does not have an incentive to match with UB_u; If $pri(CU_k, UB_u) > pri(CU_k, UB_{u'})$, then CU_k proposes UB_u before $UB_{u'}$ in Algorithm 4.1, or re-matches to UB_u before

$UB_{u'}$ in Algorithm 4.2. The result is that CU_k matches to $UB_{u'}$, meaning that CU_k is rejected at some stage in Algorithm 4.1 or Algorithm 4.2. In conclusion, in any situation in which CU_k is matched and UB_u is unmatched, a blocking pair does not exist.

- Case 2: In μ_1, UB_u being unmatched and CU_k unmatched. UB_u is unmatched means that it receives no proposal from CU, including CU_k in both Algorithm 4.1 and Algorithm 4.2. As both Algorithm 4.1 and Algorithm 4.2 terminate when every CU is matched or its preference list is empty. UB_u being unmatched means that either its preference list is empty or does not contain UB_u. Then CU_k does not have an incentive to match with UB_u. In conclusion, in any situation in which both CU_k and UB_u are unmatched, a blocking pair does not exist.

- Case 3: In μ_1, UB_u being matched with CU'_k and CU_k unmatched. CU_k is unmatched means that either it has no UB_u in its preference list, or all its proposals have been rejected in both Algorithm 4.1, and CU_k can not be matched to any UBs in the reallocation stage in Algorithm 4.2. For the former case, CU_k does not have an the incentive to match with UB_u. For the latter case, UB_u rejects CU_k because it prefers other proposer(s), and there are not enough spectrum resources in UB_u to serve CU_k. Thus, UB_u does not have incentive to match with CU_k. In conclusion, in any situation in which both CU_k is unmatched and UB_u is matched, a blocking pair does not exist.

- Case 4: In μ_1, UB_u is matched with CU'_k and CU_k with UB'_u. UB_u must be on CU'_ks preference list, and vice versa, otherwise, there is no incentive to form the (CU_k, UB_u) pair. If $pri(CU_k, UB_{u'}) > pri(CU_k, UB_u)$, then, CU_k does not have an incentive to match with UB_u if it is matched with $UB_{u'}$. If $pri(CU_k, UB_u) > pri(CU_k, UB_{u'})$, then, CU_k proposes to UB_u first and is rejected, either because UB_u prefers CU'_k to CU_k, or (UB_u, CU'_k) is formed in the re-allocation stage. For the former, UB_u does not have an incentive to match with CU'_k. For the latter, UB_u does not have sufficient spectrum resource to serve CU_k, otherwise, the (CU_k, UB_u) pair has been formed in μ_2. In conclusion, in any situation in which both CU_k and UB_u are matched, a blocking pair does not exist.

Contradictions, as (CU_k, UB_u) is any pair, thus, we could say that there is no blocking pair in matching μ_2.

If there exists one blocking individual CU_k or UB_u in μ_2:

for blocking individual CU_k:

- Case 1: In μ_2, CU_k is matched with UB_u, i.e., UB_u is on CU_k's preference list, then CU_k does not have an incentive to be unmatched. In conclusion, in any situation in which CU_k is matched and blocking individual CU_k does not exist.

for blocking individual UB_u:

- Case 1: In μ_2, CU_k is matched with UB_u, i.e., CU_k is on UB_u's preference list, then UB_u does not have an incentive to be unmatched. In conclusion, in any situation in which both UB_u is matched and blocking individual UB_u does not exist.

In the above proof, blocking pair (CU_k, UB_u), blocking individual CU_k or UB_u can be any pair or individual, thus, we could prove that there is no blocking pair or blocking individual in matching μ_2. □

Theorem 4.5. *Praeto optimality of μ_2. In any instance of one-to-many matching, Praeto optimality is achieved by using 4.2 in μ_2.*

Proof. In stable matching μ_2:

- Case 1: An unmatched CU_k exists, which can be matched to UB_u to increase the achievable EE of both CU_k and UB_u, meaning that (CU_k, UB_u) is the blocking pair of matching μ_2, contracting **Theorem 4.4**.

- Case 2: An existing a (CU_k exists, UB_u) pair. Obviously, CU_k does not have an incentive to be unmatched; CU_k has the incentive to change partner from UB_u to $UB_{u'}$ to increase its achievable EE, meaning that $(UB_u, UB_{u'})$ is a blocking pair of matching μ_2, contracting **Theorem 4.4**.

It is impossible to increase the EE of a CU without decreasing that of the remaining CUs. The statement stands for UB, which can be proven similarly as above. □

Theorem 4.6. *Complexity of Algorithm 4.2 (Convergence of Algorithm 4.2). In any instance of many-to-one matching, a matching μ_2 can be obtained by using Algorithm 4.2 based on matching μ_1 within $\mathcal{O}(mU(K-m)(U-1))$ iterations, where m is the number of unmatched CUs in μ_1.*

Proof. At proposing step in Algorithm 4.2, each one of m unmatched CUs proposes to its favourite UB, such as UB_u, in its current preference list. The maximum number of CUs being matched to UB_u in μ_1 is $(K-m)$. Then, the matched CUs of UB_u will be deleted from mu_1 and re-matched to the rest of UBs in their preference lists. The maximum number of CUs that are deleted is $(K-m)$. For each deleted CU, the maximum number of UBs in its preference list is $(U-1)$. Thus the maximum number of accepting/rejecting decisions made is $(K-m)(U-1)$ for each proposal of an unmatched CU. As there m unmatched CUs, the total number of accepting/rejecting decisions made is $(K-m)(U-1)*mU$. □

Table 4.2 Parameters for LTE-U uplink EE optimization simulation

Number of CUs	6, 9, 12, 15, 18 and 21
Network Radius	100 m
CU Traffic Level (TR^C)	10, 15, 20, 25, 30, 35 and 40 Mbps
WU Traffic Level (TR^W)	20 Mbps
Unlicensed Spectrum	5 GHz
UB Bandwidth	20 MHz
CU Transmission Power	20 mw
T	10 μ s
t	1 μ s
Packet Size	12800 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
Wi-Fi & LAA Bit Rate	50 Mbit/s
$CW_{initial}$	8
Slot Time	9 μs
SIFS	16 μs
DIFS	34 μs

4.4 Numerical Results and Analysis

4.4.1 Simulation Setting

We perform Monte Carlo simulations in a circle with a radius of 100m with CUs randomly and uniformly distributed. The throughput requirement of each WUs and CUs are both random values between the range of [0, TR^W] and [0, TR^C], respectively. We evaluate the performance of the proposed matching based resource allocation algorithm in the network versus the number of CUs and traffic load of CUs. The number of CUs varies from 9 to 21 and TR^C varies from 10 to 40 Mbps. We assume the total number of UBs to be 9. Applying frame structure in LTE, We set the slot time T to be 10 μs, and the sub-frame duration is 1 μs, which is much smaller than the channel coherence time. For each scenario with a certain network density and traffic load level, simulation is run 10,000 times. CUs are randomly located in the area of interest 100 times, and in each time channel fading is performed 100 times.

All other parameters can be referred to in Table. 4.2. MAC header, PHY header and ACK frame length are defined in 802.11 standard [90]. The maximum transmission rate of 802.11ac is 96.3 Mbit/s [90], in the simulation the transmission rate of Wi-Fi and LAA is set to be 50 Mbit/s [2], half of the maximum value for a general case. $CW_{initial}$ is the initial CW size defined in 802.11 standard [90]. CW_{min}, CW_{max}, Slot Time, SIFS, DIFS and packet size are defined in 802.11 standard [90].

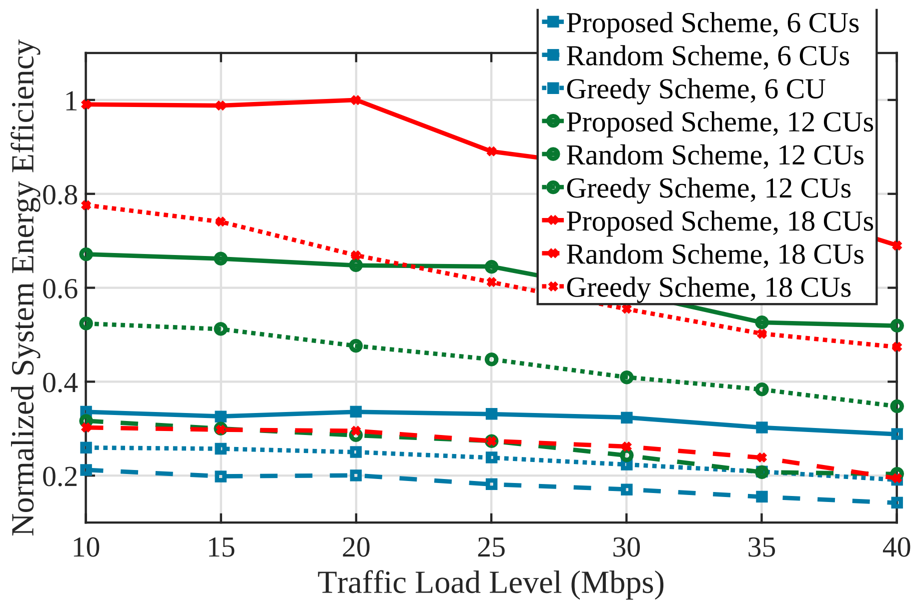

Fig. 4.3 System Energy Efficiency for Scenarios with Different Number of CUs

4.4.2 EE and Fairness Between CUs

We first analyze the system EE obtained by the proposed matching-based scheme versus the number of CUs and traffic load levels in Fig. 4.3. Our proposed algorithm outperforms the greedy algorithm and random allocation in both low-density (6 CUs) and high-density networks (18 CUs) with a light traffic load from TR^C=10 Mbps per CU and heavy traffic load with TR^C=40 Mbps per CU. In the light and the heavy traffic load scenarios, the system EE obtained by our proposed method is 30% and 50% more than that obtained by the greedy algorithm, respectively. As shown in Fig. 4.4 for the same number of CUs, with the increasing of traffic load per CU, the system EE decreases because more CUs remain unserved in the heavy traffic load scenario. This is because it occupies more resources to serve a CU with higher traffic demand, leading to a drop in the number of CUs that can be served in the network, i.e., more CUs fail to achieve their throughput requirement.

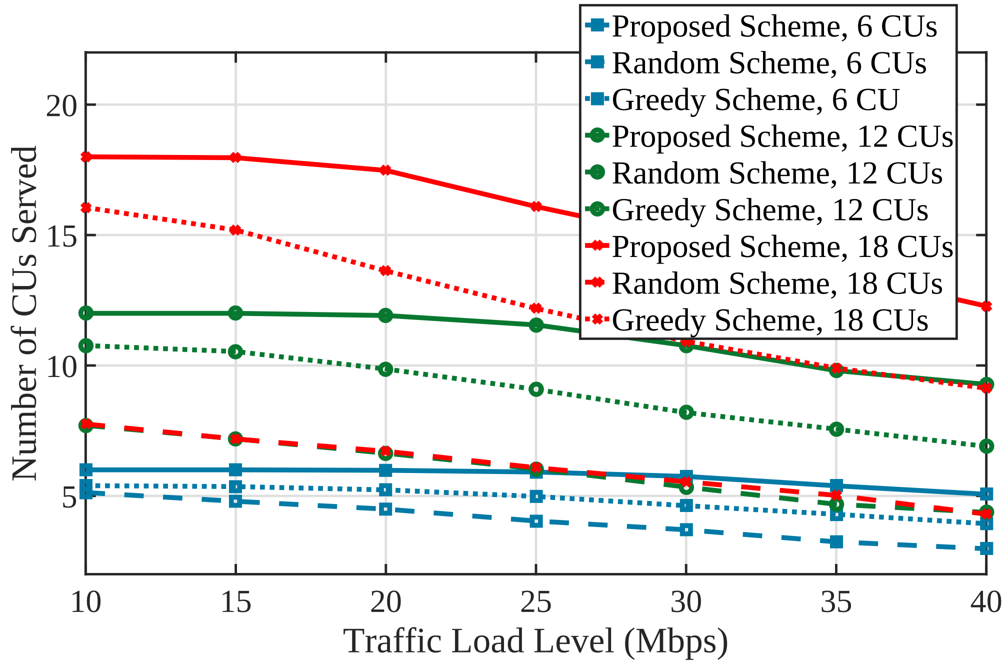

Fig. 4.4 The Number of CUs Served

On the contrary, with the same traffic load level, more CUs tend to be served in the dense scenarios, leading to an increase of system EE as shown in Fig. 4.5. In dense scenarios, more CUs have the chance to meet their throughput requirement, due to many factors, such as the distance between CU and SCBS and channel condition between CU and SCBS. Although the number of CUs served increases with the number of CUs in the network, except for the low traffic demand scenario, the percentage of CUs that have their throughput requirement fulfilled drops, as shown in Fig. 4.6. In a low traffic demand scenario, where the spectrum resource is sufficient to serve every CU with their required throughput demand, almost 100% of CUs' being served rate is achieved by the proposed algorithm, compared with less than 90% achieved by the greedy algorithm and even lower served rate using the random algorithm. In medium and high traffic demand scenario, the percentage of CUs served decreases with the increase of CUs in the network by using any one of the three algorithms. However, the proposed algorithm still outperforms the greedy algorithm and random algorithm by around 35% and 50% 120%, respectively. Thus, we could say that the proposed algorithm works more effectively in CUs' fairness compared with the greedy algorithm or the random allocation scheme.

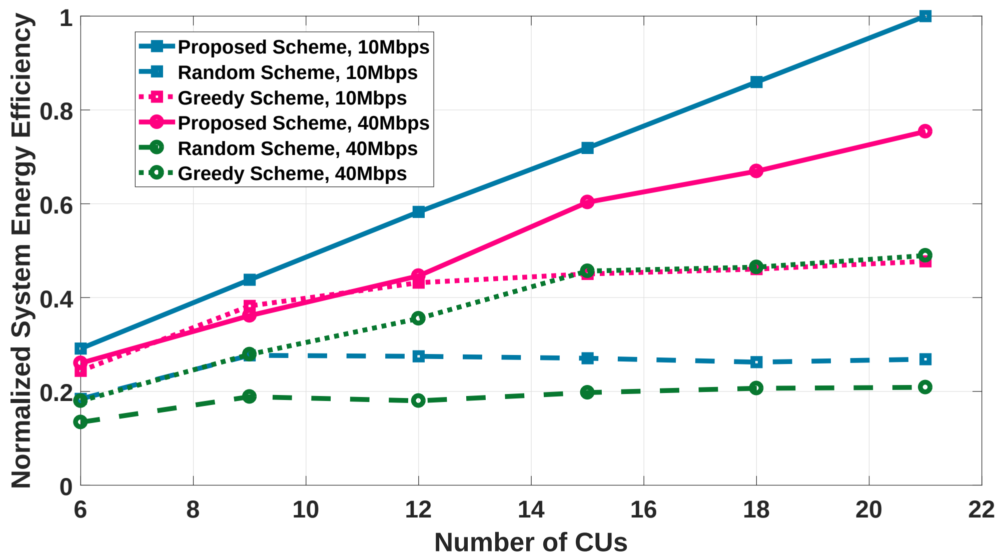

Fig. 4.5 System Energy Efficiency in Different Traffic Load Level

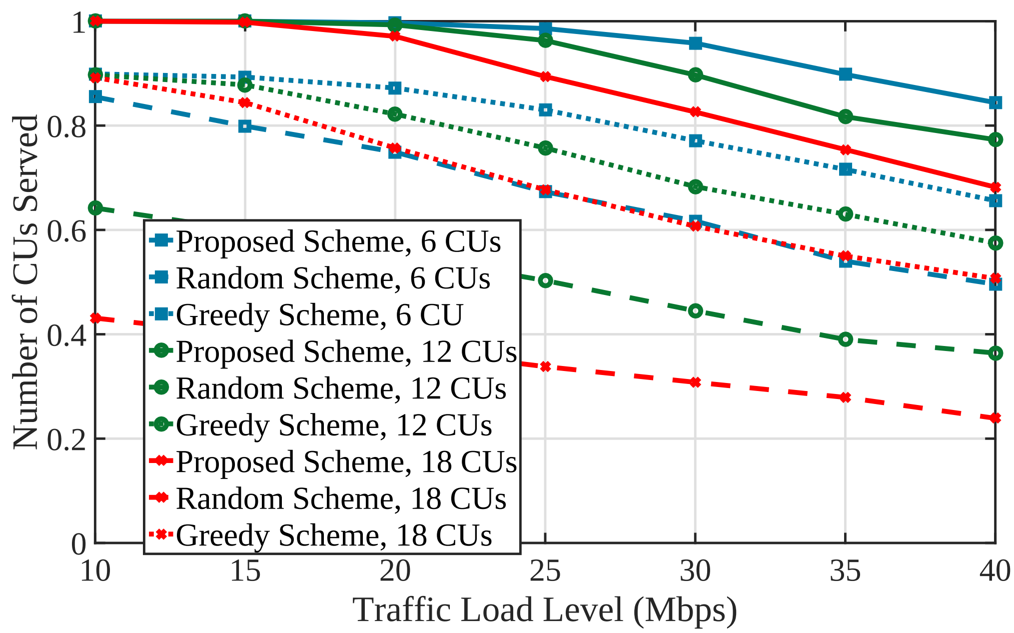

Fig. 4.6 The Percentage of CUs Served Comparison

4.4.3 Throughput Analysis

Throughput is another performance matrix for both the system and an individual CU. As shown in Fig. 4.7, in the 6 CUs scenarios with low traffic demand, three algorithms achieve similar results. This is because the unlicensed spectrum resource is sufficient to serve every CU with its relatively low traffic demands. In low traffic demand, system throughput increases with the number of CUs almost linearly by using the proposed algorithm and the greedy algorithm, because the spectrum resource is still sufficient. The proposed algorithm outperforms the greedy algorithm. However, there is another aspect of heavy traffic load. In the network with 6 CUs, the proposed algorithm achieves 66% more than the greedy algorithm, and more than 100% more than the random scheme. With the increase of the number of CUs in the network, the overall throughput achieved by using the proposed algorithm tends to saturate in heavy traffic load scenarios. This is because the capacity is limited by the available unlicensed spectrum resources.

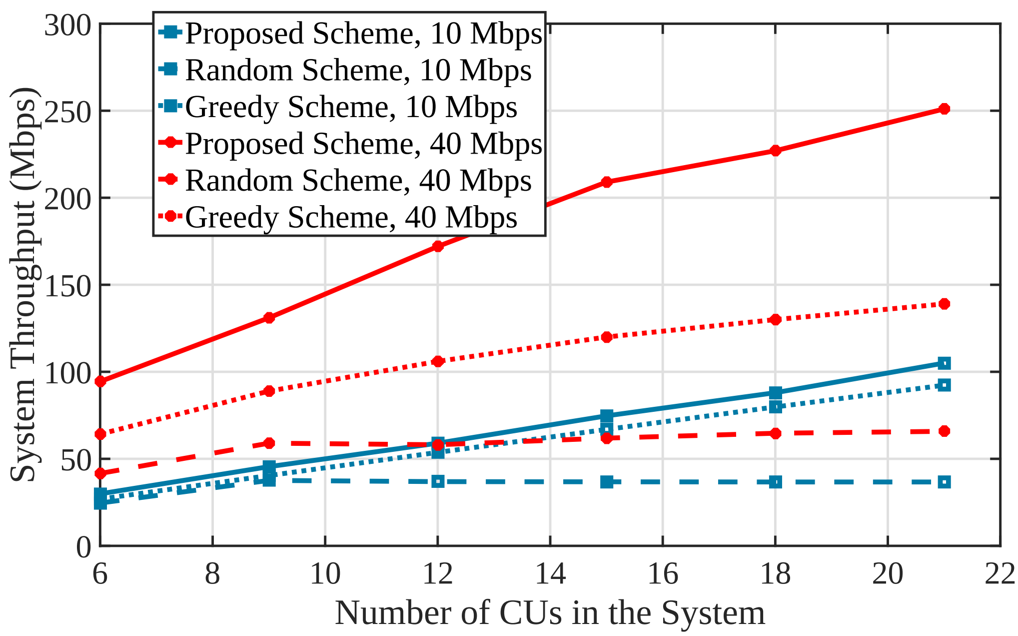

Fig. 4.7 System Throughput In Different Traffic load Level

4.4.4 Computational Complexity

The theoretical upper bound of the computation complexity of Algorithm 4.1 and 4.2 have been given in **Theorem 4.3**, and **Theorem 4.6**. Here we show the simulation computation complexity of the proposed algorithm in typical traffic load scenarios in Fig. 4.8. The computational complexity is represented in terms of iteration numbers. An iteration in **Theorem 4.3** and **Theorem 4.6** are the same, which contains two parts: 1) an unmatched CU proposed to its favourite UB in the CU's preference list, 2) an acceptance or rejection made by SCBS on the proposal. The complexity of the proposed optimization algorithm in each scenario is the summation of the iteration number of **Theorem 4.3** and **Theorem 4.6**.

There are positive correlations between the complexity and network density at the same traffic load level. Specifically, at the lowest traffic load (10 Mbps), complexity is slightly more than the number of CUs in the network. This means that due to the low traffic demand of each CU, almost all the CUs' first proposal are accepted. In a low traffic case, most CUs are matched by using Algorithm 4.1 and Algorithm 4.2 is seldom performed. The complexity increases with the traffic load level from 10 to 30 Mbps. This is because with the increase of traffic load level, increasing CUs are unmatched in μ_1 by using Algorithm 4.1 and the number of iterations that Algorithm 4.2 performs is increasing. The complexity of an iteration in Algorithm 4.2 ($\mathscr{O}((K-m)(U-1))$) is much larger than that in Algorithm 4.1 ($\mathscr{O}(U)$), leading to an increase of complexity. At an even higher traffic load level, the complexity begins to drop. At this stage, the number of UBs in a CU's preference lists is much smaller than that in a medium traffic load level. The complexity of obtaining matching μ_1 is much smaller. Although the number of unmatched CUs rises in the scenario with the same network density, elements in their preference lists are much less, the complexity in an iteration drops significantly, leading to the decrease of computational complexity at a high traffic load level.

4.5 Conclusions

In this work, we have studied the uplink resource allocation problem in a LTE-U and Wi-Fi coexistence scenario to maximize each CU's EE. We formulated the problem as a multi-objective optimization, and transformed it into a single-objective optimization by using the weighted-sum method. We proposed a semi-distributed 2-step matching with partial information based algorithm to solve the problem. Compared with the greedy algorithm based resource allocation scheme, our proposed scheme achieves improvements of up to 50% in terms of EE and up to 66% in terms of throughput. Furthermore, we have analysed the computational complexity of the proposed algorithm theoretically and by simulations, thereby showing the complexity is reasonable for real-world deployment.

In the next chapter, we will extend our work into unlicensed bands and licensed bands allocation for the sake of UE QoS, which will be the major concern regarding unlicensed

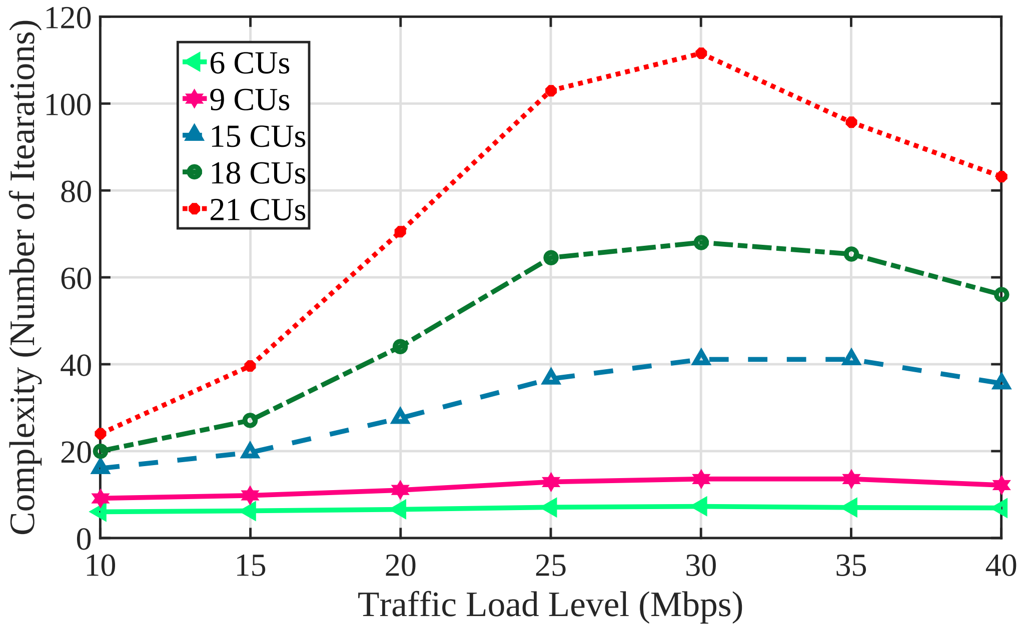

Fig. 4.8 Computational Complexity in Different Scenario

spectrum usage. Currently, a UE tends to connect to WiFi network no matter how poor the service is, which lead to poor user experience. To solve this challenge, we will consider unlicensed and licensed bands jointly allocation and develop the utility function prioritizing UE QoS. Again, this resource allocation problem can be formulated into a matching game and the QoS requirement can be transferred into the preference lists of CUs. ABS scheme of LTE in the unlicensed bands and OFDMA of LTE in the licensed bands will be performed in a many-to-one and one-to-one integrating matching.

Chapter 5

Licensed and Unlicensed Spectrum Allocation With Pricing Strategies

In this section, we extend the resource allocation problem in Chapter 4 from unlicensed bands sharing to licensed & unlicensed bands sharing, where CUs can access both licensed and unlicensed bands. A primary goal of deploying LTE in the unlicensed spectrum is to alleviate the scarcity of the licensed spectrum through offloading traffic to the unlicensed spectrum. Operators may apply pricing strategies to enhance offloading, i.e., operators set different prices for a CU to access the unlicensed and licensed bands. Another reason for the use of pricing strategies is operators pay differently for employing the unlicensed and licensed spectrum.

We aim to maximize the utility (defined as a function of CU throughput and monetary cost) of each CU while guaranteeing the throughput requirements of both CUs and WUs. Accordingly, we formulate a multi-objective optimization problem, which is further formulated into a matching game, where CUs and the licensed & unlicensed bands form two agents, and the constraints of the optimization problem are transformed into the preference lists of these two agents. Different from Chapter 4, we jointly consider the allocation of LBs and UBs by integrating one-to-one and many-to-one matching in the proposed marching-based algorithm. The stability, Pareto efficiency and convergence of the proposed algorithm is proved.

The effectiveness of the proposed matching-based algorithm is validated by comparing with exhaustive-search algorithm and is further used to evaluate the performance of different pricing strategies in terms traffic offloading, system throughput and revenue of the operators.

5.1 System Model

We consider a single small-cell base station (SCBS) and multiple Wi-Fi access points (APs) coexisting in an area, serving N WUs and M CUs, denoted by WU_n and CU_m, respectively, where $n \in \{1,2,...,N\}$ and $m \in \{1,2,...M\}$. The SCBS, Wi-Fi APs, CUs, and WUs are independently and uniformly distributed within the area of interest. The licensed spectrum is divided into L orthogonal licensed bands (LBs) with the same bandwidth B_L, denoted by $LB_l, l \in 1,2,...L$. The considered unlicensed spectrum is equally divided into U orthogonal unlicensed bands (UBs) each with the same bandwidth B_U, denoted by $UB_u, u \in 1,2,...U$. For each UB, the time is divided into time slots each with a period of T. The duration of a time slot is $T/10$, which is shorter than the channel coherence time. To guarantee WUs' QoS requirements, a certain number of sub-frames per time slot in a UB are reserved for WUs' use only. CUs are permitted to occupy the remaining sub-frames in a time slot. A CU can access either an LB following the orthogonal frequency division multiple access (OFMDA) or a UB (following an almost blank subframe (ABS) pattern [95]) to achieve its minimum throughput requirement.

We also consider pricing strategies designed by operators in this resource allocation problem for the following reasons:

- **Traffic offloading**: It has been shown that pricing strategies are effective in traffic-load balancing among base stations [10]. We also consider they can be used to offload traffic from the licensed spectrum to the unlicensed spectrum.
- **Revenues of operators**: Operators paid differently prices for using the licensed spectrum and unlicensed spectrum: it is quite expensive to use the licensed spectrum while using the unlicensed spectrum is much cheaper or even free of charge.
- **User's interest**: The achievable QoS for a user accessing the unlicensed spectrum and licensed spectrum are generally different and corresponding pricing are different as well. QoS and price should be jointly considered by a user to choose between licensed and unlicensed spectrum.

For denotational simplicity, we denote B_k as the k-th LB or the $(k-L)$-th UB as following:

$$B_k = \begin{cases} LB_k, \text{ if } k \in \{1,2,...,L\}, \\ UB_{k-L}, \text{ if } k \in \{1+L, 2+L, ..., U+L\}. \end{cases} \tag{5.1}$$

The throughput of the m-th CU in B_k is calculated by $TH_{m,k}^{CU} = \sum_i^{T_{m,k}} C_{m,k,i}^{CU}$, where $C_{m,k,i}^{CU}$ denotes the achievable data rate of CU_m using the i-th sub-frame of the k-th band, $T_{m,k}$ is the number of sub-frames in the k-th band allocated to CU_m, and $C^{CU}_{m,k,i}$, which is given by Shannon equation [96]:

$$C^{CU}_{m,k,i} = B(1+SINR) = B_k log_2(1+\frac{\chi_{m,k}P^{CU}_{m,k}g_{m,k,i}}{\sigma_N^2+\sum_{j\neq m}^{M}\chi_{j,u}P^{CU}_{j,m}g_{j,k,i}}), \tag{5.2}$$

in which $\chi_{m,k}$ is a binary indicator that equal 1 if CU_m uses B_k and 0 otherwise. $P^{CU}_{m,k}$ is the transmit power of CU_m on B_k, $g_{m,k,i}$ is the channel power gain between CU_m and the SCBS on the i-th sub-frame of B_k, and σ_N^2 is the thermal noise power.

Each WU has an equal probability to access one of the UBs. We regard the WUs sharing the same UB as one WU, thus the interactions between co-channel CUs and WUs can be simplified to the interactions between co-channel CUs and a WU [55]. The WU that occupies UB_u is denoted by WU_u. The throughput of WU_u is the same as (3.9) in Chapter 3 of this thesis:

$$Th_u^{WU} = \frac{\overline{E(p)}P_{tr}^uP_s^u}{(1-P_{tr}^u)\delta+P_{tr}^uP_s^uT_s+P_{tr}^u(1-P_s^u)T_c,} \tag{5.3}$$

where $\overline{E(p)}$ is the average packet size of Wi-Fi transmissions, P_{tr}^u is the probability that UB_u is occupied, P_s^u is the probability that a successful transmission occurs in UB_u, δ is the Wi-Fi time slot duration [59], and T_s and T_c are the average time consumed by a successful transmission and a collision in UB_u, respectively.

5.2 Problem Formulation

We define the utility of CU_m as $U_m = \sum_{k=1}^{L+U}\chi_{m,k}U_{m,k}$, where $U_{m,k}$ is the utility of CU_m using B_k following $U_{m,k}{=}TH^{CU}_{m,k}{-}M(TH^{CU}_{m,k})$. $M(TH^{CU}_{m,k})$ is the monetary cost that CU_m pays for using B_k to achieve throughput $TH^{CU}_{m,u}$. Note that the monetary cost may vary when using different bands, especially for the usage of LBs and UBs.

To guarantee the quality of service (QoS) of each WU and each CU, and the fairness between CUs, we aim to maximize the utilities of all the M CUs and formulate it as a multi-objective optimization problem as follows:

$$\max_{\{\chi_{m,l}\}} (U_1, \ldots, U_m, \ldots, U_M), \tag{5.4}$$

subject to,

$$\sum_{l=U+1}^{U+L} \chi_{m,l} \leq 1, \ \ m \in \{1, \ldots, M\}, \chi_{m,l} \in \{0,1\}, \tag{5.4a}$$

$$\sum_{m=1}^{M} \chi_{m,u} T_{m,u} T/10 \leq T(10 - l_u)/10, \ \ u \in \{1, \ldots, U\}, \tag{5.4b}$$

$$Th_u(10 - l_u)T/10 \geq R_u^W, l_u \in \{1, \ldots, 10\}, \tag{5.4c}$$

$$P_{m,u}^{CU} \leq P'_{max}, \ \ m \in \{1, \ldots, M\}, u \in \{L+1, \ldots, L+U\}, \tag{5.4d}$$

$$P_{m,l}^{CU} \leq P_{max}, \ \ m \in \{1, \ldots, M\}, l \in \{1, \ldots, L\}, \tag{5.4e}$$

$$TH_m^{CU} \geq TH_m^{Min}, m \in \{1, \ldots, M\}, \tag{5.4f}$$

where $T_{m,u}$ is the number of sub-frames in UB_u allocated to CU_m, $P_{m,u}^{CU}$ and $P_{m,l}^{CU}$ are the transmit power of CU_m in UB_u and in LB_l, respectively. Constraint (5.4a) indicates that a CU can be allocated up to 1 UB or 1 LB at a time. Constraint (5.4b) the maximum number of sub-frames of each UB reserved for LTE-U transmission, and constraint (5.4c) describes that l_u sub-frames of UB_u will be allocated to the WU to guarantee its throughput requirement. The maximum transmission power each CU in UB_u and in LB_l is set in (5.4d) and (5.4e), respectively, and (5.4f) requires that achievable throughput of a CU is greater than its minimum throughput requirement.

One possible approach to solve (5.4) is to transform it into a single-objective optimization problem by using the scalarization approach [98, 93]. As $\chi_{m,k}$ is an integer, the obtained single-objective optimization problem is a mixed integer nonlinear programming (MINLP) problem, which is NP-hard. In the next section, we develop a matching-based algorithm to solve the proposed optimization problem in (5.4), which is efficient to achieve Pareto optimality.

5.3 Matching-based Algorithm

In this section, the proposed matching-based algorithm operating in a semi-distributed manner will be introduced. Initially, each CU constructs its preference list based on local measurements of channel state information and UB availability, and reports these to its serving SCBS. The preference lists for LBs and UBs are then compiled in the SCBS along with a rejecting/accepting procedure as detailed below.

5.3.1 Preference Lists Setting

The preference list of a CU ranks its preference for each LB and UB. The preference level of B_k is based on the utility of this CU on B_k. CU_m prefers B_k over $B_{k'}$ if CU_m can achieve a higher utility using B_k than using $B_{k'}$, i.e.,

$$pri(CU_m, B_k) > pri(CU_m, B_{k'}) \Leftrightarrow U_{m,k} > U_{m,k'}, \tag{5.5}$$

where $pri(CU_m, B_k)$ is defined as the preference level of CU_m for B_k.

The preference list of B_k ranks its preferences over all CUs based on the monetary revenue obtained by serving each CU. B_k prefers CU_m over $CU_{m'}$ if a higher monetary revenue can be obtained by serving CU_m than serving CU'_m, i.e.,

$$\begin{aligned} &pri(B_k, CU_m) > pri(B_k, CU_{m'}) \Leftrightarrow \\ &P(TH^{CU}_{m,u}) > P(TH^{CU}_{m',u}), \end{aligned} \tag{6}$$

where $pri(B_k, CU_m)$ is the preference level of B_k for CU_m.

5.3.2 Matching based Algorithm

To solve the optimization problem (5.4), we propose Algorithm 5.1, which consists of two stages: the *proposing stage* and the *accepting/rejecting stage*. In the proposing stage, each CU proposes to its associated SCBS to use the favorite band in its preference list. In the accepting/rejecting stage, two types of matching are involved. The matching between LBs and CUs is a one-to-one matching following OFMDA while the matching between UBs and CUs is a many-to-one matching following ABSs [8]. Externalities exist in the many-to-one matching because the choice of one CU may affect those of other CUs. The problem of externalities is solved in line 6 of Algorithm 5.1.

Algorithm 5.1 terminates when each CU has been matched with a band or its preference list is empty and returns a stable matching μ. In the following, we prove the stability and Pareto optimality of the match μ obtained by Algorithm 5.1.

Theorem 5.1. *The matching μ returned by Algorithm 5.1 is stable.*

Proof. We assume that for an instance of the matching problem, Algorithm 5.1 terminates with an instable matching μ, i.e., there exists at least one blocking pair (CU_m, B_k) or one blocking individual CU_m or B_k in matching μ, where $m \in \{1, \ldots, M\}$ and $k \in \{1, \ldots, L+U\}$.

If there exists one blocking pair (CU_m, B_k) in μ and

Case 1: CU_m is matched with $B_{k'}$, then it is possible that

Algorithm 5.1 Matching-based algorithm

Input: LB,UB and CUs.
Output: Matching μ
Step 1: Proposing:
  All free CU_m make a proposal to their favourite band B_k in their preference lists and the band is removed from the list.
Step 2: Accepting/rejecting:
Based on (5.4b), UB_u accepts its most preferred n proposals, while the rest are rejected.
  LB_l accepts its favourite proposal, and the rest are rejected.
  All the accepted CUs are marked as engaged.
  All the rejected CUs are marker as free.
Criterion:
  The algorithm terminates with output μ if one of the following 2 criteria is satisfied for every CU:
  1. The CU is either allocated with a UB or an LB;
  2. The preference list of the CU is empty.
  Otherwise, **step 1** and **step 2** are performed again for all free CUs.

- B_k is not on the preference list of CU_m;
- $pri(CU_m, B_{k'}) > pri(CU_m, B_k)$ or
- $pri(CU_m, B_k) > pri(CU_m, B_{k'})$, but CU_m's proposal to use B_k has been rejected.

In any of the above situations, it is not possible to form (CU_m, B_k) pair.

Case 2: CU_m is unmatched, then it is impossible that

- B_k is not in the preference list of CU_m, or
- all the proposals of CU_m have been rejected, including from B_k, because B_k prefers other CUs.

In either of the above cases, it is impossible to form (CU_m, B_k) pair, thus, it is proven that there is no blocking pair in matching μ.

If one blocking individual CU_m (or B_k) exists in μ, then it is possible that CU_m is unmatched, or CU_m or B_k is matched with B_k or CU_m.

Blocking individual CU_m (or B_k) does not exist in either of above cases, thus, we can prove that there is no blocking pair or blocking individual in matching μ, i.e., matching μ is stable. $\square$

Theorem 5.2. *Praeto optimality of μ: In any instance of the matching problem, stable matching μ achieved by Algorithm 5.1 is Praeto optimal for every CU, i.e., no CUs can be better off without making at least one other CU worse off.*

Proof. In stable matching μ: a) If CU_m is matched with B_k, it tends to match with $B_{k'}$ to increase its utility. Then, $(CU_m, B_{k'})$ becomes a blocking pair in matching μ, which contradicts with **Proposition** 5.1. b) If CU_m is unmatched, it tends to match with $B_{k'}$ to increase its utility. Then, $(CU_m, B_{k'})$ becomes a blocking pair in matching μ, which also contradicts with **Proposition** 5.1.

Therefore, it is impossible to further increase the utility of any CU without decreasing those of the remaining other CUs. □

Table 5.1 Parameters used in the Simulations

Parameters	Values
Number of CUs	9, 10,...,27, 28
CU Traffic Level (TH^{min})	15 Mbps
WU Traffic Level (R^W)	20 Mbps
CU Transmission Power	20 mw
T	10 μ s
Packet Size	12800 bits
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
Slot Time	9 μs
SIFS	16 μs
DIFS	34 μs

We define the computational complexity of Algorithm 5.1 as the number of accepting/rejecting decisions required to obtain a stable matching μ.

Theorem 5.3. *Complexity and convergence of Algorithm 5.1: In any instance of the matching problem, Algorithm 5.1 terminates to a stable matching μ within $\mathscr{O}(M(U+L))$ iterations.*

Proof. In each iteration, a CU proposes to the SCBS to use its most preferred band in its current preference list, and the SCBS accepts/rejects the proposal. The maximum size of a CU's preference list is $U+L$, where U is the number of UBs and L is the number of LBs. Thus, in any instance of a matching problem, Algorithm 5.1 converges into a stable matching μ in $\mathscr{O}(M(U+L))$ iterations, where M is the number of CUs. □

5.4 Numerical Results

5.4.1 Simulation Settings

The simulation area is a circle with a radius of 100m. The proposed algorithm is evaluated in three pricing strategies (M_L=0.8M_U, M_L=0.4M_U and M_L=M_U) in terms of throughput, the ratio of traffic that offloads to the unlicensed bands, and complexity. The throughput requirements of WUs are random values within the range of [0, R^W], while those of CUs are random values within the range of [0, TH^{min}]. 4 UBs (each with a bandwidth of 20 MHz) in 5 GHz unlicensed spectrum, and 10 LBs (each with a bandwidth of 1.4 MHz) in 2.6 GHz licensed spectrums are employed in our simulations. All the simulation parameters are listed in Table 5.1. MAC header, PHY header and ACK frame length are defined in 802.11 standard [90]. The maximum transmission rate of 802.11ac is 96.3 Mbit/s [90], in the simulation the transmission rate of Wi-Fi and LAA is set to be 50 Mbit/s [2], half of the maximum value for a general case. $CW_{initial}$ is the initial CW size defined in 802.11 standard [90]. CW_{min}, CW_{max}, Slot Time, SIFS, DIFS and packet size are defined in 802.11 standard [90].

Monte Carlo simulations are performed $10,000$ times for the proposed matching-based algorithm (5.1) and an exhaustive algorithm. The exhaustive search algorithm evaluates all the possible matching in a scenario to achieve the global optimal matching. The iteration number of the exhaustive search algorithm is the number of possible matchings in a scenario.

5.4.2 Validation of The Proposed Algorithm

Fig. 5.1 shows the ratio of traffic on the unlicensed spectrum versus the number of CUs. Compared with the exhaustive search algorithm, the performance of proposed algorithm are slightly lower (around 5 %) in scenarios with different number of CUs and pricing strategies.

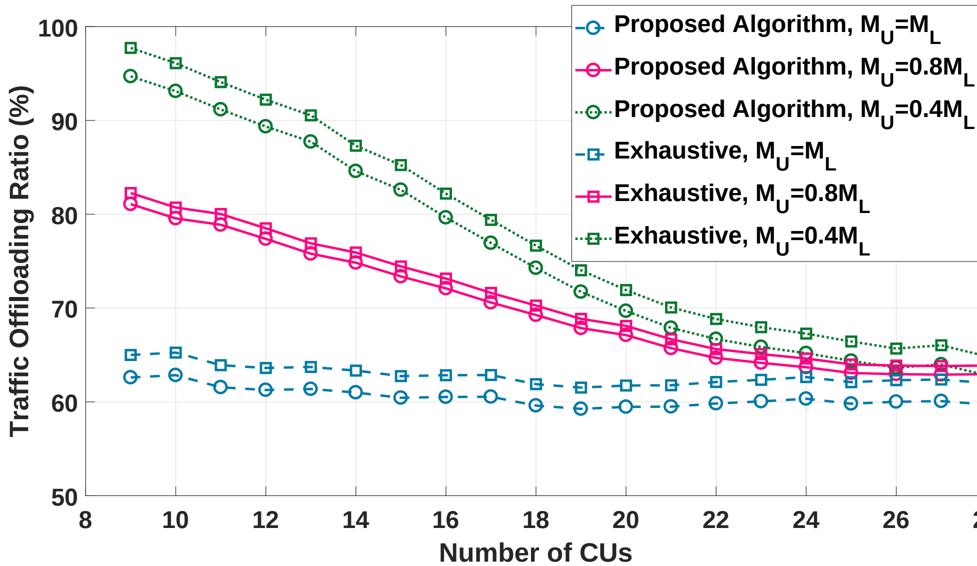

Fig. 5.1 Traffic offloading ratio on the unlicensed spectrum versus the number of CUs for different pricing strategies

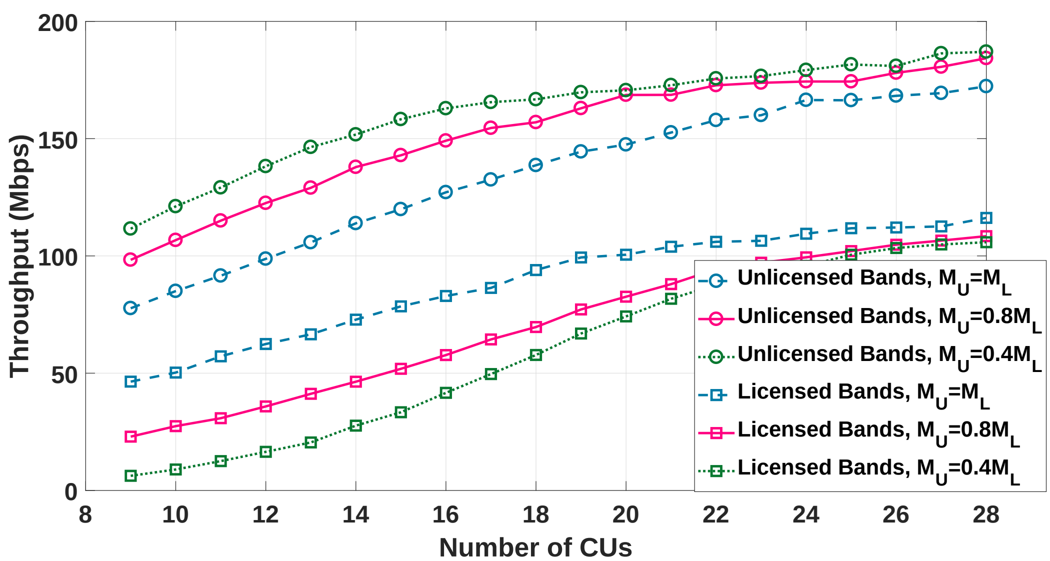

Fig. 5.2 Throughput of all the CUs achieved on the unlicensed or licensed bands versus the number of CUs for different pricing strategies

5.4.3 Performance Evaluation

Fig. 5.2 shows the throughput on the unlicensed and licensed spectrums in different CU density and pricing strategy combination. By applying pricing strategy M_L=0.4M_U, the largest throughput on the unlicensed spectrums and the smallest throughput on the licensed spectrums are achieved. It is exactly opposite in the scenario without pricing strategy (M_L=M_U). It is more clare to combine the traffic offloading ratio in Fig. 5.1. we can see that the ratio of traffic on the unlicensed spectrum is around 50% and 30% larger than that of without pricing strategy in a low-density network. Subject to pricing strategy, the ratio of traffic on the unlicensed spectrum decreases with the densification of the network and converges to approximately 63%, which is slightly larger than that of without pricing strategy, meaning that both the unlicensed and licensed bands are saturated. Similarly, the percentage of CUs offloaded to the unlicensed bands also demonstrate the effectiveness of pricing strategies in Fig. 5.4.

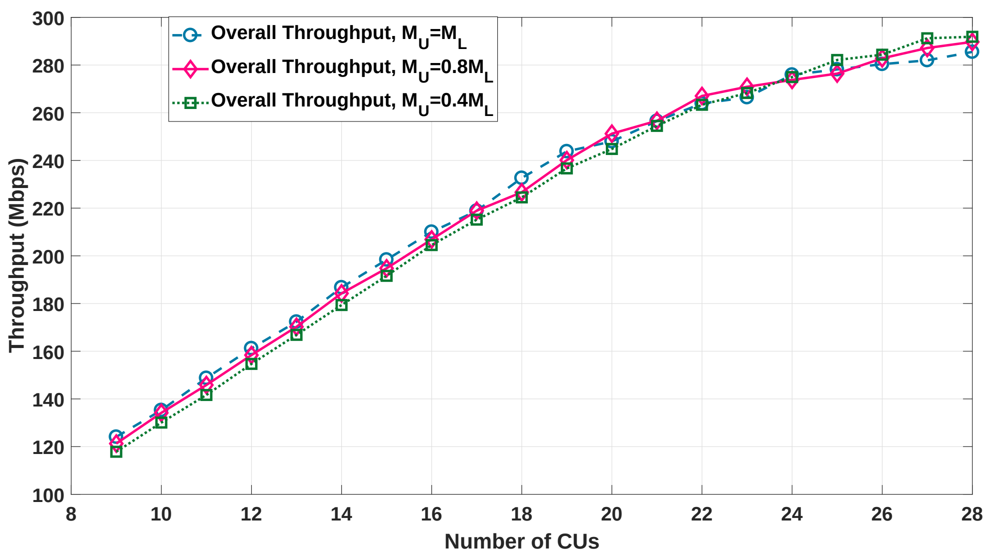

Fig. 5.3 Overall System Throughput

Although setting different prices for accessing the licensed and unlicensed bands is effective to offlaod traffic from the licensed bands to the unlicensed bands, the overall traffic served by the cellular operator remains almost the same in Fig. 5.3. With the increasing number of CUs in the network, corresponding system throughput tend to saturate due to the limited resource bands in the system. Similarly, the total number of CUs served tend to saturate with the increasing number of CUs in the network as shown in Fig. 5.5.

Fig. 5.6 shows the total revenue of the operator versus the number of CUs for different pricing strategies. The revenue of the operator with pricing strategy M_L=0.4M_U and M_L=0.8M_U increases from 34% and 69% in a loose network of that with pricing strategy M_L=M_U, respectively, to 61% and 88%, respectively. This is because in a loose network, as shown in Fig. 5.3, the total system throughput provided by are almost the same regardless of pricing strategies. With M_L=0.4M_U, the largest amount of traffic is served in the unlicensed

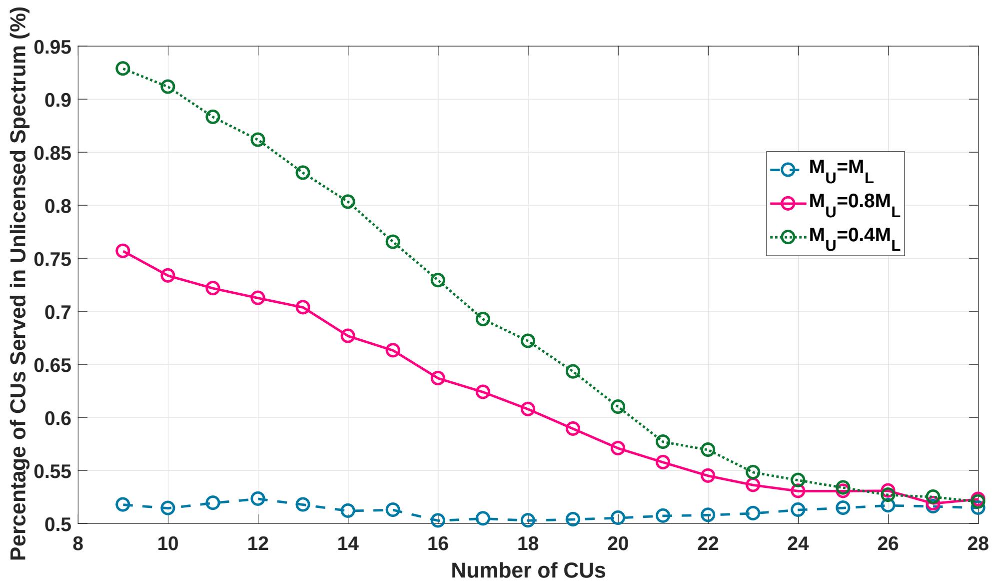

Fig. 5.4 Percentage of CUs Served in the Unlicensed Bands

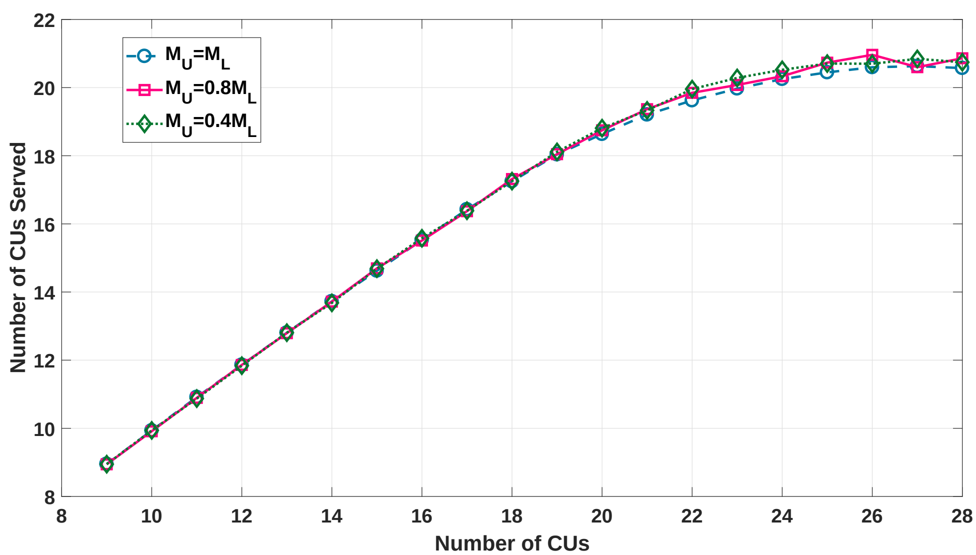

Fig. 5.5 Number of Users Served

spectrum and the least amout of traffic is served in the licensed spectrum (shown in Fig. 5.2), leading to the lowest revenue. With the increasing number of CUs in the network, increasing amount of traffic are served using the licensed bands with M_L=0.4M_U, which leads the greatest increase of revenue. In the very dense networks (28 CUs), the traffic served on the licensed and unlicensed bands of different pricing strategies converge to the same level 5.3,

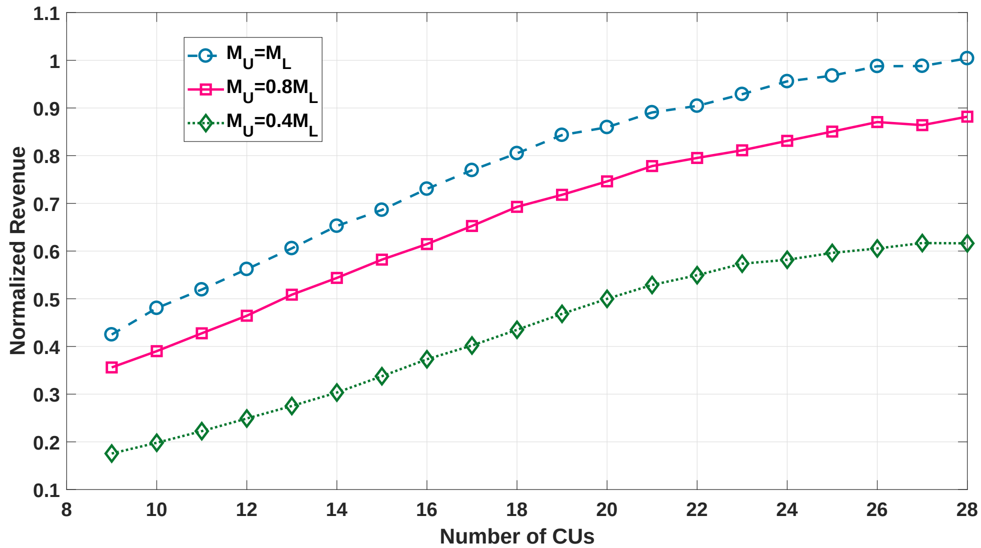

Fig. 5.6 Normalized revenue of operator versus the number of CUs for different pricing strategies

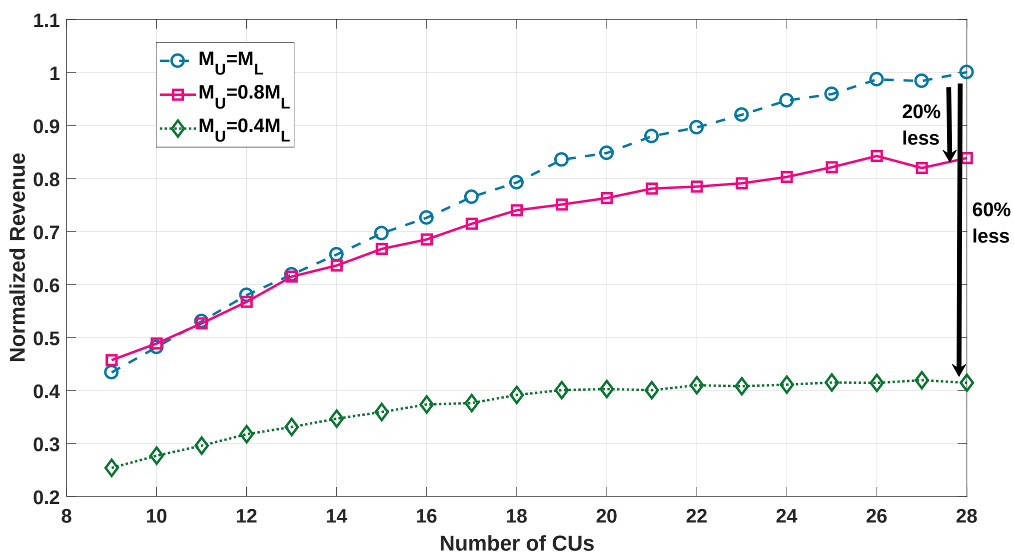

Fig. 5.7 Normalized revenue on the unlicensed spectrum of operator versus the number of CUs for different pricing strategies

the avenue differences are attributed to the price difference in using the unlicensed spectrum as shown in Fig. 5.7.

The use of pricing strategies implies that operator can make a balance between eNB load and revenue: in loose network, it is quite effective to offload traffic to the unlicensed spectrum without much revenue decrease by carefully designed pricing strategies, while in dense network where the traffic is in saturate state, pricing strategies do not make much difference in traffic load but reduce the revenue on the operator's perspective. Also, pricing strategies enabled traffic offlaoding provides possibility for smart resource allocation on service's perspective. The licensed spectrum is expected to serve delay-sensitive services while delay-tolerant services can be carried out in the unlicensed spectrum to optimize the system performance on service basis. To achieve this, utility function containing throughput and delay and other KPIs should be established and the proposed matching based framework can be used for the optimization.

5.4.4 Complexity

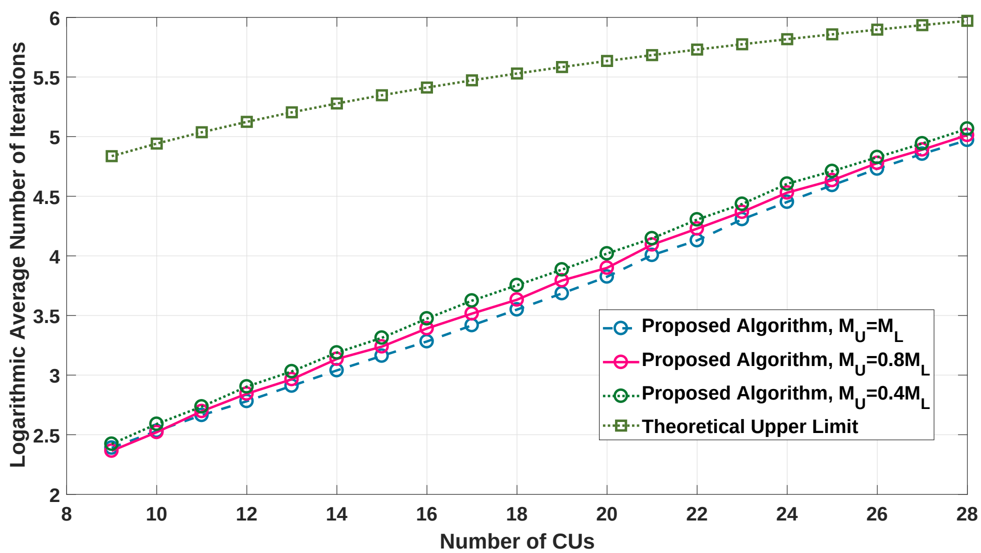

Fig. 5.8 Logarithmic average number of iterations of the proposed algorithm versus the number of CUs for different pricing strategies

Fig. 5.8 shows the logarithmic average iterations number of the proposed algorithm versus the number of CUs for different pricing strategies. An iteration two parts: 1) an unmatched CU proposed to its favourite UB or LB in the CU's preference list, 2) an acceptance or rejection made by SCBS on the proposal. A larger number of iterations is required to solve the licensed and unlicensed bands allocation problem in scenarios with lower accessing uncleaned bands price. CUs tend to propose to access the unlicensed bands because the corresponding utilities of accessing the unlicensed spectrum are larger, which increases the chance of performing many-to-one matching. Many-to-one matching is more complicated than one-to-one matching and takes larger number of iterations to converge. Also, with the densification of the network, more iterations are required to obtain stable matching by using the proposed algorithm because the average number of proposals a CU makes increase. The the average iterations number increase in a fast manner with the increasing of CUs in the network and is expected to get close to the theoretical upper limit iterations number in a very dense network.

5.5 Conclusions

In this chapter, we consider a resource allocation problem with pricing strategies set for CUs to pay for accessing the unlicensed and licensed spectrums. We propose a matching-based algorithm to allocate unlicensed and licensed bands to CUs to maximize their utilities while guaranteeing the throughput requirements of both CUs and WUs. The proposed algorithm converges to a two-sided Pareto optimal stable matching within a limited number of iterations. Near-optimal performance can be obtained by the proposed algorithm with a much smaller number of iterations than a exhaustive search algorithm. The proposed algorithm is first validated by comparing with a exhaustive search algorithm and if further used to evaluate the performance of resource allocation with pricing strategies in terms of traffic offloading, CUs offloading, system throughput, overall CUs served and revenue of operators. We observe a tradeoff between traffic/CUs offloading and revenue of the operator. The results demonstrate that pricing strategies are effective in a loose network to offload traffic to the unlicensed spectrum, while in a dense network, the traffic offloading ratio decreases because the unlicensed spectrum saturates and more traffic is served in the licensed spectrum.

Chapter 6

Conclusions and Future Works

How can we provide CUs with QoS-oriented services by using the unlicensed spectrum and ensure fair coexistence with Wi-Fi systems remain open questions. This thesis studied two promising access schemes: 1) LBT-based LAA channel access scheme; 2) ABS-based LTE-U access scheme.

Our works demonstrate that these two access schemes are promising to ensure fair coexistence between LTE-U networks and Wi-Fi systems and improve system performance. However, algorithms to tune accessing parameters in LAA or allocate resource in ABS-based LTE-U need to be careful designed.

In Chapter 3, we show that an LAA network affects the performance of a Wi-Fi system more than another Wi-Fi system does and spectral efficiency will be sacrificed to protect Wi-Fi performance. To overcome this trade-off problem, we define the coexistence fairness on Wi-Fi's side as Wi-Fi minimum throughput is guaranteed. We develop a joint CW optimization scheme to maximize LAA throughput and guarantee minimum Wi-Fi throughput. Further, to reduce the computational complexity of the joint CW optimization scheme and enable self-organizing coexistence of LAA networks and Wi-Fi system, we develop a RL-based algorithm to enable CW adjustment.

We also combine ABS-based LTE-U with microeconomics frameworks to enable fair and fast resource allocation. In Chapter 4, we show how to formulate unlicensed bands allocation problem into a matching game. The results demonstrate that near Pareto optimal resource allocation results can be obtained by using matching-based algorithms. In Chapter 5, we consider the joint allocation of both licensed and unlicensed bands with pricing strategies, in which different prices are set for CUs to access the unlicensed and licensed bands. We show pricing strategies is effective to balance or offload traffic between unlicensed and unlicensed bands.

In this chapter, we first summarize the main findings in this thesis. Then we propose future research directions of LTE-U related within the scope of this thesis.

6.1 Main Findings of the Thesis

- **QoS-oriented Fairness**: As mentioned in Chapter 2.3, fairness between LTE-U networks and Wi-Fi systems is defined as an LTE-U network should not affect a Wi-Fi system more than another Wi-Fi system. Based on this definition, we evaluate the coexistence performance of Wi-Fi and LAA in Chapter 3.2 and observe a trade-off between Wi-Fi performance protection maximum spectrum usage. If we insist this definition of fairness, spectral efficiency will be sacrificed. Thus, we consider other definition of fairness. We define the fairness in a LTE-U and Wi-Fi network as the resulted fairness [75]: each CU should be served to fulfill its minimum QoS requirements, such as throughput. This definition is applied throughout this thesis from Chapter 3.3 to Chapter 5.

- **CW optimization is efficient to enable fair coexistence and maximum spectral usage**: In both Chapter 3.3 and Chapter 3.4, the minimum Wi-Fi performance is guaranteed and LAA performance is maximized by adjusting CW sizes. In Chapter 3.3, we derive that LAA (Wi-Fi) throughput monotonically decreasing versus the increase of LAA (Wi-Fi) CW size and the decrease of Wi-Fi (LAA) CW size, respectively. Accordingly, we develop a low-complexity joint CW optimization scheme, which achieves up to 40% system throughput gain in a dense network. In Chapter 3.4, we develop an RL-based CW optimization scheme which shows better performance than the joint CW optimization algorithm with even lower computational complexity.

- **Fair and efficient radio resource allocation can be achieved by Matching-based frameworks**: Mathematical tools in economics have been developed for many years to solve resource allocation problems efficiently and matching theory is one of them. Due to the similarity between wireless communications and economics in resource allocation problems, we develop a matching-based framework to achieve fair and efficient radio resource allocation in an LTE-U and Wi-Fi coexisting scenario in 4. Different from traditional approach to solve NP-hard resource allocation problem, matching-based framework solves the problem with much lower complexity and outperforms up to 50% in terms of EE and up to 66% in terms of throughput.

- **Pricing strategies are effective for traffic balancing**: In Chapter 5, pricing strategies set by operators are effective to offload traffic from licensed spectrums to unlicensed spectrums so as to alleviate the scarcity of the unlicensed spectrums. We demonstrate a trade-off between traffic offloading ratio and total revenue of operators. Up to 93% of traffic can be served in a loose network and the ratio drops with the densification of the network.

6.2 Future Research Directions

In this thesis, we study the technologies that enables fair and efficient coexistence between LTE-U networks and Wi-Fi systems. We summarize future research directions related to the topics of the thesis.

As we can see from Chapter 3, there remain many limitations in our research on LAA. As the most promising solution for global deployment of LTE on the unlicensed spectrum, LAA is worth further research in the following areas:

- **CCA detection threshold adjustment**: In our work, we only consider tuning CW size of Wi-Fi and LAA networks to enable fair coexistence, changing the CCA detection threshold is another efficient approach. For example, the same energy detection threshold as in Wi-Fi DCF can be applied in CCA.

- **Enabling of detecting Wi-Fi permeable**: Different from carrier sense and energy detection scheme applied in Wi-Fi systems, LBT-LAA detects the availability of a unlicensed bands based on energy detection only, which means that LBT-LAA is unable to detect Wi-Fi signal. A fair coexistence could be ensured if LAA CUs are able to detect Wi-Fi signal preamble. This will definitely decrease the chance for LAA to access the spectrum but should be adjustable in response to different wireless communications environment.

- **Inter-operator LAA coordination schemes**: In scenarios where multiple cellular operators access the same unlicensed spectrum at the same time, cross-interference among different operators. A hierarchical game [101] and a multi-leader multi-follower Stackelberg Game [102] are proposed to mitigate interference across multiple CUs. However, these schemes are complex and lack of complexity analysis, which requires further research to develop efficient inter-operator coordination schemes.

Chapter 4 and 5 focus on the resource allocation schemes to enable fair coexistence between ABS-based LTE-U networks and Wi-Fi systems. We list the limitations as follows.

- **Complexity reduction**: One of the possible future researches is reducing the computational complexity of the proposed algorithm in dense networks, which is observed to approach theoretical upper limit due to the increasing number of redundant iterations. Using machine learning frameworks, especially neural networks, is a promising solution by training the network with raw input (preference lists of CUs, LBs and UBs) and output (bands allocation). A well-trained neural network is similar to a black box, which performs the function of the matching-based algorithm and maps the input to output.

- **Developing service-oriented utility function**: Another improvement is developing a comprehensive service-oriented utility function with different service types, for example, latency has the largest weight in the utility function for latency-sensitive services, while throughput has the largest weight in the utility function for large-file services. Based on these utility functions, resource allocation schemes along with pricing strategies can provide CUs with tailored services, balance traffic load and increase the operator's revenue.

- **Sophisticated incentive algorithms design**: Pricing strategies is an easy example of incentive design, which shows great potential in traffic offloading. However, a more sophisticated incentive algorithm is required for real life communications systems, such as tuning the pricing setting according to traffic load of the network.

Last but not least, it is promising to combine LTE-U with other latest technologies, which are summarized as follows:

- **Big data in LTE-U**: Big data analysis is a hot topic for traffic prediction [103, 104] and we can combine this with LTE-U networks to enable real time fair coexistence between Wi-Fi systems. For example, long-term traffic demand can be predicted by big data analysis tools, which enables operators to set pricing strategies accordingly for the interest of both operators and users.

- **LTE-U with SDN**: Combining LTE-U with SDN enables cloud-computing based network management and efficient network configuration [105–107], which could improve system performance.

We hope that continued researches in LTE-U can improve its ability to coexist with Wi-Fi systems fairly and optimize the spectral efficiency of unlicensed spectrums. Advancements in LTE-U access design, resource allocation scheme, etc., can inspire researchers in wireless communications to push this area forward and benefit the whole human society.

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