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Long Term Evolution in Unlicensed Bands

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Preface

Global mobile traffic is expected to increase nearly tenfold between 2014 and 2020 due to increasing number of mobile-connected devices and the explosion of data-hungry mobile applications. Pushing traffic towards the network capacity quickly deteriorates the Quality of Services (QoSs) perceived by the users. Acquiring additional licensed spectrum to increase the capacity of Radio Access Networks (RANs) is certainly very expensive. Mobile operators are also challenged by the revenue gap, i.e., the exponential increase in mobile traffic does not generate sufficient additional revenues required for upgrading their RANs. This circumstance has fostered the interest in cost-effective solutions to increase the capacity of RANs. Long-Term Evolution (LTE) in unlicensed bands (U-LTE) is among promising solutions. However, since U-LTE is a nascent LTE technology, there are still various associated concerns and challenges to be addressed.

This brief first presents a comprehensive survey on U-LTE, focusing on technical issues and the impacts of this technology to other neighboring networks in shared frequency bands. Specifically, concepts, motivations, benefits, obstacles, and coexistence requirements of U-LTE are presented. Three typical types of U-LTE including LTE-U, LAA-LTE, and MuLTEfire are explained. Next, regulations specified by standard institutes for radio systems operating in unlicensed spectrum are reviewed. Third, due to the fact that technical knowledge on medium access mechanisms of LTE and IEEE 802.11/Wi-Fi technologies is strongly required to understand and analyze the interactions between these two technologies when they operate in the same frequency band, high-level network architectures and technical details of LTE and Wi-Fi are presented. Especially, distinguishing features of CSMA/CA employed by Wi-Fi networks compared to standardized regulations are highlighted. Forth, in order to capture the ongoing activities on U-LTEs coexistence mechanisms, related works are surveyed with insight observations on their limitations and concerns.

This brief also presents our Network-Aware Adaptive LBT mechanism (NALT) which is proposed for LTE networks for its coexistence with Wi-Fi networks. It a nutshell, the NALT monitors both channel conditions and usage activity to maximize its transmission opportunities, while maintaining fair sharing of the channel, in a way that is transparent to incumbent Wi-Fi devices. Finally, towards future working directions, in the light of the survey, this brief identifies a number of open technical questions as well as related potential research issues in U-LTE.

The findings in this brief provide telecom engineers, researchers, and academic professionals with valuable knowledge and potential working or research directions when designing and developing medium access protocols for next generation wireless access networks.

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Contents

Acronyms

3G,4G,5G Third, Fourth, Fifth Generation cellular networks
3GPP 3rd Generation Partnership Project
AC Access Category
ACK Acknowledgment, a postive response of reception
AP Access Point, Wi-Fi station which acts as base station in infrastructure mode
BI Backoff Interval
CAP Controlled Access Phase
CCA Clear Channel Assessment
CFP Contention-free Period, in which polling is completed under the PCF
CoMP Coordinated Multi-Point
CoT Channel Occupancy Time
CP Contention Period, in which STAs contend with each other under the PCF
CSAT Carrier-sense Adaptive Transmission, a proposed LAA-LTE/Wi-Fi coexistence mechanism
CSMA/CA Carrier-sense Multiple Access with Collision Avoidance
CTS Clear to Send, channel reservation response in 802.11 Wi-Fi
CW Contention Window, range of possible backoff values a Wi-Fi station will select from
DCF Distributed Coordination Function, a random access based MAC protocol used in IEEE 802.11 Wi-Fi
DCS Dynamic Channel Selection
DIFS DCF Inter-frame Space, minimum delay after channel becomes free before a Wi-FI station will attempt to transmit
DL Downlink, transmission from base station to user equipment
ECCA Extended Clear Channel Assessment, additional CCA done in ETSI LBT when channel is known to have been recently busy
EDCA Enhanced Distributed Channel Access, QoS enhancements for Wi-Fi in 802.11e
EDCF Enhanced Distributed Coordination Function, a random access based MAC protocol used in IEEE 802.11e Wi-Fi

EDGE Enhanced Data rates for GSM Evolution
ED Energy Detect
EIRP Equivalent Isotropically Radiated Power
eNB eNodeN, an evolved Node B base stations used in LTE/LTE-A networks
EPC Evolved Packet Core
ETSI European Telecommunications Standards Institute
E-UTRA Evolved Universal Terrestrial Radio Access
E-UTRAN Evolved Universal Terrestrial Radio Access Network
FBE Frame-based Equipment
FCC Federal Communications Commission
FDD Frequency Division Duplex
GC Global Controller
GSM Global System for Mobile communication
HARQ Hybrid Automatic Repeat Request
HCCA HCF Controlled Channel Access
HCF Hybrid Coordination Function, a polling based MAC protocol used in IEEE 802.11e Wi-Fi
HetNet Heterogeneous Network, a wireless network made up of different types of access nodes
HSPA High Speed Packet Access
IEEE Institute of Electrical and Electronics Engineers
IFS Inter-frame Space
IoT Internet of Things
IP Internet Protocol
ITU Internation Telecommunications Union
LAA/LAA-LTE Licensed-Assisted Access LTE using LBT
LBE Load-based Equipment
LBT Listen-Before-Talk Medium Access Strategy
LTE Long Term Evolution, 3GPP Releases 8 and 9
LTE-A LTE-A LTE Advanced, 3GPP Releases 10 to 13, possibly more
LTE-U LTE-U LTE in Unlicensed bands using a duty-cycled coexistence mechanism
MAC Medium Access Control, sublayer of the Data Link Layer
MIMO Multiple Input Multiple Output
MME Mobility Management Entity
MTC Machine Type Communications
NALT Network-aware Adative Listen-Before-Talk, a proposed LAA-LTE/Wi-Fi co-existence mechanism
NAV Network Allocation Vector
OFDM Orthogonal Frequency Division Multiplexing
OFDMA Orthogonal Frequency Division Multiple Access
PCF Point Coordination Function, a polling based MAC protocol used in IEEE 802.11 Wi-Fi
PDN Packet Data Network
P-GW PDN Gateway

PHY Physical Layer
PRB Physical Resource Block
QAM Quadrature Amplitude Modulation
QoS Quality of Service
RAN Radio Access Network
RAT Radio Access Technology
RC Regional Controller
RSSI Received Signal Strength Indicator, measure of received power in wireless networks
RTS Request to Send, channel reservation request in 802.11 Wi-Fi
SAE System Architecture Evolution
Rx Receiver or Reception
SC-FDMA Single-Carrier Frequency Division Multiple Access
SDL Supplemental Downlink
SDN Software Defined Networking
S-GW Serving Gateway
SIFS Short Inter-frame Space, delay before a response is made or expected to certain frames in 802.11
ST Slot Time, duration of an OFDM symbol in 802.11
STA Station, a member of wireless network
TC Traffic Classes
TDD Time Division Duplex
TDM Time Division Multiplex
TS Traffic Streams
Tx Transmitter or Transmission
TXOP Transmission Opportunity
UE User Equipment
UL Uplink
U-LTE LTE LTE in Unlicensed bands, catchall phrase to cover all methods of using LTE in unlicensed frequency bands
UMTS Univesral Mobile Telecommunications System
VoIP Voice over IP
VoLTE Voice over LTE
WLAN Wireless Local Area Network

Chapter 1
Introduction

Abstract The increasing penetration of mobile-connected devices and the emergence of numerous data-hungry mobile applications have been creating a wide range of business opportunities for mobile network operators and service providers. Meanwhile, they are placing a greater pressure on the capacity that the Radio Access Networks (RANs) have to provide. This chapter starts with technical challenges that urge for developments of cost-effective solutions to improve the capacity of RANs. The technology which utilizes the unlicensed frequency bands in Long-Term Evolution (LTE), namely U-LTE, is singled out as the most promising solution. Benefits and obstacles of this technology are then presented. Next, three typical forms of U-LTE including LTE-U, LAA-LTE, and MuLTEfire are explained. Concerns on the interactions between U-LTE and Wi-Fi in radio channel access and their coexistence are discussed in details. Finally, key requirements for the coexistence of U-LTE and Wi-Fi are summarized.

1.1 Motivations and Concepts of U-LTE

Global mobile traffic is expected to increase nearly tenfold between 2014 and 2020 due to increasing number of mobile-connected devices and the explosion of data-hungry mobile applications [1]. As visualized in Fig. 1.1, in 2015, global mobile data traffic amounted to 3.7 exabytes per month. In 2020, mobile data traffic worldwide is expected to reach 30.6 exabytes per month at a compound annual growth rate of 53 percent. Pushing traffic towards the network capacity quickly deteriorates the Quality of Services (QoSs) perceived by the users. As a result, increasing the capacity of Radio Access Networks (RANs) is one of the top-priority action plans of mobile service providers. Purchasing additional licensed spectrum is a straightforward solution to this but radio spectrum is very much limited and expensive. Furthermore, mobile operators are at the same time challenged by the "revenue gap", i.e., the exponential increase in mobile traffic does not generate sufficient additional revenues required for upgrading their RANs. This circumstance has fostered the in-

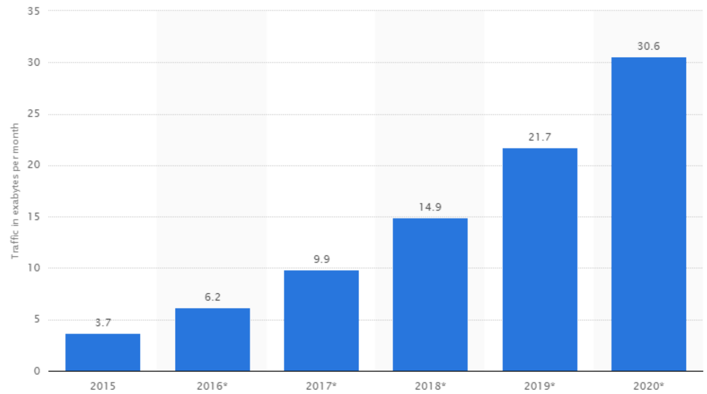

Fig. 1.1 Global mobile data traffic from 2015-2020 [1].

terest in cost-effective solutions to RAN capacity increase. *Mobile data off-loading* and *Long-Term Evolution (LTE) in unlicensed bands (U-LTE)* are among promising solutions.

Mobile data offloading is the use of a complementary wireless technology to transport data originally flowing through the cellular mobile network. Wi-Fi offload and Device-to-Device (D2D) communications are the two main data offload technologies. Rules determining when and how the mobile offloading actions are triggered are set by either mobile subscribers or network operators. For the subscribers, data offloading helps them to exploit the availability of higher bandwidth data service at lower costs. For the operators, the most obvious benefit of this kind of approach is the mitigation of cellular mobile network load and thus congestion. Besides, shifting data to a complementary wireless technology leads to a number of other improvements including: the increase of the overall throughput, the reduction of content delivery time, the extension of network coverage, the increase of network availability, and better energy efficiency. Unfortunately, these benefits come with a number of challenges related to infrastructure coordination, network/technology hand-overs, service continuity, pricing, business models, and lack of standards.

Recently, U-LTE has appeared as the most promising approach to enhance RAN capacity and address the revenue gap in mobile networks. By definition, it is an LTE technology that puts cellular signals into the unlicensed spectrum with the supports of existing LTE features including Supplemental Downlink (SDL, proposed in LTE Release 9 and later) and Carrier Aggregation (CA, proposed in LTE Release 10 and later). The original idea of LTE-U is fairly straightforward. As mentioned, mobile operators are facing a great pressure on capacity and cost. If LTE can exploit the unlicensed band (where IEEE 802.11/Wi-Fi and other radio systems are using), then it will have a considerable additional capacity at a minimal cost. U-LTE can be used to boost downlink or both uplink and downlink of LTE networks, as illustrated in Fig. 1.2.

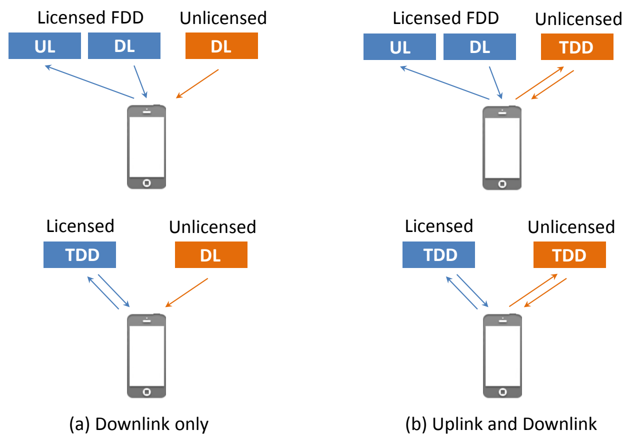

Fig. 1.2 Use cases of U-LTE.

Historically, U-LTE was originally proposed and officially announced by Qualcomm in 2013 [2]. Currently, it focuses on 500 MHz of spectrum available in the 5 GHz band. Specifically, according to the proposal from Qualcomm, U-LTE uses the U-NII-3 part of the 5 GHz band, which has highest allowed Equivalent Isotropically Radiated Power (EIRP). While in 2.4 GHz regulatory bodies limit EIRP to 100 mW (in Europe) or 200 mW (in United States), the U-NII-3 enjoys the rights to go as high as 1000 mW outdoors.

1.2 Benefits and Obstacles of U-LTE

U-LTE is expected to offer numerous benefits to mobile network operators, service providers, and consumers. *First*, free unlicensed spectrum provides additional capacity to the network at a minimal cost. Therefore, U-LTE appears to be a very inexpensive way to meet the future traffic growth. *Second*, U-LTE will give operators the option to make use of unlicensed spectrum with a unified network, offering potential operational cost saving, improving spectral efficiency, and providing a better user experience. Compared to the Wi-Fi offloading technology, U-LTE has the potential to offer significantly better coverage and higher spectral efficiency while allowing seamless flow of data across licensed and unlicensed in a single core network. *Third*, U-LTE could also take advantage of the robust security features of LTE networks. *Finally*, while Wi-Fi offloading leads to less traffic on mobile networks and thus may result in revenue losses in data services, U-LTE could represent an incremental ability on mobile service providers to directly bill for data usage.

U-LTE is also facing a number of substantial obstacles. *First*, even though U-LTE is not charged for the use of unlicensed spectrums, compared to Wi-Fi, its network deployment could be more expensive. LTE chipset itself is several times more expensive than that of Wi-Fi (a few tens of dollars compared to a few dollars or less than one dollar). LTE base stations and other network devices are likely to cost substantially more. Also, LTE operators need to deploy and maintain expensive backhaul links. *Next*, U-LTE will work only with LTE-capable devices while there have been many more devices that feature Wi-Fi connectivity than LTE. Wi-Fi is nearly always integrated with laptops, tablets, cameras, and other connected consumer devices. *Additionally*, from technical perspectives, the premium features provided by U-LTE (e.g., seamless voice and data roaming) may not prove sufficiently more valuable than those offered by emerging Wi-Fi technologies such as Hotspot 2.0, so-called Wi-Fi Certified Passpoint, which is a new standard for public-access Wi-Fi that enables seamless roaming among Wi-Fi networks and between Wi-Fi and cellular networks. *Finally*, the biggest challenge of U-LTE is its coexistence with other radio networks operating in the same frequency bands. This challenge will be studied in subsequent sections.

1.3 Three Types of U-LTE

U-LTE comprises of three different flavors: LTE unlicensed (LTE-U), Licensed Assisted Access LTE (LAA-LTE), and MuLTEfire. The first two flavors require "anchoring licensed spectrum", i.e., they operate primarily in licensed spectrum and opportunistically exploit unlicensed spectrum for an additional bandwidth boost. Devices are still anchored in licensed spectrum for LTE management/control signaling and high QoS data while using the unlicensed spectrum for only best-effort or delay-tolerant data. The third flavor is developed by Qualcomm and requires no licensed spectrum at all, therefore, it is often referred to as "standalone" U-LTE. MuLTEfire is designed for indoor use and deployments by enterprises, cable companies and other service providers without ownership of expensive bandwidth licenses. However, at present time, there are very few technical details available about MuLTEfire.

1.3.1 LTE-U

This is the simplest form of U-LTE that requires minor modifications in LTE protocol stack. Therefore, it can quickly facilitate pre-standard equipment manufacturing and deployment. LTE-U first attempts to select clear channel to access. If no clear channel is found, it will employs Carrier-Sensing Adaptive Transmission (CSAT) which is a Time-Division Multiplex (TDM) coexistence based on medium sensing. CSAT employs "duty-cycling" instead of LBT mechanism. Compared to LBT or CSMA, the small cell senses the medium for a longer duration (around 10s of millisecond to 200 millisecond) and according to the observed medium activities, the algorithm gates off LTE transmission proportionally. In particular, CSAT defines a

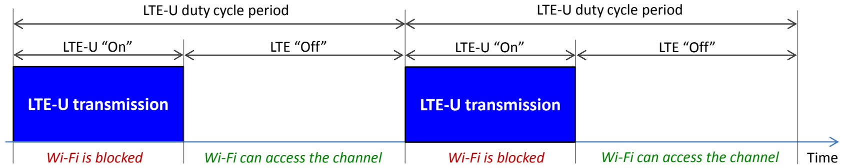

Fig. 1.3 Duty-cycling mechanism employed by LTE-U.

time cycle where the small cell transmits in a fraction of the cycle and gates off in the remaining duration. The duty cycle of transmission versus gating off is dictated by the sensed medium activity of neighboring RANs. The TDM cycle can be set to a few tens or hundreds of millisecond, which can effectively accommodate the activation/de-activation procedures while controlling the data transmission delay. CSAT is illustrated in Fig. 1.3. An important observation from Fig. 1.3 is that during the LTE "on" period, Wi-Fi is blocked by LTE-U transmissions. During the LTE "off" period, Wi-Fi will detect that the channel is free and can schedule its transmissions following its CSMA-CA protocol.

LTE-U is only applicable in areas where there are no strict LBT requirements for operations in unlicensed bands (e.g., US. Korea, China). It is a non-standard version of U-LTE, being developed outside of the 3GPP standards process. LTE-U is supported by LTE-U Forum formed in 2014 by Verizon in cooperation with Alcatel-Lucent, Ericsson, Qualcomm Technologies Inc. (a subsidiary of Qualcomm Incorporated), and Samsung.

1.3.2 LAA-LTE

In many areas such as Europe, Japan and India, there exist regulations for unlicensed spectrum that require equipment to periodically check for presence of other occupants in the channel, so-called LBT, in millisecond scale. LAA-LTE is designed for use in those areas or for global use. It requires a number of modifications so that LTE transmissions can meet regulatory requirements in LBT regions. Similar to LTE-U, LAA-LTE first tries to choose the cleanest channel based on Wi-Fi and LTE measurements to operate on. In the event that no clean channel is available, LBT algorithm is used to compete the medium with other RANs in the same channel. For LBT, FBE- and LBE-based mechanisms specified in [1] have been used. Details of these two mechanisms have been presented in section **??**.

Assuming that LBE-based LBT is employed for LAA-LTE. Before transmission, CCA using ED is performed. If the channel is clear during a CCA slot (20 microseconds or longer), transmission is started immediately. Otherwise, ECCA is performed. If the channel is clear during N CCA slots, transmission is started immediately. N is a random integer uniformly distributed from 1 to q, where $q \in \{4, 5, ..., 32\}$. The total time to occupy the channel without CCA is limited by

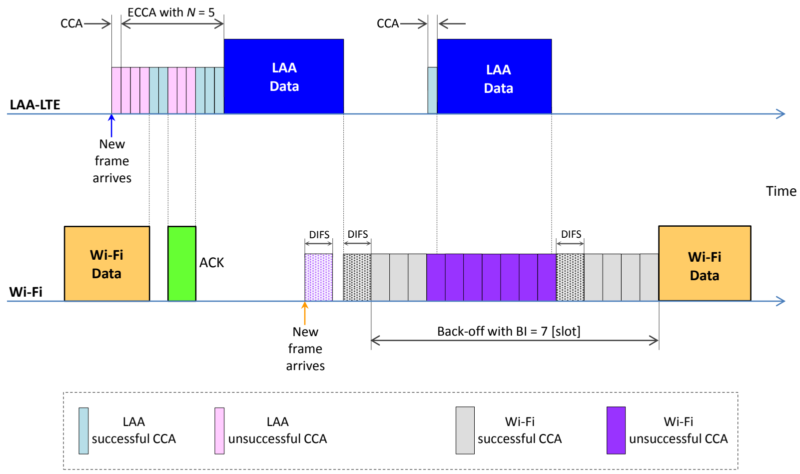

Fig. 1.4 CCA and ECCA mechanisms employed by LAA-LTE.

$(13/32)q$ milliseconds (e.g., 13 milliseconds when q is 32). Two simplified scenarios with LAA-LTE (employing LBE-based LBT) and Wi-Fi systems operating in the same channel are illustrated in Fig. 1.4. In the first scenario, the LAA-LTE system, upon having data frames to send, performs CCA and then ECCA (with $N = 7$) since there is an ongoing Wi-Fi transmission. The ECCA procedure is frozen and then resumed when another Wi-Fi transmission takes place and then completes, respectively. The LAA-LTE system finally transmits its frames once ECCA counter N reaches zero. In the second scenario, the Wi-Fi system, upon having data frames to send, performs CCA and then back-off procedure (with $\mathrm{BI}_{\mathrm{slots}} = 7$) since there is an ongoing LAA-LTE transmission. The back-off procedure is frozen and resumed when another LAA-LTE transmission takes place. The Wi-Fi system finally transmits its frames once back-off counter w reaches zero.

LTE was originally designed for licensed spectrum and a centralized management (i.e., network-controlled) model, it is generally an "always-on" technology. As a result, adapting to LBT is a marked change for the LTE protocol. Compared to LTE-U which is downlink-only in unlicensed bands, LAA-LTE may allow bi-directional traffic in unlicensed bands.

LAA-LTE is currently actively supported by 3GPP and will be included in 3GPP LTE Release 13 (to be published by March 2016). T-Mobile USA and Verizon Wireless have indicated their interests in deploying pre-standard LAA-LTE systems for evaluations and commercial services in 2016.

1.3.3 MuLTEfire

At this time there are very few technical details available about MuLTEfire. It is unknown which MAC protocols or coexistence mechanisms are employed in this type of U-LTE. Also, since licensed frequency is not used for LTE network management and control signaling, as opposed to the conventional LTE and the other two variants of U-LTE (i.e., LTE-U and LAA-LTE) that are license anchored, MuLTEfire may lose all advantages of native LTE technologies. It is expected that MuLTEfire will be less efficient than LTE-U and LAA-LTE and therefore its achievable performance/efficiency may be just marginally better than that of Wi-Fi. Then the question on the applicability of MuLTEfire needs to be answered.

1.4 Coexistence of U-LTE and Wi-Fi

It is well known that multiple radio communications technologies operating in a common frequency band will negatively affect each other if respectful coexistence mechanisms are not employed. As a result, despite the fact that U-LTE can offer various benefits as mentioned before, its coexistence with Wi-Fi and other radio systems that operate in the 5 GHz frequency band is the biggest concerns. In details, it has been believed that U-LTE may considerably interfere Wi-Fi systems and/or grasp more radio resources when they are operating in the same frequency band due to the following facts.

First, LTE was originally designed to work in its own licensed band rather than to coexist with Wi-Fi in a shared band. LTE employs Orthogonal Frequency-Division Multiple Access (OFDMA) and transmits almost continuously without any mechanism for spectrum sharing. Wi-Fi, on the other hand, employs Listen Before Talk (LBT) MAC with a few key additional features that go beyond LBT requirements specified by European Telecommunications Standards Institute (ETSI) [1]. As a result, U-LTE might overwhelm Wi-Fi neighbors with its aggressive transmissions if no relevant coexistence measure is implemented.

Second, the typical lengths of each transmission of these two technologies are not the same. LTE, due to its basic protocol design and scheduled nature, generally transmits long frames (i.e., multiple ms), whereas a large percentage of Wi-Fi frames are sub-millisecond in duration. For this reason, equitable access to the medium, evaluated in terms of how often a technology is able to start a transmission, does not necessarily translate into equitable airtime.

Third, a license-anchored system (LTE-U or LAA-LTE) operates simultaneously in licensed and unlicensed bands and thus can dynamically move traffic between the bands on a granular basis (e.g., per-user and per-flow). As a result, such a system is inherently less sensitive to collisions and congestion in the unlicensed bands than is a system operating solely in unlicensed spectrum. This may reduce the incentive for a license-anchored system to develop effective coexistence mechanisms in the unlicensed band.

In fact, U-LTE is still a nascent LTE technology with many technical details to be determined. Proponents of U-LTE include Qualcomm, Ericsson, Alcatel-Lucent, Huawei, LTE-U Forum, 3rd Generation Partnership Project (3GPP), Verizon Wireless, T-Mobile US, etc. At the same time, CableLabs, Google, Wi-Fi Alliance, The Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) and many Wi-Fi interested companies are participating in and following closely the development of U-LTE technology. They have been expressing their concern on a critical need for strong coexistence between U-LTE and Wi-Fi to ensure responsible and fair use of unlicensed spectrum. As a result, various studies on the coexistence of U-LTE and Wi-Fi have been carried out by both industry and academia. Besides, a number of reports and comments related to this concern have been filed with the Federal Communications Commission (FCC).

1.5 Requirements of U-LTE Coexistence Mechanisms

Even though the unlicensed bands may be used by anyone, there is a series of government guidelines and regulations to be followed. Those guidelines and regulations aim to ensure that different radio systems that operate in the same frequency bands are good neighbors of each other.

In particular, for coexistence with Wi-Fi, at least U-LTE must satisfy local regulations such as the maximum transmission power in specific bands and the avoidance of bands dedicated to protected services. Furthermore, an U-LTE system should not cause any higher interference to a neighboring Wi-Fi system than a typical Wi-Fi system operating on the same channel. In other words, the impact of a U-LTE device to Wi-Fi devices (in terms of collision rate and probability of successful channel access) should be similar to that caused by a typical Wi-Fi device. These requirements ask for inclusions of a number of new features in LTE. For example, U-LTE should select a carrier which is least occupied in the area and it should dynamically change operating frequency to avoid conflict with protected systems, such as radar. It should also apply LBT or Clear Channel Assessment (CCA) techniques to check that a channel is free before making a transmission. Exactly how these decisions are made will be key aspects of U-LTE system designs.

1.6 Structure of This Brief

This Springer Brief is divided into seven chapters. This chapter has just provided an introduction to the emerging U-LTE technology with its motivations, concepts, benefits, and challenges. The technical concern on the coexistence of this new LTE technology and the existing Wi-Fi technology in the 5 GHz unlicensed frequency band has also been addressed. The remainder of this brief is organized as follows:

For background knowledge, chapter 2 provides an overview on radio spectrum and related management/allocation concerns in the 5 GHz unlicensed frequency band. It also summarizes a number of key requirements and regulations specified by the European Telecommunications Standards Institute (ETSI) and the Federal Communications Commission (FCC) on radio channels, operating channel selection, transmission power, and channel access rules. These technical details are the baselines to be followed when designing medium access control protocols for U-LTE and any other technologies.

Next, chapter 3 presents a high-level overview of LTE-Advanced (LTE-A) networks and associated technologies to form a basis for discussion of the co-existence issues that exist for unlicensed LTE and Wi-Fi. Understanding the underlying architecture and protocols employed in LTE-A will provide readers a comparative framework to grasp how, and at what levels, LTE and Wi-Fi networks may interact and interfere with each other, and form a greater understanding of the challenges to be address in designing coexistence mechanisms.

Chapter 4 then focuses on the Wi-Fi technology and starts with an overview of IEEE 802.11/Wi-Fi evolutions. Existing generations as well as the next generation of IEEE 802.11/Wi-Fi are presented. The majority of the chapter provides ideas and detailed mechanisms of the CSMA/CA MAC protocol. Important observations on how the CSMA/CA sense and occupy the radio medium when the LTE network is operating in vicinity are highlighted.

Chapter 5 presents a big picture of research activities related to the coexistence of U-LTE and Wi-Fi technologies. The following questions are addressed in the chapter. First, what issues arise from simultaneous operation of LTE and Wi-Fi in the same spectrum bands. Second, which technology is affected the most. Third, which factors determine the impacts of U-LTE to Wi-Fi. Finally, the chapter identifies the strengths and weaknesses of existing solutions and suggests potential strategies to improve performance of these two technologies.

In chapter 6, a network-aware adaptive Listen-Before-Talk mechanism (NALT) proposed for U-LTE is presented. The NALT passively monitors both channel conditions and usage activity to maximize transmission opportunities while respecting fair sharing of the channel, in a way that is transparent to incumbent Wi-Fi devices. Simulation results are presented demonstrating the effectiveness of NALT in providing proportional fair sharing among LAA-LTE and Wi-Fi devices.

Finally, chapter 7 ends this Springer Brief by addressing a number of research issues and associated potential research directions. Potential solutions to those issues are also identified. Most of them suggest the cooperation of LTE and Wi-Fi so that they could have a better understanding of each other when operating in the same area using the same radio frequency band. This understanding is used to have more vigilant actions that help to avoid aggressive channel access that could corrupt on-going transmissions and to design relevant protocols for a fair spectrum sharing.

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Chapter 2
Requirements and Regulations in the 5 GHz Unlicensed Spectrum

Abstract License and fee are not required for operators to use the 5 GHz unlicensed spectrum. However, in order to avoid interference and to ensure a fair use of this resource, numerous requirements and regulations are imposed on this band by national and international organizations. The emerging U-LTE technology, therefore, needs to follow them as any other existing technologies, esp., IEEE 802.11/Wi-Fi, when deployed in this band. This chapter provides an overview on radio spectrum and related management/allocation concerns. It then summarizes a number of key requirements and regulations specified by the European Telecommunications Standards Institute (ETSI) and the Federal Communications Commission (FCC) on radio channels, operating channel selection, transmission power, and channel access rules. These technical details are the baselines to be followed when designing medium access control protocols for U-LTE and any other technologies operating in the 5 GHz unlicensed radio band.

2.1 An Overview on Radio Spectrum Management

The Radio Frequency (RF) spectrum is the part of the electromagnetic spectrum from 3 Hz to 3000 GHz (3 THz). Radio waves in this frequency range are widely used in modern technologies, especially in telecommunications. The radio spectrum is divided into different chunks or bands, each of which can be used by one or multiple technologies. Radio Frequency Interference (RFI) is the conduction or radiation of radio frequency energy that causes an electronic or electrical device to produce unwanted noise that typically interferes with functions of adjacent devices. In radio communications, RFI can disrupt and disturb the normal functioning of devices, and thus it is always important to avoid or keep the RFI within acceptable levels. For this, the generation and transmission of radio waves is strictly regulated by national laws, coordinated by international organizations, e.g., Federal Communications Commission (FCC), Inter-American Telecommunication Commission (CI-

TEL), International Telecommunication Union (ITU), European Telecommunications Standards Institute (ETSI), etc.

Most countries consider RF spectrum as a national resource. The process of regulating the use of this resource is spectrum management or allocation. Spectrum allocation varies by country and/or regulatory domain. In United States, for example, FCC regulates inter-state communications by radio, television, wire, satellite, and cable in all states and territories. From management perspectives, radio bands are categorized into *licensed* and *unlicensed*. Licensing is a way of ensuring that wireless operators do not interfere with each others by giving each of them an exclusive use of one or multiple bands in given geographical areas over a set period of time. Licensed bands are mainly sold/assigned to operators through spectrum auction precess. They are mostly used by television broadcasting, commercial radio and cellular voice and data. Operating in licensed bands, operators can avoid RFI and thus guarantee quality of services they deliver to their subscribers. However, licensing would be very impractical for certain use cases, like communications between cordless handsets and base units. Instead, such a kind of wireless technology transmits its radio signals in unlicensed frequency bands - usually the Industrial, Scientific and Medical (ISM) band defined by the ITU radio regulations and allocated in most countries for free use by anyone without any license and fee. Unlicensed bands enable numerous technologies and products, e.g., Wi-Fi, Bluetooth, and many other low-power short-range communications technologies. They are open sandboxes where users can operate without the high barriers to entry. The availability of unlicensed bands provides a platform for innovation, a greenfield space for technology start-ups and entrepreneurs, as well as established companies. Internet of Things (IoT) - the development and deployment of networking technologies that provide connectivity for everyday objects for many innovative applications - is essentially enabled by unlicensed spectrum.

Today, most people are within a few meters of consumer products (microwave ovens, Wi-Fi, Bluetooth, etc.) that use unlicensed bands. In other words, there is a great chance for RFI in these bands. As a result, even though no permission is required for the use of unlicensed bands, manufacturers and users must comply with numerous rules and regulations (related to transmission power, transmission time, etc.) in order to minimize the RFI to others as well as to ensure a fair sharing of the radio resource in these bands. IEEE 802.11/Wi-Fi is the most successful and popular technology operating in unlicensed spectrum. Wi-Fi manufacturers need to obtain compliance certifications from Wi-Fi Alliance whose certification program is designed following rules imposed by radio spectrum management organizations/authorities such as ETSI and FCC.

The two most widely-used unlicensed bands are 2.4 GHz and 5 GHz. These two bands have their own advantages and disadvantages in various perspectives. 5 GHz provides faster data rates at a shorter distance, whereas 2.4 GHz offers coverage for farther distances but support lower rates. New technologies, particularly unlicensed LTE variants including LTE-U, LAA, and MulteFire (as mentioned in Chapter 1), have been targeted to operate in the 5 GHz band alongside Wi-Fi. The selection of the 5 GHz band for U-LTE technologies (rather than the 2.4 GHz band) is mainly due to the following reasons:

- *More available channels:* In the 2.4 GHz band, only 14 channels, each of with provides 20 MHz of bandwidth, are defined. In U.S. (or Europe), only 11 (or 13) of those channels are legally available. However, those channels overlap excessively with one another. Due to this overlapping, the maximum possible number of parallel independent connections is limited to 3 channels (channels 1, 6, and 11). In the 5 GHz band, there are 21 non-overlapping 20 MHz channels (or 9 non-overlapping 40 MHz channels). Figs. 2.1(a) and (b) depict spectrum analyzer views of radio channels defined in 2.4 and 5 GHz bands, respectively.
- *Lower level of interference:* Since the 2.4 ISM band was released for Wi-Fi technology use more than fifteen years ago, this band is over-crowded with billions of existing Wi-Fi devices. There are also many consumer products use this band, including microwave ovens, cordless phones, baby monitors, garage door openers, etc. In contrast, the relatively recent release of the 5 GHz band for private use makes this band much less crowded and thus having a much lower level of RFI.
- *Higher performance:* The 5 GHz band operates on a larger spectrum and does not suffer the over-crowding. Therefore, compared to the 2.4 GHz band, each channel in the 2.4 GHz band allows for much better spectrum efficiency and therefore higher data rates.

As just mentioned, any technology operating in unlicensed bands needs to comply with unlicensed band rules and regulations in order to limit the RFI and to ensure that it does not unfairly grab a larger portion of the shared spectrum. Coexistence is one of the most notable concerns when U-LTE technology in introduced in the 5 GHz unlicensed band considering the fact that a sheer number of Wi-Fi devices/networks has been deployed in the same band for everyday applications in homes, offices, and buildings. Since the number of wireless devices using the 5GHz band has grown rapidly over the last few years, ETSI has updated its related regulations. For background knowledge necessary for developments of radio channel access protocols for U-LTE and Wi-Fi technologies in this band, the following sections summarize a number of key requirements/mechanisms presented in ETSI EN 301 893. Specifically, frequency channels, transmission power, and channel access mechanisms are focused.

2.2 Frequency Channels

The ETSI EN 301 893 V1.7.2 regulations [1] released in July 2014 defined three unlicensed frequency bands as follows:

- RLAN band 1: 5150 to 5350 MHz, divided into 2 sub-bands

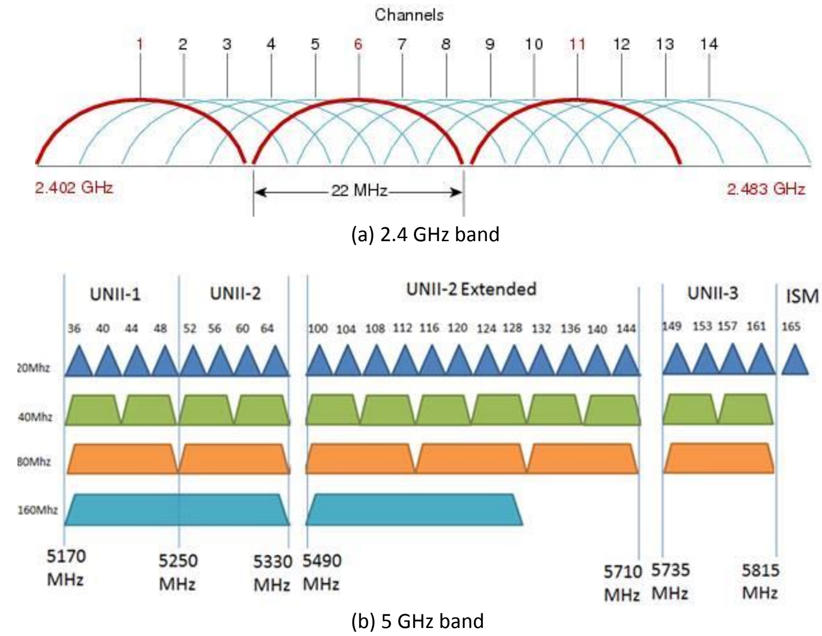


Fig. 2.1 2.4 GHz and 5 GHz Unlicensed Spectrums.

– Sub-band I: 5150 MHz - 5250 MHz. This sub-band is comparable to FCC U-NII-1.
– Sub-band II: 5250 MHz - 5350 MHz. This sub-band is comparable to FCC U-NII-2.
– RLAN band 2: 5470 MHz - 5725 MHz. This band comparable to FCC U-NII-2 extended (U-NII-2e).
– RLAN band 3, also known as Broadband Radio Access Networks (BRAN): 5725 5875 MHz. This sub-band is comparable to FCC U-NII-3 (5725 5825 MHz) band with a higher upper frequency range,.

Fig. 2.1(b) summarizes radio channels defined in the 5 GHz band by ETSI 301 893 standard (with a reference to FCC regulations). Technical details and the availability of each channel in four main regions (U.S., Europ, Japan, and China) are presented in Fig. 2.2.

2.3 Transmission Power

Each of the three bands defined by ETSI EN 301 893 V1.7.2 regulations [1] have different maximum allowable transmission power levels. Note that the RF output

Channel Number	Center Frequency	U.S.	Europe	Japan	China
36	5180	Yes	Indoors	Yes	Yes
38	5190	No	No	Client Only	No
40	5200	Yes	Indoors	Yes	Yes
42	5210	No	No	Client Only	No
44	5220	Yes	Indoors	Yes	Yes
46	5230	No	No	Client Only	No
48	5240	Yes	Indoors	Yes	Yes
52	5260	DFS	Indoors/DFS/TPC	DFS/TPC	Yes
56	5280	DFS	Indoors/DFS/TPC	DFS/TPC	Yes
60	5300	DFS	Indoors/DFS/TPC	DFS/TPC	Yes
64	5320	DFS	DFS/TPC	DFS/TPC	Yes
100	5500	DFS	DFS/TPC	DFS/TPC	Yes
104	5520	DFS	DFS/TPC	DFS/TPC	Yes
108	5540	DFS	DFS/TPC	DFS/TPC	No
112	5560	DFS	DFS/TPC	DFS/TPC	No
116	5580	DFS	DFS/TPC	DFS/TPC	No
120	5600	No	DFS/TPC	DFS/TPC	No
124	5620	No	DFS/TPC	DFS/TPC	No
128	5640	No	DFS/TPC	DFS/TPC	No
132	5660	DFS	DFS/TPC	DFS/TPC	No
136	5680	DFS	DFS/TPC	DFS/TPC	No
140	5700	DFS	DFS/TPC	DFS/TPC	No
149	5745	Yes	SRD	No	Yes
153	5765	Yes	SRD	No	Yes
157	5785	Yes	SRD	No	Yes
161	5805	Yes	SRD	No	Yes
165	5825	Yes	SRD	No	Yes

Fig. 2.2 Details of 5 GHz Unlicensed Channels in Different Regions.

power is defined as the mean Equivalent Isotropic Radiated Power (EIRP) of the equipment during a transmission burst. In general, the limits are valid for the device with antenna gain and cable loss and not only the output power of WLAN module.

2.3.1 RLAN band 1 (5150 to 5350 MHz)

2.3.1.1 Indoor only Sub-band I (5150 - 5250 MHz)

The first RLAN sub-band includes the channels 36 to 48 and has an EIRP power limit to 23 dBm (200 mW). These channels are considered for indoor only usage and do not require any Dynamic Frequency Selection (DFS) or Transmit Power Control (TPC) features.

2.3.1.2 Indoor only Sub-band II (5250 - 5350 MHz)

In the second sub-band of the RLAN band 1 with channels 52 to 64, the ETSI has set the EIRP power limit to 23 dBm (200 mW) for devices with TPC and 20 dBm (100 mW) for devices without TPC. For a device with TPC, the mean EIRP at the lowest power level of the TPC range must not exceed 17 dBm (50 mW). This band requires DFS support and

2.3.2 RLAN band 2 (5470 to 5725 MHz)

Channels from 100 to 140 are part of the second RLAN band and have an EIRP power limit of 30 dBm (1000 mW) for TPC and 27 dBm (500 mW) for non-TPC devices or 20 dBm (100 mW) for devices without any TPC or DFS support. The mean EIRP power level for a slave device with TPC must not exceed 24 dBm at the the lowest TPC power level if the device is also capable of radar detection or 17 dBm otherwise.

2.3.3 BRAN (5725 to 5875 MHz)

ETSI has defined the channels 155 to 171 (155, 159, 163, 167, 172) for Broadband Wireless Access (BWA) use only. The idea is to give internet access to locations without any wired access network available. The maximum EIRP output power has been set to 36 dBm (4000 mW) with the limitation of RF power into antenna of 304 dBm (1000 mW).

2.4 Transmission Power Control (TPC)

Dynamic adjustment of the transmission power is intended to reduce RFI. Dynamically adjusting the transmission power facilitates the shared use of the 5250-5350 MHz and 5470-5725 MHz frequency bands with satellite services. TPC should cause an average reduction in the transmission power by at least 3 dB compared with the maximum permitted transmission power. TPC determines the minimum transmission power necessary to maintain the connection with the partner (such as an access point).

If TPC is not used within these frequency bands, then the highest permissible average EIRP and the corresponding maximum EIRP density are reduced by 3 dB. This restriction does not apply to the frequency range of 5150-5350 MHz. Without DFS and TPC, a maximum of only 30 mW EIRP is permitted. When DFS and TPC are used, a maximum 1000 mW EIRP is permitted as the transmission power (compared with 100 mW with 802.11 b/g, 2.4 GHz, DFS and TPC are not possible here). The higher maximum transmission power not only compensates for the higher attenuation of 5 GHz radio waves in air, it also makes noticeably longer ranges possible than in the 2.4 GHz range.

2.5 Dynamic Frequency Selection (DFS)

DFS was stipulated to (i) detect interference from radar systems (radar detection) and to avoid co-channel operation with these systems; and (ii) to provide on aggregate a near-uniform loading of the spectrum (Uniform Spreading). DFS is stipulated for the frequency ranges of 5250-5350 MHz and 5470-5725 MHz. It is optional for the frequency range of 5150-5250 MHz.

DFS initially assumes that no channel is available in the corresponding frequency band. The WLAN device selects an arbitrary channel at the start and performs what is known as a Channel Availability Check (CAC). Before sending to a channel for 60 seconds (Channel Observation Time, COT), a check is run to see if a different device is already working on this channel and the channel is therefore occupied. If this is the case, then a different channel is checked by the CAC. If not, then the WLAN device can perform the transmission operation. Even during operation, a check is run to see if a primary application such as a radar device is using this channel. This exploits the fact that radars frequently work according to the rotation method, whereby a tightly bundled directional transmission signal is transmitted by a rotating antenna. A remote receiver perceives the radar signal as a short pulse (radar peak). If a device receives such a radar peak, it pauses the transmission operation and monitors the channel for further pulses. If additional radar peaks occur during the COT, then a new channel is selected automatically. A check of this type is required to be carried out every 24 hours. This is why interrupting the data transmission for 60 seconds is unavoidable.

2.6 Channel Access Mechanisms

In order to avoid channel collisions when two or more than two devices transmit the signal in the same channel at the same time, Listen Before Talk (BLT) strategy is employed. ETSI EN 301 893 V1.7.2 [1] describes two mechanisms that require an equipment or a device to apply CCA before using the channel. The first mechanism is Frame Based Equipment (FBE) which defines a fixed (not directly demand-driven) timing frame for channel access. The second mechanism is Load Based Equipment (LBE) which defines demand-driven timing frame.

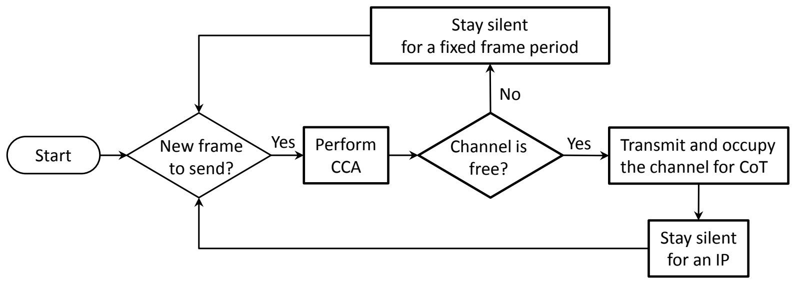


Fig. 2.3 Simplified flowchart of FBE.

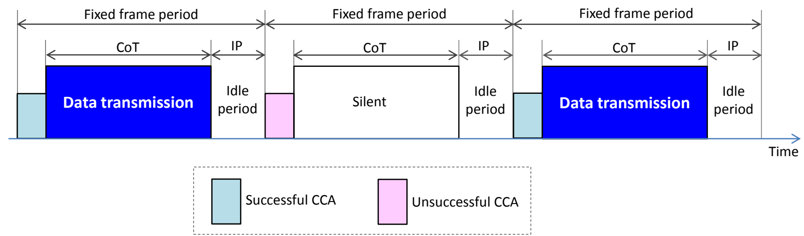


Fig. 2.4 An illustrative example of FBE.

2.6.1 FBE-based Mechanism

FBE shall comply with the following requirements:

- *R1:* Before starting transmissions on an operating channel, the equipment shall perform a CCA check using Energy Detect (ED). The equipment shall observe the channel for the duration of the *CCA observation time*. The operating channel shall be considered occupied if the energy level in the channel exceeds the *threshold* corresponding to the power level.
- *R2:* If the CCA procedure finds the channel clear, the equipment may transmit immediately and occupy the channel for a *fixed time period*.
- *R3:* If the CCA procedure finds the channel occupied, the equipment shall not transmit on that channel during the next fixed frame period.
- *R4:* The total time during which an equipment has transmissions on a given channel without re-evaluating the availability of that channel is defined as the *Channel Occupancy Time* (CoT).
- *R5:* After occupying the channel for CoT, the equipment keeps silent and waits for a short time, namely *Idle Period* (IP).
- *R6:* Towards the end of the idle period, the equipment shall perform a new CCA procedure as described in R1 above.
- *R7:* The equipment, upon correct reception of a packet which was intended for this equipment, can skip CCA and immediately proceed with the transmission of

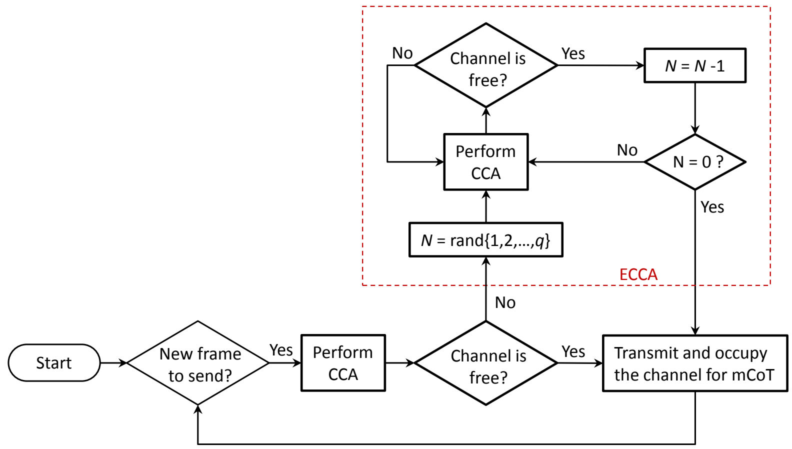


Fig. 2.5 Simplified flowchart of LBE.

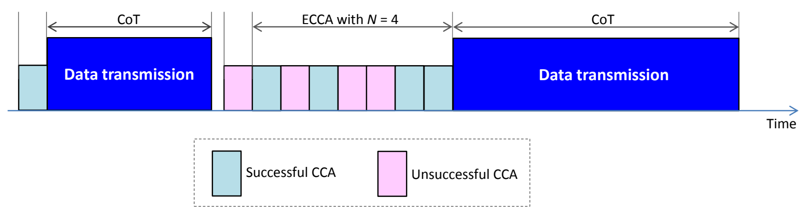


Fig. 2.6 An illustrative example of LBE.

management and control frames, e.g., acknowledgment (ACK) and block ACK frames.

- *R8:* A consecutive sequence of such transmissions by the equipment, without it performing a new CCA, shall not exceed the maximum CoT.
- *R9:* CCA observation time shall be not less than 20 μs.
- *R10:* CoT shall be in the range from 1 ms to 10 ms.
- *R11:* The minimum IP shall be at least 5% of CoT used by the equipment for the current fixed frame period.

A simplified flowchart and an illustrative of FBE are given in Figs. 2.3 and 2.4, respectively.

2.6.2 LBE-based Mechanism

LBE shall comply with the following requirements:

- *R1:* Before starting transmissions on an operating channel, the equipment shall perform a CCA check using ED. The equipment shall observe the channel for the duration of the *CCA observation time*. The operating channel shall be considered occupied if the energy level in the channel exceeds the threshold corresponding to the power level.

- *R2:* If the CCA procedure finds the channel clear, the equipment may transmit immediately on that channel.
- *R3:* If the CCA procedure finds the channel occupied, it shall not transmit in that channel. The equipment shall perform an Extended CCA (ECCA) procedure in which the channel is observed for a random duration.
- *R4:* If the ECCA procedure has determined the channel to be clear, the equipment may start transmissions on this channel.
- *R5:* The total time that an equipment makes use of the channel (without performing CCA) is the *maximum Channel Occupancy Time* (mCoT), after which the device shall perform a new CCA procedure as described in R1 above.
- *R6:* The equipment, upon correct reception of a packet which was intended for this equipment, can skip CCA and immediately proceed with the transmission of management and control frames, e.g., ACK and block ACK frames.
- *R7:* A consecutive sequence of transmissions by the equipment, without it performing a new CCA, shall not exceed mCoT.
- *R8:* CCA observation time shall be not less than 20 μs.
- *R9:* The random duration in an ECCA procedure is $N\times$ (CCA observation time), where N is randomly selected in the range $\{1,2,...,q\}$, $q \in \{4,5,...,32\}$ (declared by the manufacturer).
- *R10:* mCoT should be less than $(13/32) \times q$ ms (mCoT is in the range from 1.625 to 13 ms).

A simplified flowchart and an illustrative of LBE are given in Figs. 2.5 and 2.6, respectively.

References

1. *ETSI EN 301 893 V1.7.2 (2014-07): Broadband Radio Access Networks (BRAN); 5 GHz high performance RLAN; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive*, European Telecommunications Standards Institute Std., 2014.

Chapter 3
An Overview of LTE Advanced

Abstract This chapter provides a high-level overview of LTE-Advanced (LTE-A) networks and associated technologies to form a basis for discussion of the co-existence issues that exist for unlicensed LTE and Wi-Fi. Understanding the underlying architecture and protocols employed in LTE-A networks will provide readers a comparative framework to grasp how, and at what levels, LTE and Wi-Fi networks may interact and interfere with each other, and form a greater understanding of the challenges to be address in designing coexistence mechanisms. Specifically, this chapter will overview the LTE-A network, its capabilities and protocols, with specific emphasis on the physical layer and medium access sub-layers to illuminate specific sources of co-existence issues. Proposed changes which may be included in future LTE releases are discussed in the context of LTE/Wi-Fi coexistence.

3.1 System Overview

The enhancements to the Long Term Evolution/System Architecture Evolution (LTE/SAE) to meet the requirements set out for fourth generation (4G) cellular networks are collectively known as LTE-Advanced (LTE-A). The LTE-A requirements were formalized by the 3rd Generation Partnership Project (3GPP) in LTE releases 10 through 13 [1]. LTE itself was a logical evolution from the technologies used in previous generations in order to meet the increasing demands for higher data rates and improved quality of service. LTE met these demands at the access level through increased spectral efficiency and improved mobility support and cell edge data rates. The increased spectral efficiency was achieved by using orthogonal frequency division multiple access (OFDMA) and single-carrier frequency division multiple access (SC-FDMA) in the downlink and uplink, respectively. Improvements in mobility support and cell edge data rates were achieved through enhanced adaptive modulation and bandwidth selection and downlink spatial multiplexing and multiple input/multiple output support. Beyond the access layer, LTE transitioned to an all IP packet switched core network with the introduction of the evolved packet core, and a flattened network architecture of enhanced base stations called evolved NodeB's (eNB) interconnected via high-speed data links. Combined, these fundamental changes to the cellular network architecture has allowed LTE networks to significantly increase user data rates and reduce control and user plane latency and connection set-up and handover times. LTE-A represents the further, and ongoing, evolution of cellular networks to continue to meet the every increasing demands for higher data rates, user mobility support, and efficient support of a growing number of wireless devices.

3.1.1 Network Architecture

The requirements to provide high data rates while supporting high-speed mobility requires the ability to set up and tear down user connections and manage inter-cell handoffs with as little latency as possible. In previous generations of cellular networks, a hierarchical structure consisting of base stations or NodeBs connected to a central controller had been used. This star or cluster architecture requires additional hops in both data transmissions and hand off negotiation which can introduce significant delay. Controllers were are responsible for managing all data and control traffic, as well as handoffs betweens several pairs of base stations. For many increasingly ubiquitous end-user applications, such as online gaming and voice/video over the internet, the additional latency in connection set up and handover can impair the user quality of experience.

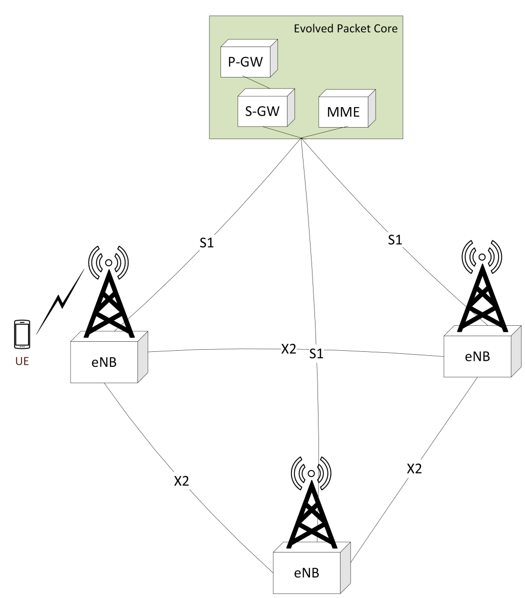


Fig. 3.1 Basic structure of LTE cellular networks.

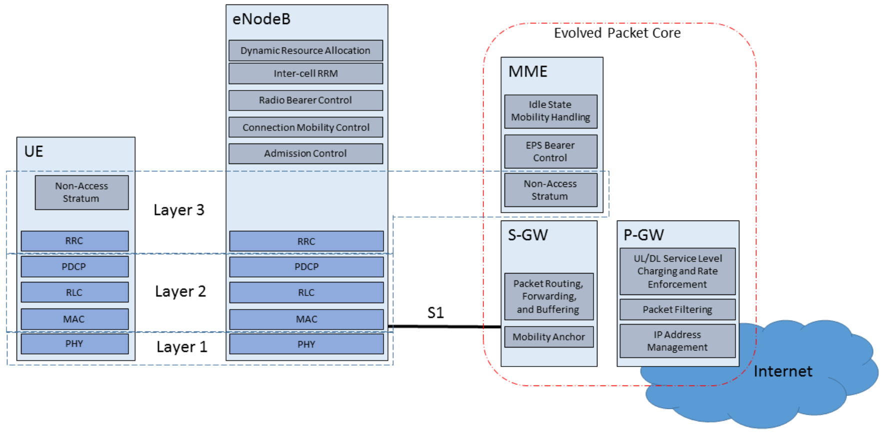


Fig. 3.2 Functional split between various entities in LTE under the system architecture evolution.

The flat architecture adopted by LTE networks is depicted in Fig. 3.1. The migration of local functions to eNBs and global functions to the EPC were driven by the requirements of reduced latency and higher data rates. The functions of radio network and medium access control, handoff requests, negotiations, and management, as well as some other truly local functions, are migrated to the eNBs, which are interconnected via high-speed, low latency, connections in a mesh configuration [4]. The low-latency X2 interface connections between eNBs allows for fast user handover, including forwarding of queued data for seamless user experience. Additionally, with direct connections between neighboring cells, this architecture facilitates more effective multi-point transmission and coordination and inter-cell interference and load management, independent of conditions in other areas of the network. The global functions and connections to external networks are handled at the evolved packet core (EPC). The functional split between the various components of the network, as well as the implementation of the necessary layers of the network protocol stack, is shown in further detail in Fig. 3.2. In addition to those listed in the figure, the mobile management entity (MME) handles authentication, authorization and accounting functions. The packet data network gateway (P-GW) and serving gateway (S-GW) handle user data packet forwarding, filtering, and usage tracking, as well as acting as a mobility anchor for inter-eNB and inter-RAT handovers. Further, the distributed radio network and resource management and medium access control allows eNBs to quickly adapt to changing radio medium condition and provide timely user scheduling based on local information.

3.1.2 Capabilities and Features

While the gains made by LTE were significant, they fell short of the requirements set out for 4G networks by the International Telecommunications Union, specifically in the case of peak data rates, spectral efficiency, and cell edge performance [10]. The continuing evolution which became LTE-A was finally able to achieve the necessary targets to meet the ITU requirements for 4G. Some important ITU requirements, and achieved performance levels for LTE and LTE-A, are highlighted in Table 3.1.

Table 3.1 ITU-A Requirements for 4G vs. LTE/LTE-A Achievements [7][8][10][12]

Description/Requirements	ITU-A	LTE	LTE-A
DL peak spectral efficiency (bps/Hz)	15	15	30
UL peak spectral efficiency (bps/Hz)	6.75	3.75	15
Min. cell edge spectral efficiency (bps/Hz)	0.04	0.024	0.04
DL Peak data rates (Mbps)	1000[1]	300	1000
UL Peak data rates (Mbps)	1000[1]	75	500
Scalable bandwidth up to (MHz)	40	20	100[2]

[1] For low mobility with requirement of min. 100 Mbps for speeds of up to 350 km/h.
[2] With carrier aggregation of up to five carrier components.

Among other innovations, in order to meet these requirements, LTE-A extended bandwidth scalability in LTE by supporting carrier aggregation, both within and across frequency bands. Discontiguous aggregation is supported to ensure a higher bandwidth is available for providers who cannot support it in contiguous spectrum allotments, allowing the development of license-assisted access (LAA-LTE) into the unlicensed and TV whitespace bands. Backwards compatibility is maintained by using bandwidths for each carrier component which match those used in LTE. LTE-A also expands MIMO/spatial multiplexing support up to 8x8 for DL and 4x4 for UL, adds coordinated multi-point operation to increase spectral efficiency and cell edge data rates, and improves heterogeneous network planning with the enhancement of support for small cells and relay nodes to increase area coverage with reduced power requirements.

3.2 Channel Access Mechanisms

Like other cellular access technologies, LTE-A has been designed for use on dedicated licensed spectrum allocations where there is, generally, no need to contend for channel access. While interference, fading, and path loss can corrupt LTE transmissions, and recovery and retransmission functions are necessary, in general a centrally controlled and tightly scheduled channel access mechanism is able to guarantee service levels required by all uplink and downlink traffic [4]. Channel access is achieved through frequency division multiple access (FDMA) and either time or frequency division duplexing. Orthogonal frequency division (OFDMA) is used in the downlink, allowing the eNB to efficiently schedule transmissions for many users in the same transmission time interval. Single carrier frequency division (SC-FDMA) is used in the uplink in order to reduce the power consumption requirements of battery dependent user equipment (UE) to communicate with the eNB. Further, coordinated multipoint (CoMP) is supported by allowing UEs to be configured to process channel state information from multiple eNBs, and both single-user and multi-user MIMO are supported in multiple configurations to achieve transmit diversity or multi-layer transmissions with beamforming possible in both horizontal and vertical dimensions.

The basic structure of the protocol stack used in LTE networks to facilitate channel access is shown in Fig. 3.3 [5]. UL and DL transmissions are divided amongst

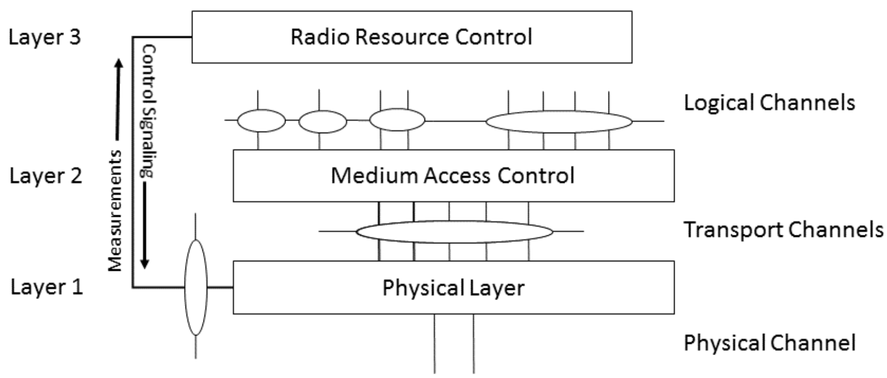
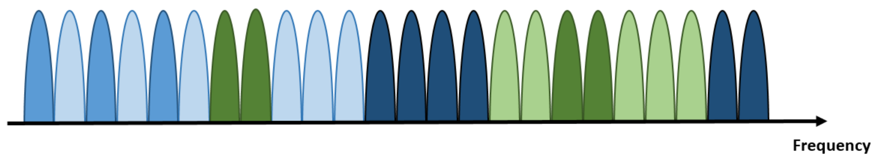


Fig. 3.3 E-UTRA radio interface protocol architecture.

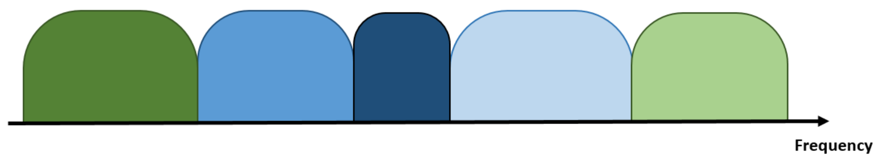
several physical channels, according to the type of transmission, i.e. user traffic or control information, and the type of transmission, i.e broadcast or unicast and scheduled or random access (random access is primarily used by a UE which has not yet associated to an eNB). The information bearing physical channels are mapped by the PHY layer into transport channels supplied to the MAC sublayer, which in turn remaps these into several logical channels provided to the higher layers.

3.2.1 LTE-A Physical Layer

The LTE PHY layer is designed to be both highly adaptable as well spectrally and power efficient. In the DL, OFDMA is used to schedule many signals in the same transmission time interval and achieve a high spectral efficiency, however, the very high peak to average power ratio makes this multiple access strategy unattractive in the UL for battery dependent devices [5][6]. SC-FDMA is used in the UL to maintain a satisfactory spectral efficiency while significantly improving power efficiency and battery life. Example carrier allocations for both DL and UL are shown in Fig. 3.4. Each color and shade represents the carriers allocated to a specific user. The



(a) OFDMA used in downlink.



(b) SC-FDMA used in uplink.

Fig. 3.4 Multiple access strategies used in LTE for uplink and downlink.

assignment of sub-carriers to a given UE are driven by the specific loss and interference experienced by that user, called channel state information (CSI), in order to maximize the overall achieved rate of all users. As shown in Fig. 3.4a, in the DL LTE-A supports both localized (contiguous) and distributed allocations. Sub-carrier assignments can further span disjoint frequency bands, including into unlicensed bands, through carrier aggregation. In Fig. 3.4b, which depicts an example UL allocation, a given sub-carrier, with variable bandwidth, is assigned to a single UE, again based on CSI. It should be emphasized that Fig. 3.4 shows a single instant of time, over subset of the available band.

All transmission are organized into frames comprised of twenty slots, every two of which comprise a subframe [6]. An example of one configuration for the LTE frame structure is shown in Fig. 3.5. A single sub-carrier, with either 7.5 or 15 kHz bandwidth, paired with a transmission duration required to transmit a single OFDM symbol is called a resource element. The minimum unit which can be allocated to a physical channel or user is the physical resource block (PRB). For simplicity, in the breakout, a single PRB is depicted, though a single PRB spans only a small subset of the available sub-carriers. Depending on the configuration used, a PRB is formed of either 7, 6, or 3 OFDM symbols and 12 or 24 sub-carriers allocated for one 0.5 ms slot. Between 6 and 10 PRBs will then be allocated to UE in order to achieve bandwidths between 1.4 and 20 MHz (though the occupied bandwidth will be smaller, 1.08 to 18 MHz). Higher bandwidths are achieved through carrier aggregation in the same slot, either contiguous or not.

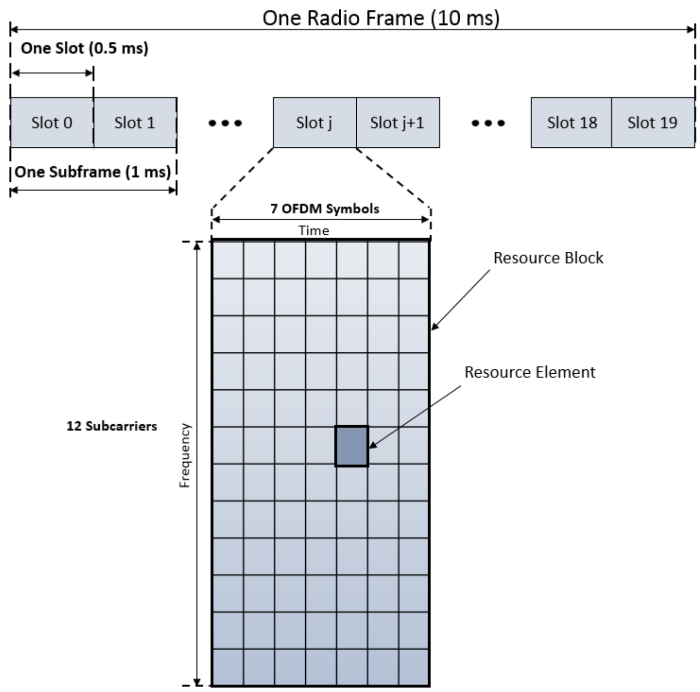


Fig. 3.5 LTE frame and resource block structure.

Two distinct frame structures are defined to support both time division duplexing (TDD) and frequency division duplexing (FDD), as well as a third frame structure specifically for license assisted access (LAA-LTE). All three frame types have the same basic structure shown in Fig. 3.5, with the differences being in how transmission are scheduled. Both half and full duplex are supported in FDD and all 10 subframes are available for both UL and DL. In half duplex configurations, transmission are seperated in both time and frequency, while for full duplex transmissions separation is in frequency only. For TDD, the frame is organized into two 5 ms half-frames, with several UL/DL configurations and switching patterns supported. As of Release 13, the special frame structure defined for LAA-LTE reserves all 10 subframes for DL, with transmission able to occupy one or more consecutive subframes, but required to start somewhere within the first subframe. LAA-LTE is expected to support for UL and DL in future releases.

Beyond the features discussed in detail, the LTE-A PHY layer provides forward error correction and automatic repeat request functions, modulation/demodulation of physical signals, mapping and rate matching of physical channels to transport channels, frequency and time synchronization, and MIMO antenna processing, including transmit diversity and beamforming. A variety of modulation schemes are supported depending on channel conditions, distance from receiver, and power requirements (up to 256 QAM in the downlink).

3.2.2 LTE-A Medium Access Control

Medium access in LTE is tightly controlled and scheduled in both UL and DL, with the eNB controlling the time and frequency resource block assignment for all but random access channels (used for UE connection requests and some other procedures) [3]. Distinct MAC sublayers for the eNB and the UE are defined, optimized to their specific functions and resources. Additionally, several MAC configurations are defined for UE depending on the specific functions implemented, such as dual connectivity to support Coordinated Multipoint (CoMP) transmission and sidelink channels for UE device-to-device communication. The basic structure of the MAC sublayer, without CoMP or sidelink configured, is shown in Fig. 3.6. The exten-

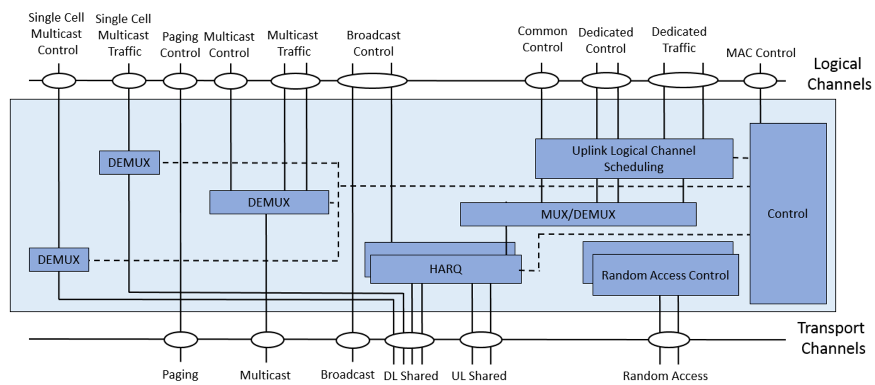


Fig. 3.6 LTE MAC sublayer structure and channel mapping.

sion to other MAC configurations requires the duplication of this basic structure, and separate control and traffic channels required. In dual connectivity, for example, two such MAC structures are implemented for the master and secondary cell group, however only the broadcast, shared UL and DL, and random access channels are needed for the secondary cell group. In sidelink configuration, only broadcast, discovery and duplex UL/DL shared channel are required.

The MAC sublayer facilitates reliable data transfer through radio resource allocation, UL traffic prioritization in the UE, and the mapping and multiplexing between transport channels and one or more logical channels. Further, the MAC sublayer handles hybrid automatic repeat requests (HARQ) signaling, a combination of forward error correcting coding and error detection, as well as channel prioritization with dynamic scheduling, random access control, and scheduling information reporting and requests.

The specific implementation of these, and other layer 2 functions such as radio link control, are quite complex and beyond the scope of this brief, however the underlying design paradigm is that global of knowledge facilitating tight control over medium access. The MAC sublayer in the eNB is aware of the channel conditions for each UE to be scheduled in both the UL and DL, and the UE adheres to the schedule of time and frequency provided by the eNB. PRBs are assigned to UL and DL transmissions to achieve the greatest advantage from local channel conditions. Little consideration of inter-user or inter-carrier interference is necessary, due to the dedicated frequency bands and orthogonal carriers discussed in Sec. 3.2.1. As result, LTE-A is able to achieve high spectral efficiency and reliability

3.3 Changes Expected for Future Releases

LTE-A brings cellular networks into the realm of 4G, as defined by [10]. As far as LTE-A has taken us, it will not be enough for fifth generation networks which are expected to support existing and new use cases ranging from smart cities and Internet of Things devices (massive machine type communication) to self-driving vehicles and industrial automation (ultra-reliable and low latency communications) with high speed mobile broadband on the order of *gigabytes* per second [11]. Some of the specific requirements are outlined in Table 3.2. Beyond these specific targets

Table 3.2 ITU-A Requirements for 4G vs. ITU-2020 Requirements for 5G [11]

Description/Requirements	ITU-A	ITU-2020
Peak data rates (Gbps)	1	20
Average user data rates (Mbps)	1	100
Mobility support(km/h)	350	500
Connection density (devices/km)	10^5	10^6
Traffic capacity (Mbits/s/m^2)	0.1	10

set by the ITU, 5G networks must also achieve 10× reduced latency, 3× improved spectral efficiency and 100× network energy efficiency, compared to 4G networks

In order to move towards 5G networks, 3GPP has numerous study items underway and planned for future releases, to meet the ITU requirements in [11]. These include significant enhancements to inter- and intra-band carrier aggregation and licenses-assisted access to ISM bands, TV white space, and other under-utilized spectrum resources, as well as multi-carrier enhancements and improved CoMP and device to device communications [9]. Wireless network virtualization and hardware resource sharing, cloud-based radio access networks, and new system architectures are under consideration to support the requirements around energy efficiency and and low-latency communications, among others. Additionally, the possibility of moving to an entirely new radio and medium access protocols is also under consideration, which would not be hindered by the need to be backwards compatible, and move forward with only the necessity of meeting the ITU 5G requirements.

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Chapter 4
An Overview on IEEE 802.11/Wi-Fi Medium Access Control

Abstract In order to understand and analyze the interactions between U-LTE and Wi-Fi in the 5 GHz frequency band, knowledge on the architectures and Medium Access Control (MAC) mechanisms currently adopted by these two technologies is highly desired. This chapter focuses on the Wi-Fi technology and starts with an overview of IEEE 802.11/Wi-Fi evolutions. Five existing generations as well as the next generation of IEEE 802.11/Wi-Fi are presented. The majority of this chapter provides ideas and detailed mechanisms of the CSMA/CA MAC protocol. Important observations on how the CSMA/CA sense and occupy the radio medium when the LTE network is operating in vicinity are highlighted.

4.1 IEEE 802.11/Wi-Fi Evolution

The IEEE 802.11 is a branch of 802 family of standards created and maintained by the Institute of Electrical and Electronics Engineers (IEEE) Local Area Network (LAN)/Metropolitan Area Network (MAN) Standards Committee (IEEE 802). It defines a set of specifications of physical (PHY) and MAC layers of Wireless Local Area Networks (WLANs) operating in a number of unlicensed radio frequency bands including sub-Ghz, 2.4, 5, and 60 GHz. Commercial products using IEEE 802.11 standards are branded as Wi-Fi. Wi-Fi Alliance is an organization made up of leading wireless equipment and software providers with the missions of certifying all 802.11-based products for interoperability and promoting the term Wi-Fi as the global brand name. According to statistics made by Wi-Fi Alliance in January 2016, about 12 billions of Wi-Fi units have been shipped and deployed in homes, offices, buildings, factories, and so on. As a result, Wi-Fi has become one of the most prolific technologies around the world.

The first IEEE 802.11 standard was introduced in 1997. Since then, this technology has evolved with different generations to meet the increasing demand in system throughput and to support a wider range of features/applications. The most commonly deployed standards are 802.11a, 802.11b, 802.11g, 802.11n and 802.11ac.

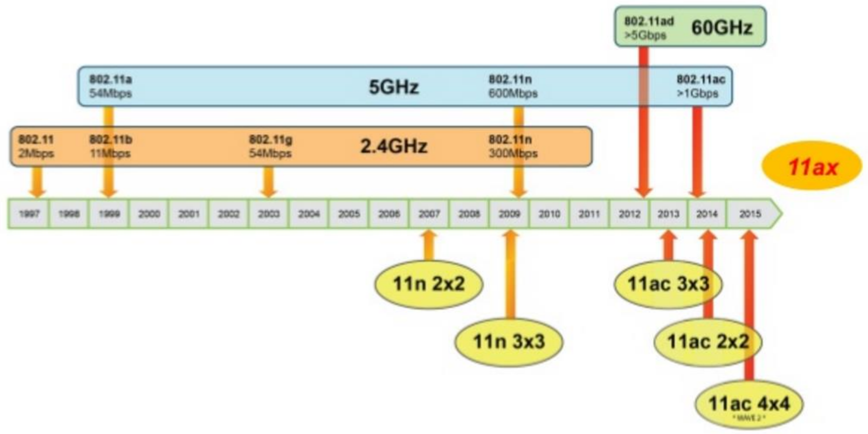

Fig. 4.1 IEEE 802.11/Wi-Fi Standard Evolution.

Today, most businesses are using 802.11n and are looking to adopt 802.11ac as it is the fastest and latest available. Fig. 4.1 sketches the evolution of IEEE 802.11/Wi-Fi technology.

The original 802.11 standard (introduced in 1997) can support only 1 or 2 Mbps which is quite low. It was aimed to provide an alternative to and/or to replace wired Ethernet connectivity. The WLAN rate is then significantly improved with IEEE 802.11b and IEEE 802.11a rectified in 1999. The 802.11b, considered as the *first generation* WLAN technology, features two well-known spread spectrum technologies to distribute packets over a wireless medium: Frequency-Hopping Spread Spectrum (FHSS) and Direct-Sequence Spread Spectrum (DSSS) that are still in use by most wireless networks today. It operates in 2.4 GHz frequency band and can support a maximum data rate of 11 Mbps. The IEEE 802.11a - the *second generation* WLAN technology - employs the Orthogonal Frequency Division Multiplexing (OFDM) technology to enable a higher data rate of 54 Mbps. Using the 5 GHz band, this standard has a significant advantage when the 2.4 GHz band is heavily crowded. Next, the *third generation* WLAN technology - the IEEE 802.11g - was released in 2003. It operates in the 2.4 GHz band (as the IEEE 802.11b) and uses OFDM to match the 54 Mbps data rate achieved by the 802.11a. The 802.11e was then introduced in 2005 to enhance the 802.11a and b with the support of QoSs. It operates at radio frequencies of up to 5.8 GHz and is most suitable for networks with multimedia applications. In order to further boost the data rate, in 2007, the 802.11n using Multiple Input Multiple Output (MIMO) technology was introduced. It is considered as the *fourth generation* WLANs, using both 2.4 and 5 GHz frequency bands and can support up to 600 Mbps. The 802.11n is now becoming the dominant deployed standard.

The demand for higher throughput over the wireless medium escalated in the late 2000s, driven by mass adoption of smart phones, tablets, and video on demand services such as YouTube and Netflix. To address this, the 802.11ac, also known as the *fifth generation* or gigabit Wi-Fi, was approved in 2014. It operates only in 5 GHz band, incorporating the enhanced air interface of 802.11n with wider bandwidth, more MIMO streams, and high-density modulation to support at least 1 Gbps. This standard is now incorporated in many mainstream Wi-Fi products. The 802.11ad is another gigabit Wi-Fi which was introduced in 2012, operating in the unlicensed 60 GHz band and offering much higher transfer rates than previous 802.11 standards (its theoretical maximum transfer rate is up to 7 Gbps). Technology based on the 802.11ad standard can supplement existing wireless networks for high-definition video streaming, offering the ability to offload heavy demands on 2.4 and 5 GHz that other 802.11 standards are operating on. The 802.11ax - the successor to the 802.11ac and also called High-Efficiency Wireless (HEW) - is currently at its early stage of development that has the goal of providing 10 Gbps in both 2.4 and 5 GHz bands. This new standard implements several technologies to enhance the efficiency of channel utilization and is therefore expected to provide users with consistent and reliable data throughput in crowded wireless environments. One of the biggest enabling technologies of this efficiency is multi-user technology, both in the form of Multi-User MIMO (MU-MIMO) and Multi-User OFDMA (MU-OFDMA).

4.2 IEEE 802.11 CSMA/CA

Despite that fact that many generations of IEEE 802.11 has been developed to enhance data rates and support additional features as presented in previous section, they basically share the same MAC mechanism which dictates how multiple devices can share the radio channel. In a nut shell, the 802.11 standard defines two operating modes. In the infrastructure mode, wireless clients are directly connected to an Access Point (AP) in the star topology. APs are connected to a distribution network, usually wired LANs, for Internet connection. In the ad-hoc mode, clients are connected to one another without any AP. While ad-hoc mode is only used in a limited number of scenarios, the infrastructure mode is deployed in almost all Wi-Fi networks. The MAC layer for the infrastructure Wi-Fi networks is composed of two radio channel coordination functions: distributed coordination function (DCF) and point coordination function (PCF).

4.2.1 PCF and DCF

DCF is a contention-based LBT mechanism called *Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)* that *works in an entirely distributed manner without any coordination*. With CSMA/CA, stations (STAs) independently perform

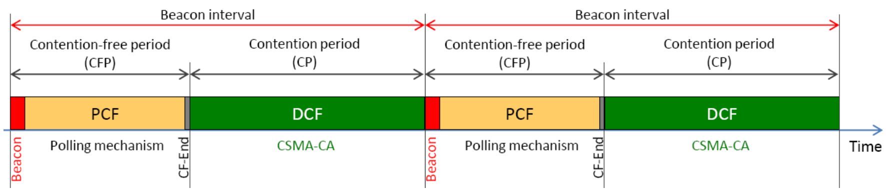

Fig. 4.2 PCF and DCF in IEEE 802.11.

carrier sensing and back-off procedures to compete for the channel access. DCF is a mandatory MAC function and implemented in all IEEE 802.11/Wi-Fi devices. CSMA/CA is focused in this chapter and its technical details will be presented in section 4.2.3.

PCF is built on the top of DCF. It aims to support applications that require near real-time services. Basically, PCF splits the time into periodic interval called beacon intervals, each of which is composed of contention-free period (CFP) and contention period (CP). *CFP requires coordination from the access point (AP)* and allocates resources to STAs using polling mechanism. Specifically, AP maintains a list of registered PCF-enabled STAs and polls each of them using CF-Poll frames. Only after a STA is polled, it can start its data transmission. In case the polled STA does not have any frames to send, then it must transmit null frame. Channel access in CP of PCF is handled by CSMA/CA protocol. PCF is specified as an optional MAC function and has not been widely implemented due to its complexity.

The timing of PCF and DCF of IEEE 802.11 is sketched in Fig. 4.2. Within a given beacon interval, the start and end of CFP are marked by beacon and CF-End control frames, respectively. CP follows CFP and is terminated by a beacon frame of the next beacon interval.

4.2.2 Basic Medium Access

The LBT mechanism employed by the IEEE 802.11/Wi-Fi CSMA/CA basically follows the same philosophy of carrier sensing protocol family. When a STA needs to transmit a new frame, the channel is sensed and if it is found idle the frame is transmitted immediately. This simple mechanism is very effective when the medium is not heavily loaded since it allows STAs to transmit with a minimum delay. However, it cannot prevent channel access collisions when multiple STAs detect free channel and decide to transmit their frames at the same time. As a result, in addition to this basic channel access, a number of important mechanisms are mandated in CSMA/CA.

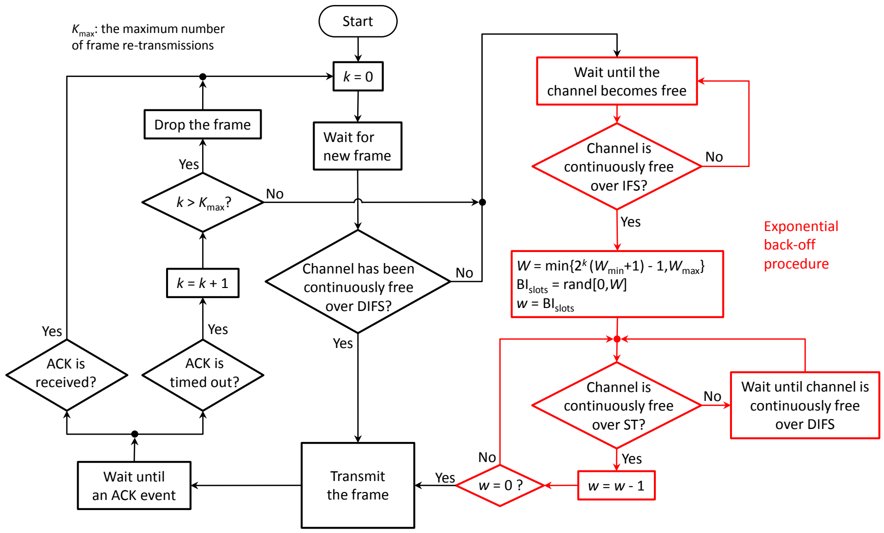

Fig. 4.3 Simplified flowchart of CSMA/CA.

4.2.3 Medium Access with Collision Avoidance

Since it is difficult to detect collisions at a wireless receiver, the IEEE 802.11 protocol tries to avoid collisions rather than detect and recover from collisions. This means that CA mechanisms are mandated to reduce the collision probability at the points where collisions would most likely occur. Specifically, most collisions happen when the medium has become idle (as indicated by CS function) after a busy state: several STAs could have been waiting for the medium to be available again, then all transmit at the same moment the medium is detected free. This situation necessitates a "random" back-off procedure to resolve medium contention conflicts. Also, the use of various Inter-Frame Spaces (IFSs) helps to resolve the problem. The CSMA/CA protocol is outlined as follows.

When a STA needs to transmit a new frame, if the channel has been continuously free over a Distributed IFS (DIFS) interval, it transmits immediately. Otherwise, STA defers its transmission until the channel becomes available. Then if the channel is detected to be continuously free over a Distributed IFS (DIFS) interval, the STA will initiate the back-off procedure to further defer its transmission over a random time interval. The back-off procedure starts with the selection of a random "slotted" back-off interval $BI_{slots} = rand[0,W]$, where $rand[0,W]$ is a random number uniformly distributed in the range from 0 to W, W is back-off window (when the system is started W is assigned to its minimum value W_{min}). Next, back-off counter w is initialized with BI_{slots} and decreased every time the medium is idle over a Slot Time (ST). This counter is frozen when a transmission is detected on the medium, and resumed when the channel is detected idle again for a DIFS interval. As soon as w finally reaches zero, the STA transmits its frame. It is important to note that this

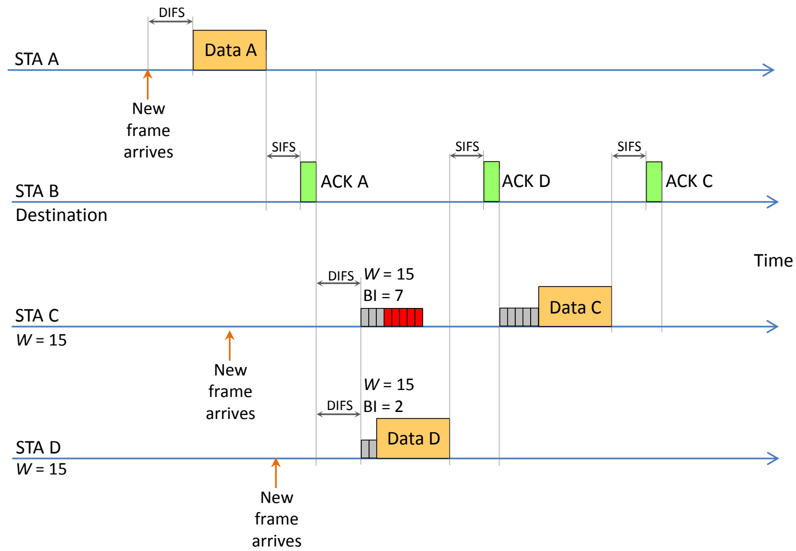

Fig. 4.4 CSMA/CA: An example of back-off procedure when there is no collision.

back-off procedure randomizes the channel access among STAs and thus helps to reduce the chance of collision. It also gives all STAs their fair shares of the channel.

The destination STA, upon receiving a frame correctly, waits for a Short IFS (SIFS) interval immediately after the reception has completed and transmits an ACK frame back to the source STA in order to confirm the correct reception. SIFS is the smallest IFS to give the highest priority channel access to ACK frames. If the source STA receives a confirmation, transmissions of the second and subsequent frames of a fragment burst will use SIFS instead of DIFS. Otherwise, the source STA activates the re-transmission procedure for the lost frame.

When a transmission is lost (due to channel collision when two or more STAs decrease their back-off counter to zero at the same time and transmit their frames at the same time or transmission errors), the contention window W is doubled and applied for the re-transmissions until it reaches a maximum value $W_{\max}$. For the re-transmissions, the back-off procedure is activated after the channel remains idle for an Extended IFS (EIFS) interval. When a frame transmission is successful, contention window W is reset to its minimum value $W_{\min}$. When a maximum number of frame re-transmissions is exhausted, the frame is discarded and W is also reset to its minimum value $W_{\min}$.

The reason behind the exponential growth of contention window W is explained as follows. When a STA experiences a collision, it has no information on how many STAs are involved in the collision. If there are only few colliding frames, it would make sense to choose the random back-off interval from a small set of small values, i.e., W is small. But if many STAs are involved in a collision, then it makes sense to choose the back-off interval from a larger, more dispersed set of values, i.e., W

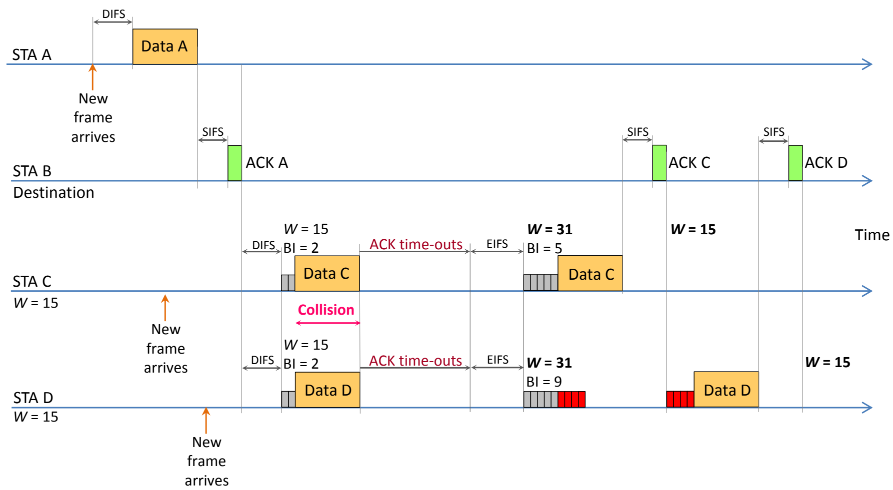

Fig. 4.5 CSMA/CA: An example of back-off procedure when there is a collision (the contention window is exponentially increased).

is large. Otherwise, if several STAs select the back-off interval from a small set of values, more than one STA would choose the same back-off value with high probability. This will result in high probability of collision.

Fig. 4.3 shows the flowchart of CSMA/CA protocol. Figs. 4.4 and 4.5 demonstrates the operations of the back-off procedure in two typical scenarios. As visualized in Fig. 4.4, by randomly selecting back-off intervals, STAs C and D randomize their channel access to minimize the chance that they transmit their frames at the same time. In case a collision takes place, as shown in Fig. 4.5, STAs C and D double their contention windows to further increase the randomness in their back-off interval generations.

Here are some illustrative values of CSMA/CA operation parameters: ST = 20 μs, SIFS = 10 μs, DIFS = SIFS + 2×ST = 50 μs, EIFS = Transmission time of ACK frame at lowest physical mandatory rate + SIFS + DIFS, W_{min} = 31, and W_{max} = 1023. Contention window of the initial transmission attempt is $W(0) = W_{\text{min}} = 31$. Contention window of the k-th re-transmission is $W(k) = \min\{2^k(W_{\text{min}}+1)-1, W_{\text{max}}\}$, where $k \in \{1,2,...,K_{\text{max}}\}$, K_{max} is the maximum number of re-transmission attempts. Assuming $K_{\text{max}} = 7$, then the progression of contention window with frame transmission/re-transmissions is as follows: $W(0) = 31$ (the initial transmission attempt), $W(1) = 63$ (the first re-transmission attempt), $W(2) = 127$ (the second re-transmission attempt), $W(3) = 255$ (the third re-transmission attempt), $W(4) = 511$, $W(5) = 1023$, $W(6) = 1023$, and finally $W(7) = 1023$. Different IEEE 802.11 physical layer standards could specify different values for these parameters to optimize their operations.

In order to provide guaranteed reservation of the channel and hence uninterrupted data transmission, CSMA/CA protocol can be enhanced with Request-To-

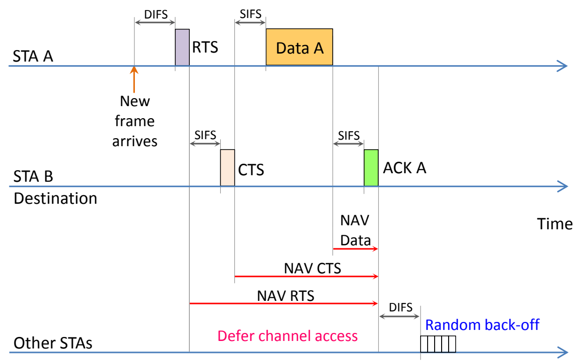

Fig. 4.6 CSMA/CA enhanced with RTS/CTS handshake and NAV.

Send (RTS)/Clear-To-Send (CTS) handshake and virtual carrier sense using Network Allocation Vector (NAV). The former is an optional mechanism and only employed for transmissions of long frames (determined by RTS threshold which is typically around 500 bytes). The latter is a prominent mechanism which is widely used with CSMA/CA protocol.

In RTS/CTS access mode, prior to the data transmission, the source STA will send a RTS frame to announce the upcoming transmission. When the destination STA receives RTS, it will send a CTS frame after a SIFS interval if it is available to receive the data. The source STA is allowed to transmit its data frame only if it receives the CTS frame correctly. The purpose of this RTS/CTS exchange is to clear hidden areas and avoid long collisions. RTS/CTS is illustrated in Fig. 4.6.

To implement virtual carrier sensing, each STA sends duration information in frame headers. This duration information indicates the amount of time (in microseconds) the medium is to be reserved after the end of the current frame. STAs listening on the wireless medium read the duration fields and set their NAVs, which is an indicator for a STA on how long it must defer from accessing the medium. They count down their NAVs and do not access the channel (even if their physical carrier sense indicates that the channel is free) until NAVs reach zero. NAV is illustrated in Fig. 4.6. As can be seen, the NAV field in RTS frame allows CTS, data, and ACK frames to be completed (or allows only CTS frame to be completed in some implementations). The NAV in CTS frame allows data and ACK frames to be completed. Finally, the NAV in data frame allows the ACK frame to be completed.

4.3 IEEE 802.11e EDCA

The biggest limitation of IEEE 802.11 CSMA/CA is its lack of capability to differentiate frames in terms of channel access priorities for different applications. As a result, the IEEE developed enhancements in IEEE 802.11e to both coordination modes to facilitate QoS. The following sections will present details of 802.11 CSMA/CA protocol and its enhancements introduced in 802.11e.

The enhancement to DCF, namely Enhanced Distribution Coordination Function (EDCF), introduces the concept of access categories (ACs). Each STA has four kinds of ACs that define four respective priority levels to differentiate the channel access probability for different traffic types. With EDCF, high priority traffic has a higher chance of being sent than low priority traffic: a STA with high priority traffic waits a little less before it sends its packet, on average, than a STA with low priority traffic. This is accomplished by using a shorter contention window and shorter Arbitration Interframe Space (AIFS).

IEEE 802.11e extends the polling mechanism of PCF with the Hybrid Coordination Function (HCF). The HCF controlled channel access (HCCA) works similarly to PCF. However, in contrast to PCF, in which the interval between two beacon frames is strictly divided into two periods of CFP and CP, the HCCA allows CFPs to be initiated at almost any time during a CP. This kind of CFP is called a Controlled Access Phase (CAP) in 802.11e. A CAP is initiated by the AP whenever it wants to send a frame to a STA or receive a frame from a STA in a contention-free manner. In fact, the CFP is a CAP too. During a CAP, the Hybrid Coordinator (HC), which is also the AP, controls the access to the medium using polling mechanism. During the CP, all STAs function in EDCA. The second difference with PCF is that Traffic Class (TC) and Traffic Streams (TSs) are defined. This means that HC is not limited to per-station queuing and can provide a kind of per-session service. Also, HC can coordinate these streams or sessions in any fashion it chooses (not just round robin). Moreover, STAs give information about the lengths of their queues for each TC. HC can use this information to give priority to one STA over another, or better adjust its scheduling mechanism.

IEEE 802.11e additionally introduces the concept of transmission opportunity (TXOP). A STA which obtains medium access must not utilize radio resource for duration longer than a limit specified by TXOP. The use of TXOPs reduces the problem of low-rate STAs gaining an inordinate amount of channel time in the conventional 802.11 DCF MAC. Another enhancement is that a STA is only allowed to initiate a frame exchange if it can complete the exchange before the start of the next beacon interval.

4.3.1 QoS Provisioning Mechanisms

4.3.2 EDCA and HCCA

Basic operations of HCCA are illustrated in Fig. 4.7. HCCA is generally considered as the most advanced and complicated coordination function. With HCCA, QoS can be configured with great precision. QoS-enabled STAs have the ability to request specific transmission parameters (data rate, jitter, etc.), which should allow

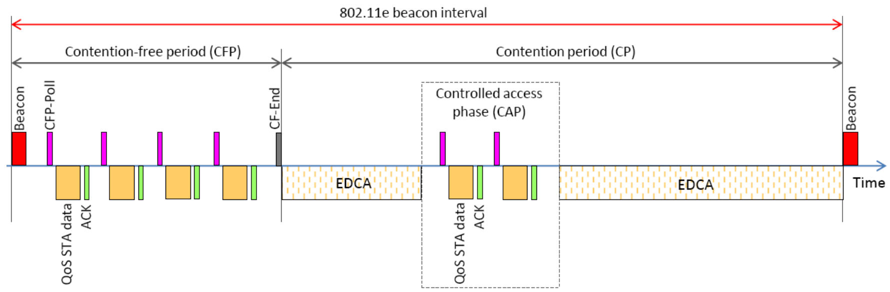

Fig. 4.7 HCCA in IEEE 802.11e.

advanced applications like voice over IP (VoIP) and video streaming to work more effectively on Wi-Fi networks. However, due to its complexity and signaling overhead, HCCA has not been widely implemented.

It can be seen IEEE 802.11 CSMA/CA is the most fundamental protocol for medium access in WLANs. In fact, IEEE 802.11e EDCA is primarily designed based on CSMA/CA. As a result, in-depth knowledge on medium access mechanisms employed by this protocol is imperative to unde

4.4 Important Observations on CSMA/CA

It is important to note that IEEE 802.11 CSMA/CA is specified with a few key additional features that go beyond LBT requirements specified by ETSI [1]. *First*, a Wi-Fi device defers to signals that are much weaker than the minimum level required by ETSI. ETSI LBT requires a transmitter to defer if the received energy is above −60 dBm (for 20 MHz), while Wi-Fi defers if the received energy is above −62 dBm (this level is referred to as the energy detect threshold, or ED for short) or if a valid Wi-Fi preamble is detected. Wi-Fi's ED threshold is nearly the same as ETSI's LBT threshold, but Wi-Fi preamble detection is required to work to at least −82 dBm, and in reality works to −90 dBm or lower in most products. Hence, Wi-Fi devices defer to other Wi-Fi transmissions much more conservatively (i.e., at a much larger distance) than a device which only meets ETSI requirements. *Second*, Wi-Fi goes beyond the ETSI requirements in specifying how long a device must wait after the on-air energy falls below the threshold before initiating a transmission. *Third*, when a collision is detected, Wi-Fi employs exponential back-off rule that doubles the contention window size and thus significantly increases the random back-off time in order to avoid future collision.

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Chapter 5
A Survey on Related Work

Abstract Coexistence between U-LTE and Wi-Fi networks is a deciding factor on the acceptance of U-LTE. As a result, a large number of studies have been carried out to identify what could be the affects that U-LTE may cause to Wi-Fi and which mechanisms could be used for ensure that these two technologies share the 5 GHz unlicensed frequency band in an efficient and fair manner. This chapter presents a survey on related work to answer the following questions: (i) what issues arise from simultaneous operation of LTE and Wi-Fi in the same spectrum bands, (ii) which technology is affected the most, and (iii) which factors determine the impacts of U-LTE to Wi-Fi. It also identifies the strengths and weaknesses of existing solutions and suggests potential strategies to improve performance of these two technologies.

5.1 The Impacts of U-LTE on Wi-Fi Operation and Performance

In [4], extensive simulations have been performed to assess the performance of LTE and Wi-Fi coexisting in an office environment. Single-floor and multi-floor office environments with different assumptions on the density of Wi-Fi and LTE nodes have been considered. The simulation results in [4] have shown that, in the absence of any modification to LTE channel access mechanism, channel sharing between LTE and Wi-Fi networks is significantly unfair for Wi-Fi networks. While LTE only marginally loses (about 4% of the performance) when Wi-Fi is present on the same band, Wi-Fi could lose up to 70% performance in a sparse deployment (1 AP per system per floor) and to almost 100% in a dense deployment (5 APs per system per floor). Detailed investigations in [4] have indicated that Wi-Fi channel is blocked when LTE interference is present, and thus Wi-Fi nodes keep staying on the "listen" mode most of the time.

The authors in [5] present observations similar to those in [4] on the effects of unmodified LTE to Wi-Fi networks in the shared frequency band. Specifically, when network load is increased, LTE performance suffers only a minor degradation, while Wi-Fi performance drops significantly. This can be explained by the increasing LTE occupancy on the shared band. LTE does not follow the same rules as Wi-Fi in shared medium access. When there is ongoing transmission on the channel, while Wi-Fi politely defers its transmission, LTE always choose to transmit by selecting a more robust transmission mode by adapting its modulation and channel coding scheme in order to cope with the higher interference. This aggressive behavior quickly results in a situation where LTE terminals take all transmission opportunities while Wi-Fi devices are locked in back-off procedures. Unfortunately, the results in [5] have also demonstrated that the severity of this negative impact on Wi-Fi can be efficiently controlled by restricting LTE activity.

The authors in [6] analyze the performance degradation of Wi-Fi in the presence of LTE-U. The probability of Wi-Fi accessing the channel is used as the main metric. Numerical results in [6] indicate that Wi-Fi is negatively affected by conventional LTE operation due to LTE's almost continuous transmission that subsequently blocks Wi-Fi. Specifically, given two modes of operations currently proposed for LTE-U in the unlicensed spectrum, the "off" period presented by the LTE protocol is too short for Wi-Fi users to access to the channel. As a result, Wi-Fi is at risk of spending a significant amount of time in the "listening" mode when LTE transmission is present in the same channel.

The work in [7] presents initial investigations on the coexistence of two versions of license-anchored U-LTE (i.e., LTE-U and LAA-LTE) and Wi-Fi in 5 GHz frequency band. Results in [7] show that LTE-U poorly coexists with Wi-Fi primarily due to two factors: (i) the incompatibility of LTE-U's duty-cycling mechanism with Wi-Fi equipment and (ii) the lack of an effective coexistence mechanism in scenarios where LTE-U and Wi-Fi devices hear each other at moderate but non-negligible power levels. Additionally, LAA-LTE with LBT does not by itself guarantee successful coexistence with Wi-Fi and other purely unlicensed technologies. The results in [7] were submitted to FCC in June 2015 to demonstrate that, although any wireless technology should have the ability to utilize unlicensed spectrum within the FCC's rules, U-LTE has the potential to crowd out unlicensed services.

An experiment-based study on the effect of LTE-U to Wi-Fi is presented in [8]. The LTE signal level is set higher than the Wi-Fi clients' LBT energy detection threshold (i.e., when LTE is on, the Wi-Fi client should sense their presence and not transmit). Wi-Fi throughput and latency are measured when data is transmitted through the Wi-Fi network with varying duty cycles and periods of LTE signals. The results in [8] indicate that, as expected, increasing the LTE-U duty cycle degrades both Wi-Fi throughput and latency performance since it decreases Wi-Fi transmission opportunity accordingly. If the duty cycle period is too high, Wi-Fi latency is negatively impacted (while Wi-Fi throughput is nearly unchanged, given the same duty cycle) since Wi-Fi frames have to be buffered during long LTE "on" period. However, if the duty cycle period is configured as too low (e.g., 10 msec), Wi-Fi throughput degrades due to the fact that LTE "on" and "off" periods are too short for Wi-Fi users to access to the channel and to complete their transmissions, respectively. Furthermore, the authors in [8] indicate that LTE-U duty cycle cannot strictly results in corresponding air time and throughput sharings. For example, with a duty cycle of 50%, LTE-U is likely to capture more than 50% of the channel resources.

The reason is that when LTE-U starts its transmissions (regardless of ongoing Wi-Fi frame transmissions), many Wi-Fi frames are corrupted. Transmission failures lead to multiple frame re-transmissions and, more importantly, mistakenly force Wi-Fi transceivers to operate at lower rates (in this case, lowering the channel coding and modulation modes is not necessary and waste of channel efficiency).

5.2 Existing Solutions to Address the U-LTE and Wi-Fi Coexistence Concern

Various coexistence mechanisms proposed for U-LTE are surveyed in [1, 2, 3]. They include: Dynamic Channel Selection (DCS), power control, opportunistic secondary cell “off”, CSAT (in LTE-U), and LBT (in LAA-LTE). When U-LTE and Wi-Fi share the common 5 GHz radio frequency band, those mechanisms are found to useful to reduce RFI and improve the spectrum utilization efficiency. The roles of each of them, however, greatly varies depending on network/system parameters including network scale, node density, deployment/radio environment (i.e., indoor, outdoor, short range, long range, ...), network load profiles, etc.

In order to see how LBT mechanisms employed by LAA-LTE can help for the coexistence, a simulation-based study is carried out and reported in [9]. LBE LBT specified by ETSI [1] and IEEE 802.11e Enhanced Distributed Channel Access (EDCA) are assumed for LAA-LTE and Wi-Fi, respectively. The most important observation from [9] is that LBT compliant to ETSI regulation is not sufficient for fair coexistence: Wi-Fi STAs have much lower probability of successful channel access compared to LAA-LTE users. One major reason for this phenomenon is the non-exponential back-off LBT employed by LAA-LTE. Unfortunately, no form of exponential back-off LBT is studied in [9].

In [10, 11, 12, 13], the performance of LTE-U and LAA-LTE and Wi-Fi in a shared frequency band is evaluated. DCS and opportunistic secondary cell “off” in unlicensed spectrum (U-LTE small cells would release the unlicensed carriers and fall back to the anchor carrier in licensed spectrum at low traffic load) are jointly used with CSAT and LBT. The results show that co-existence has a negative but controllable impact on Wi-Fi performance. In [10, 11, 12], LTE-U can be a better neighbor to Wi-Fi than Wi-Fi to itself in some scenarios. The underlying design that allows LTE-U to achieve high spectral efficiency while being a good neighbor to Wi-Fi is achieved through a set of carefully designed coexistence techniques, including DCS, secondary cell “duty cycle” in unlicensed spectrum (i.e., CSAT), and opportunistic secondary cell “off” in unlicensed spectrum. Specifically, in scenarios where the density of Wi-Fi APs and small cells is low or moderate, DCS and opportunistic secondary cell “off” are sufficient to meet the coexistence requirement. When LTE-U devices replace Wi-Fi devices, they can achieve significantly higher throughputs due to their high spectral efficiency. In addition, the performance of neighboring Wi-Fi is unchanged or even slightly improved since LTE-U devices can finish transmission faster and incur less interference. However, as the density of Wi-Fi devices and LTE-U small cells is high, DCS and opportunistic secondary cell "off" alone cannot guarantee harmonious coexistence with Wi-Fi and therefore CSAT or LBT is required. Resutls in [11, 13] were submitted to FCC in 2015 to support U-LTE technologies.

A systematic and large-scale network-wide study of LAA-LTE and Wi-Fi performance in a wide range of realistic deployment scenarios and network densities in the unlicensed 5 GHz band is presented in [5]. The simulation results in all considered coexistence scenarios demonstrate that both LAA-LTE and Wi-Fi significantly benefit from the large number of available channels and the isolation provided by building shielding at 5 GHz. They also suggest that deploying LAA-LTE with a random channel selection scheme is feasible for lower network densities. For typical indoor deployments of high density, implementing LTE-U interference-aware channel selection with respect to Wi-Fi is superior to LBT in terms of achieved throughput for both technologies. Additionally, LBT can increase LAA-LTE user throughput when multiple outdoor LAA-LTE networks deployed by different cellular operators coexist.

The work in [6] investigates the behavior and performance of two existing LBT mechanisms that are designed following the coexistence standard specified by ETSI [1]: LBE and FBE-based mechanisms. The Jain's fairness index has been used to access the coexistence of LAA-LTE using these two LBT mechanisms and Wi-Fi using CSMA-CA. The simulations in [6] show that FBE-based mechanism using fixed contention window penalizes the channel access opportunity of Wi-Fi's CSMA-CA using adaptive contention window. They also reveal that FBE-based mechanism tends to aggressively occupy the channel. In some cases, Wi-Fi is starved with very less (or even no) chance on the channel access. This poor fairness is mainly caused by the short CCA sensing period of FBE-based mechanism. CCA is applied only once and then FBE-based mechanism may start its transmission immediately while LBE and Wi-Fi-based mechanisms are still decrementing their respective back-off counters. The fairness is worsened with longer FBE's frames. Another observation is that, again due to equal CCA sensing time, when multiple FBE-based equipment are contending for the channel, they are prone to serious collisions (if they are accidentally synchronized) or suffer a significant unfairness (if they are asynchronous). To cope with those issues, tuning the values of back-off scaler (q) to extend the contention window size and using CCA procedure similar to that of LBE-based mechanism have been suggested for LBE and FBT-based mechanism, respectively. The results in [6] demonstrate that the modified LBE-based mechanism still cannot sufficiently improve the fairness with others. This could be because simply empirically tuning back-off scaler while keeping the CCA principle unchanged cannot compensate for exponential growth of window size adopted by Wi-Fi's CSMA-CA. The modified FBE-based mechanism can offer better fairness when coexisting with Wi-Fi.

A comparison of LTE-U and LAA-LTE is presented in [16]. The analysis in [16] shows that for sufficiently long LTE transmission times, the LTE throughputs achieved by CSAT and LBE are almost identical. However, for shorter LTE transmission times, LTE-U provides lower LTE throughput than LAA-LTE due to higher

LTE/Wi-Fi collision probability of LTE-U. Besides, while shorter LTE transmission time decreases the tail of the Wi-Fi delay distribution, the percentage of packets that suffer from long delays increases. The results also indicate that when appropriately configured, LTE-U and LAA-LTE provide the same level of fairness to Wi-Fi. The selection of co-existence mechanisms is primarily driven by the operator's interests that include implementation complexity, LTE throughput, operational and management costs as well as strategic decisions on targeted markets.

Coordinated coexistence between U-LTE and Wi-Fi is investigated in [3, 4]. The authors in [3] propose a method of centralized system management to combine LTE-U and Wi-Fi through network function virtualization (NFV) interconnections. It may enable seamless transfer of resources between LTE-U and Wi-Fi using in-the-cloud control of distributed access points. *However*, only *conceptual* network architectures and mechanisms are presented [3]. The authors in [4] present a Software Defined Networking (SDN) architecture to support logically-centralized dynamic spectrum management involving multiple autonomous networks to improve spectrum utilization and facilitate co-existence. The basic design goal is to support the seamless communication and information dissemination required for coordination of heterogeneous networks. The system consists of two-tiered controllers are mainly responsible for the control plane. Global Controller (GC) acquires and processes global network state information (radio coverage maps, coordination algorithms, policy and network evaluation matrices, etc.) and controls the flow of information between RCs and databases based on authentication and other regulatory policies. Regional Controllers (RCs) acquire local visibility needed for radio resource allocation at wireless devices: device location, frequency band, duty cycle, power level, and data rate, etc. Joint power control and time division channel access optimizations are proposed. Analytical results in [4] demonstrate that, *with full buffer traffic assumption*, centralized optimization approaches can provide fair access to the spectrumfor LTE-U and Wi-Fi networks.

An experimental evaluation of U-LTE interference effects on Wi-Fi performance under various network conditions along with some suggestions for better coexistence of U-LTE and Wi-Fi networks are presented in [18]. Various system parameters (bandwidth, center frequency, etc.) are swept to identify the most significant ones that determine the levels of LTE interference introduced to Wi-Fi carrier sense and performance. The results indicate that Wi-Fi throughput can be heavily degraded by LAA-LTE transmissions with 3/5/10 MHz bandwidth (especially 3/5 MHz). Besides, LAA-LTE transmissions can have small impact on Wi-Fi throughput when using a 1.4 MHz channel with center frequencies located on the guard bands or the center frequencies of Wi-Fi channels. However, the authors in [18] do not clearly define what LAA-LTE really mean in their work. It seems to be that they simply perform experiments with conventional LTE transceivers of varying power spectral densities and do not incorporate any coexistence mechanism into the LTE system.

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Chapter 6
Network-aware Adaptive Listen Before Talk Co-existence Mechanism

Abstract In the absence of coordination between radio access technologies (RATs), and with the goal of deploying unlicensed LTE without requiring changes to the Wi-Fi MAC layer, it falls to the LTE base stations to ensure fair coexistence. The multiple access method used in Wi-Fi is designed for fair sharing of the channel with devices operating towards the same goal. Following this paradigm, if LAA-LTE is not carefully designed to ensure fairness, can easily lead to Wi-Fi stations being barred from the channel. The greatest gains in fair coexistence are achieved when LAA-LTE behaves in as Wi-Fi like a manner as possible, however, this may not allow LTE to make the best use of the channel. In this chapter, a network-aware adaptive LBT mechanism (NALT) is presented which passively monitors both channel conditions and usage activity to maximize transmission opportunities while respecting fair sharing of the channel, in a way that is transparent to incumbent Wi-Fi devices. Simulation results are presented demonstrating the effectiveness of NALT in providing proportional fair sharing among LAA-LTE and Wi-Fi devices.

6.1 Background and Theoretical Basis

As discussed in Chapter 4, Wi-Fi employs a fairly simple multiple access strategy which can be easily overwhelmed if competing devices are not also designed for fair coexistence. The Wi-Fi MAC protocol employs listen-before-talk (LBT) and is based on a probabilistic model of channel access which minimizes collisions through the use of random backoff to limit the probability that two stations will transmit at the same time after the channel has become idle [3]. When a collision is inferred after a failed transmission, the set of possible backoff values grows exponentially to further reduce the probability of subsequent transmission failures. While the ETSI LBT standard, on which the recommended mechanism for LAA-LTE is based, is also probabilistic it employs a random backoff from a fixed set of possible backoff values [1], which does not attempt to reduce the probability of collision on repeated failed transmission. Thus, if a collision occurs, Wi-Fi will react by reducing its probability of gaining access to the channel, however a device modeled on the ETIS LBT mechanism will maintain the same probability of channel access. Additionally, LAA-LTE used for supplemental downlink or carrier aggregation is expected to align subframes with the licensed band, and such subframes have a duration of 1ms, which can be significantly longer than the average channel occupancy time of a Wi-Fi station. Combined, these two factors will lead to LAA-LTE stations both winning the channel more frequently, and then occupying the channel for significantly longer than an average competing Wi-Fi station would, even if the number of channel accesses were equal. Since Wi-Fi stations may operate at any of several modulation and coding schemes, it is also difficult to provide throughput fairness across a large number of Wi-Fi devices. However, airtime fairness can be achieved by leveraging the principles developed for the 802.11e Enhanced Distributed Channel Access (EDCA) function for service differentiation between traffic priorities in Wi-Fi.

In EDCA, Wi-Fi parameters such as contention window and inter-frame spacing are set up to provide quality of service differentiation and priority enforcement between varying types of traffic [3]. By changing these parameters, it is possible to impact the probability of channel access in a predictable way. By constantly managing these parameters in response to network activity, it is possible to maintain long run proportionally fair sharing between the two devices, traffic categories, or two classes of devices on competing networks.

Specifically, the relationship between minimum contention window size for two traffic classes, and their relative proportion of channel access has been found to be

$$\frac{\theta_i}{\theta_j} \approx \frac{CW^j_{min}}{CW^i_{min}} \tag{6.1}$$

where, $\frac{\theta_i}{\theta_j}$ is the ratio of channel access i sees relative to class j, and CW^x_{min} is the minimum contention window used by class x [2][5].

To use Eq. 6.1 to balance airtime between LAA-LTE and Wi-Fi, it is necessary to treat all Wi-Fi stations and all LAA-LTE networks as traffic classes and account for the duration of channel access for each class. Between the two traffic classes, this duration will generally be longer for LAA-LTE than for Wi-Fi due to the synchronization between licensed and unlicensed transmissions and the range of data rates available for Wi-Fi stations over clean channels, and as such LAA-LTE will receive fewer channel accesses in order to achieve the same airtime allocation. For example, if a Wi-Fi channel access takes half the time of a LAA-LTE channel access, in the case of a single LAA-LTE station competing with a single Wi-Fi station, the Wi-Fi station should receive twice as many transmission opportunities as the LAA-LTE station in order to achieve equal airtime. If there were two Wi-Fi stations, in order for each to have equal airtime, the LAA-LTE station should receive one quarter as many transmission opportunities as the combined Wi-Fi stations, so that proportionally each of the three stations would receive equal airtime on average. Adding a proportionality constant ρ, which is the ratio of LAA-LTE transmission time to average Wi-Fi transmission time, and solving Eq. 6.1 for the required CW_{min} values to realize equal airtime,

$$CW_{min}^{LTE} = \rho \cdot CW_{min}^{WiFi} \tag{6.2}$$

Since we seek equal airtime, we require that $\rho \cdot \frac{\theta_{WiFi}}{\theta_{LTE}} = 1$, or in other words, the Wi-Fi traffic class receives ρ times as many channel accesses as the LAA-LTE class.

The relation in Eq. 6.2 provides an approximation of the optimal CW_{min}^{LTE} to provide airtime fairness, however, the Wi-Fi traffic class may be made up of stations which are using different transmission rates and CW_{min} values. In order to estimate the CW_{min}^{WiFi} to use in Eq. 6.2, and adjust to changing network topologies, an estimate of the average current Wi-Fi contention window being used is required. Such an estimate can be obtained from the relationship between contention window and the probability of collision. For Wi-Fi networks, the probability of collision, p, in a saturated network is given by,

$$p = 1 - (1 - 1/CW_{avg})^{n-1} \tag{6.3}$$

where CW_{avg} is the average contention window currently being employed in the network, and n is the number of competing stations [4]. Rearranging and solving for CW_{avg} yields,

$$CW_{avg} = \frac{1}{1 - e^{ln(1-p)/(n-1)}} \tag{6.4}$$

Eq. 6.4 provides the average contention window size for all stations, both LAA-LTE and Wi-Fi, i.e. $n = n_{WiFi} + n_{LTE}$. In order to consider only the average contention window size for the Wi-Fi stations, and noting the optimal CW_{min}^{LTE} to CW_{min}^{WiFi} ratio, we can estimate CW_{min}^{WiFi} as

$$CW_{avg}^{WiFi} = CW_{avg} \left(\frac{n_{WiFi} + n_{LTE}}{n_{WiFi} + \rho \cdot n_{LTE}} \right) \tag{6.5}$$

then combining Eq. 6.2 through Eq. 6.5, we set

$$CW^{LTE} = \rho \cdot CW_{avg}^{WiFi} = \frac{\rho}{1 - e^{ln(1-p)/(n_{WiFi}+n_{LTE}-1)}} \left(\frac{n_{WiFi} + n_{LTE}}{n_{WiFi} + \rho \cdot n_{LTE}} \right) \tag{6.6}$$

Adapting the contention window used in each LAA-LTE network according to Eq. 6.6 will provide proportional fair channel access across the two classes of devices in the long run. In order to make use of this relation, the LAA-LTE base stations must know, or be reasonably able to estimate, the probability of collision in the network, p, as well as the number and type of competing devices.

6.2 Proposed Mechanism

NALT is defined as a simple distributed coordination function to be implemented by LAA-LTE base stations, allowing several LAA-LTE networks to effectively and independently fairly share the channel with each other and incumbent Wi-Fi stations, without any changes being required in the Wi-Fi stations.

To make use of the relationships in the previous sections, the following assumptions are made:

- NALT-enabled base stations are able to:
  - Analyze traffic on the channel and determine the number of competing stations and their types
  - Determine average transmission durations either by decoding transmission headers, actively timing the transmissions, or some other suitable mechanism
- Successfully gaining access to the channel means that the transmission was successful, i.e. ignoring noise sources and the hidden terminal problem, which NALT does not attempt to address
- Failed LAA-LTE transmissions on unlicensed channels can be reported to the base station on control channels in the licensed spectrum
- Collisions experienced on the LAA-LTE network occur with approximately the same probability as collisions experienced by Wi-Fi stations

In order to use Eq. 6.6 in an implementable algorithm, the unknown probability of collision p and knowledge of the number of competing Wi-Fi stations and LAA-LTE networks is required. Since these values cannot be known beforehand, the number of competitors is learned over time and the required probability of collision is estimated in each NALT-enabled LAA-LTE network as the ratio of observed LAA-LTE collisions to the number of LAA-LTE channel uses, on a network by network basis. Noting that this is an empirical estimate of the true statistic, its reliability is inversely proportional to the number of samples and, although it improves over time, it must be considered highly suspect for a limited number of samples and be restricted to some reasonable range.

The relationship in Eq. 6.6 is exploited to achieve fair airtime allocation by tuning the CW_{min} values used by competing stations in each LAA-LTE network. Since it is desired to avoid any changes to Wi-Fi, and fairer coexistence can be achieved by designing a more "Wi-Fi-like" MAC layer for LAA-LTE, i.e. the contention window used by LAA-LTE must increase as the number of collisions increases. To facilitate fair airtime allocations across all competing devices, the contention window should follow Eq. 6.6. Based on the limitations of the estimates employed, and to ensure that the contention window stays within reasonable bounds, the maximum and minimum values for CW^{LTE} are chosen to match the range of possible values for Wi-Fi [3].

Combining these requirements, and the preceding equations and assumptions, at each time instance an LAA-LTE station will estimate the average Wi-Fi contention window as follows:

$$CW_{avg}^{WiFi} = CW_{min}^{WiFi}, \text{ if } \{\text{ \# of Wi-Fi Tx}\} > \rho \cdot \{\text{ \# of LAA-LTE Tx}\}$$
$$\text{Otherwise, update according to Eq. 6.5.} \qquad (6.7)$$

LAA-LTE will follow the same backoff procedure as Wi-Fi, and increase its contention window after a collision according to

$$CW^{LTE} = \ min\left[max\left(CW^{LTE} * 2, \rho \cdot CW_{avg}^{WiFi}\right), CW_{MAX}^{LTE}\right] \tag{6.8}$$

and decreasing its contention window after a successful transmission according to

$$CW^{LTE} = \ min\left[max\left(CW_{MIN}^{LTE}, \rho \cdot CW_{avg}^{WiFi}\right), CW_{MAX}^{LTE}\right] \tag{6.9}$$

These equations, in addition to channel usage statistics gathering function, are implemented in each of the competing LAA-LTE eNBs. This mechanism requires no explicit coordination between the LAA-LTE base stations, nor any changes to Wi-Fi stations. The operation of NALT is depicted in Fig. 6.1. The operation is di-

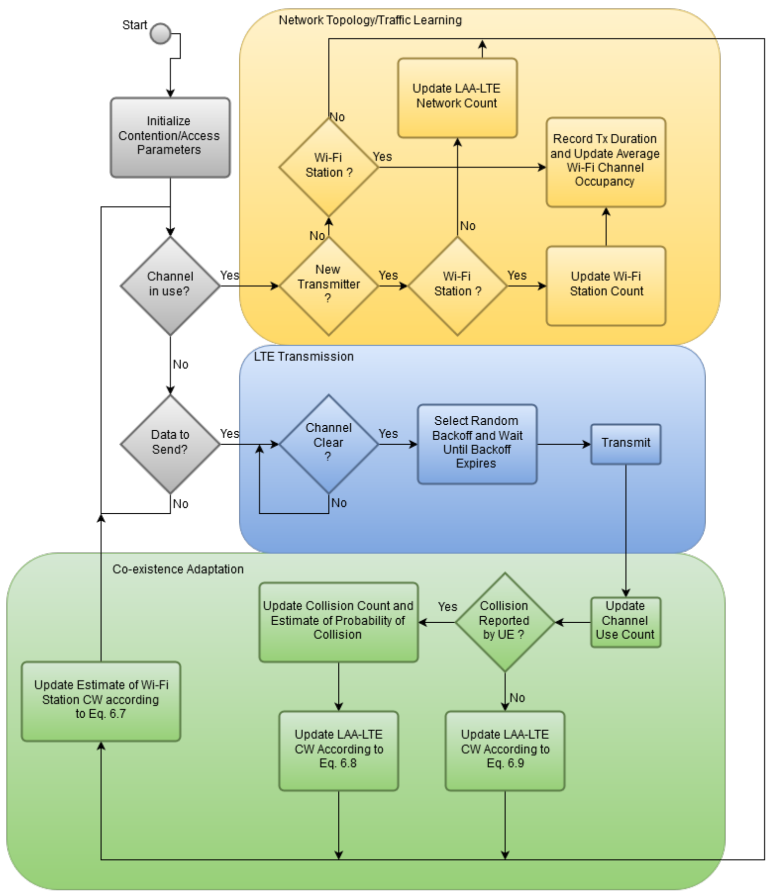

Fig. 6.1 Network aware adaptive listen before talk algorithm.

vided into three main functions: Learning (highlighted in yellow), where the NATL-enabled eNB learns about the other occupants of the network and their transmission profiles; Transmission (highlighted in blue), which follows a random back off interval; and Adaptation (highlighted in green), which uses the data gathered and employs exponential backoff to ensure fair coexistence

6.3 Performance Evaluation

To evaluate the performance of NALT, a high-level MATLAB simulation was developed in which the proportion of successful channel accesses achieved by each class of devices was tracked. Since NALT is an adaptive medium access strategy, the simulation looks only at the proportion of successful channel accesses, and assumes all attempted transmissions only fail if a collision occurs. That is, other interferences sources and problems such as hidden terminals, are ignored. The ETSI LBT mechanism was simulated as a benchmark against which to measure the effectiveness of NALT.

6.3.1 System Model

The system models a number of NALT-enabled LAA-LTE networks interacting with a varying number of Wi-Fi devices. LAA-LTE transmissions in the unlicensed bands are expected to be aligned with the LTE-A frames in the licensed spectrum, thus it can be assumed that LAA-LTE user equipment will be coordinated via licensed control channels, with scheduling done by the eNB so that there is coordinated channel accesses for both uplink and downlink traffic. The system model incorporates this by assuming the eNB will not over-schedule its own DL transmission, or two UE UL transmissions, in the same time-frequency slot, so that the only sources of collisions are from Wi-Fi stations and other LAA-LTE networks. Thus, each simulated LAA-LTE device in fact represents an independent network of LAA-LTE devices which are not required to contend with each other. Additionally, although the NALT-enabled eNB would be capable of analyzing traffic on the channel to determine the average Wi-Fi transmission parameters, such as bitrate and channel occupancy time, for simplicity, we assume that both LAA-LTE and Wi-Fi stations use the same modulation and coding scheme and channel bandwidth, resulting in a data rate of 135 Mbps. Wi-Fi stations are modeled after 802.11n [3]. Other than the adaptive contention window, the LAA-LTE channel occupancy and minimum time idle were modeled after ETSI LBE LBT and the proposed mechanisms for LAA-LTE [1]. The other pertinent simulation parameters are listed in Table 6.1.

Table 6.1 NALT Simulation Parameters

Parameter	Value
Number of competing Wi-Fi stations	1 – 15
Wi-Fi OFDM Symbol Duration (slot)	9 μs
DCF Interframe Spacing [1]	34 μs
Short Interframe Spacing [1]	16 μs
Wi-Fi Frame Size	1536 bytes
Wi-Fi Tx Duration [2](Frame Tx + SIFS +ACK)	198 μs
Number of independent LTE Networks	1, 5
LAA-LTE Channel Occupancy Time	1000 μs

[1] Defined inter-frame spacing per 802.11n operating in the 5 GHz band
[2] Based on header transmitted at lowest supported rate and remaining frame at specified bitrate

6.3.2 Simulation Results

NALT is a probabilistic coexistence mechanism, so to evaluate the fairness provided by NALT the average of numerous trials were considered. Network topologies of between 1 and 15 Wi-Fi stations contending with LAA-LTE networks were examined and the proportion of successful channel accesses for each class of devices, related to airtime by the class' transmission duration, was tracked across all trials.

Initially, NALT was tested with a single LAA-LTE network competing with between 1 and 15 Wi-Fi stations. The resulting proportion of airtime for each device when using NALT is shown in Fig. 6.2. In each configuration, fair sharing was

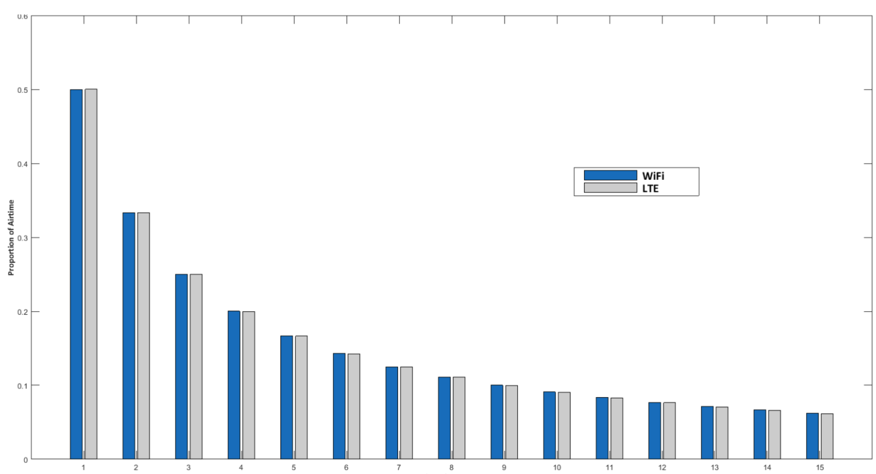

Fig. 6.2 Airtime allocations for each station with LAA-LTE using NALT.

achieved, with every member of each class receiving a proportional airtime allocation.

For comparison, the simulation was run with the same parameters as in Table 6.1, but with a fixed contention window size of 16, corresponding to the midpoint of possible values under ETSI LBE LBT [1]. The resulting airtime allocations, normalized to the number of devices, are shown in Fig. 6.3. As expected, LAA-LTE

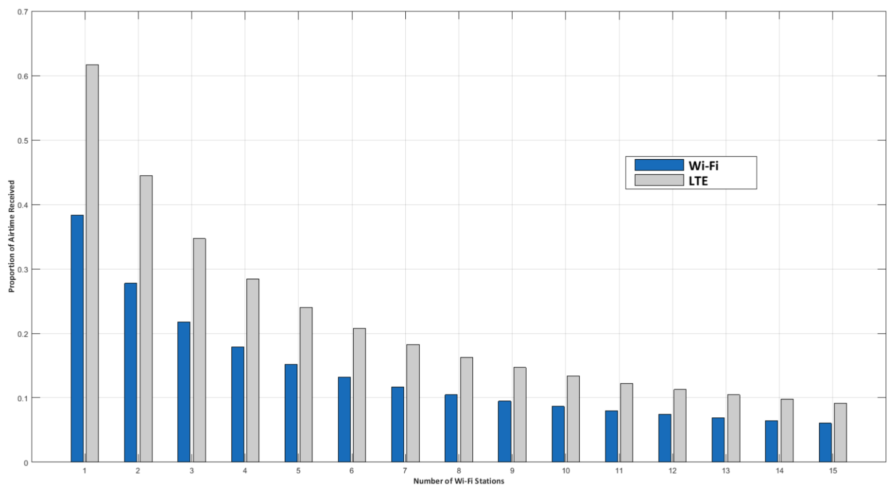

Fig. 6.3 Airtime allocations for each station with LAA-LTE using ETSI LBE LBT.

transmission receive a disproportionately high airtime allocation as a result of the static contention window providing an increasingly higher proportion of channel accesses, when compared to Wi-Fi, as collisions on the channel occur.

Since it is likely that LAA-LTE networks will be deployed alongside other competing LAA-LTE networks, the simulation was extended to evaluate the effectiveness of NALT under these conditions. The simulation was run with 5 independent NALT-enabled LAA-LTE networks competing against each other as well as Wi-Fi stations. The resulting proportion of airtime for each device when using NALT is shown in Fig. 6.4.

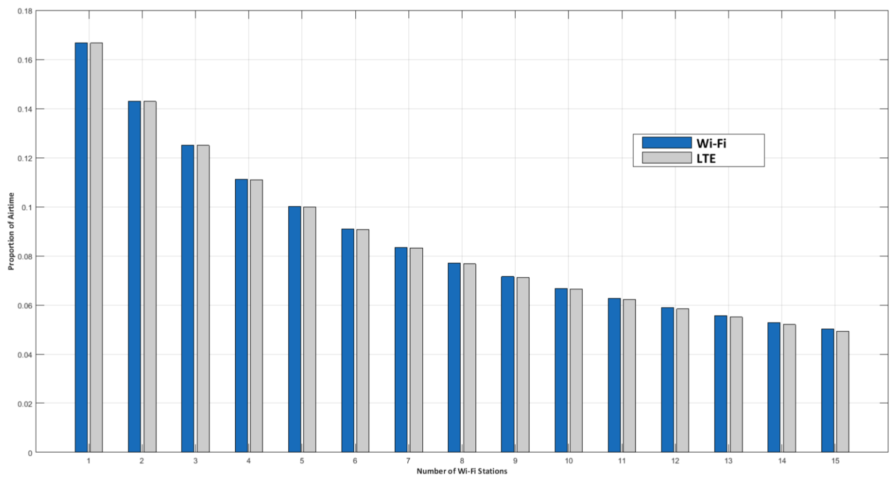

Fig. 6.4 Airtime allocations for each station with five LAA-LTE networks using NALT.

If it further conceivable that LAA-LTE networks will be deployed where there are either no competing Wi-Fi stations, or the level of interference between the RATs is negligible. Fig. 6.5, shows the resulting fair allocation of airtime for each device when NALT is used in a LAA-LTE only deployment.

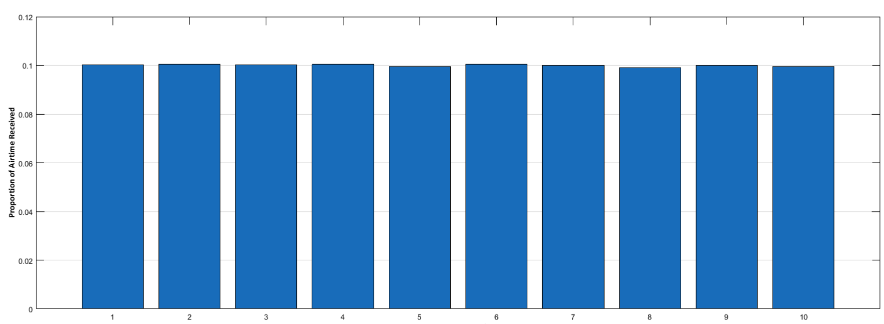

Fig. 6.5 Airtime allocations from LAA-LTE only channel contention when using NALT.

6.4 Discussion and Future Work

NALT requires no changes to Wi-Fi devices and in high-level simulations it shows promise in providing fair coexistence in several deployment scenarios. In each of cases examined, NALT provides approximately equal airtime to each station, regardless of type or how many competing stations exist.

As noted, several simplifying assumptions were made which may affect the results. It is reasonable that LAA-LTE would be able to analyze the channel and determine the number or competing Wi-Fi stations as well as their transmission profiles, from the Wi-Fi preamble and MAC header, however a learning period to gather sufficient data to make reasonable estimates of the averages may or may not be necessary. If necessary, it would negatively impact overall performance. The assumption was made that all Wi-Fi stations were using the same data rate, which should provide the same results as an average data rate, but the impact on individual Wi-Fi stations utilizing the channel access opportunities in a multi-rate environment have not explored. It is desirable to implement the learning functions depicted in Fig. 6.1 and determine if the processing overhead could reasonably meet the timing constraints. Further, the impacts of hidden terminals, non-saturated stations, and lossy channels, were not explored, and may have interesting implications.

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Chapter 7
Open Questions and Potential Research Directions

Abstract Since U-LTE is a nascent LTE technology, the coexistence of this technology and Wi-Fi technology is still one of the most active research/working areas. Based on observations obtained from the survey and our study presented in chapters 5 and 6, this chapter attempts to highlight a number of open research questions and issues. Potential solutions to those issues are also identified. Most of them suggest the cooperation of LTE and Wi-Fi so that they could have a better understanding of each other when operating in the same area using the same radio frequency band. This understanding is used to have more vigilant actions that help to avoid aggressive channel access that could corrupt on-going transmissions and to design relevant protocols for a fair spectrum sharing.

7.1 LTE-U-aware CSMA-CA and LTE-U with LBT

LTE-U mostly assumes neither coordination nor synchronization between itself and Wi-Fi system. LTE-U's "on" and "off" cycles are only known by LTE devices themselves. Vice versa, Wi-Fi control and management frames are known by Wi-Fi devices themselves. This independent operation results in various transmission issues. *First*, in cases when LTE-U's "on" duration is not sufficiently long while Wi-Fi exponential back-off procedure generates long back-off intervals, Wi-Fi STAs may not have a chance to utilize the channel when LTE-U is not active. Such a conservative channel access principle wastes the radio resources and results in Wi-Fi's poor performance. *Second*, an unfinished Wi-Fi frame transmission that was started during the LTE-U's "off" duration might be corrupted by the LTE frames once LTE switches to "on" cycle. Fig. **??** visualizes two examples.

To mitigate these issues, inter-RAT communications between LTE and Wi-Fi could be employed to inform Wi-Fi system the LTE-U's "on" and "off" cycles. Wi-Fi system then can adapt its MAC protocol (i) to occupy the channel more opportunistically during LTE-U's "off" period (but not to increase the collision probability among Wi-Fi STAs) and (ii) to schedule frame transmissions in such a way that

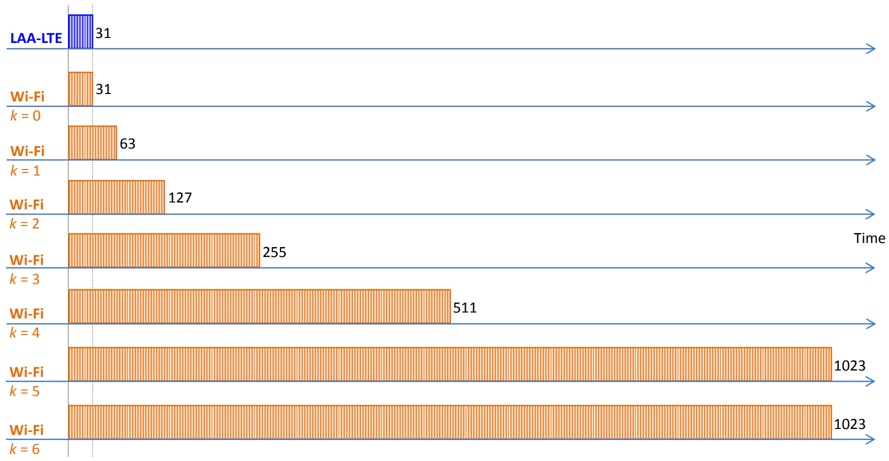

Fig. 7.1 Wi-Fi exponential back-off competes for the channel more conservatively, compared to LAA-LTE.

they will not step on the next LTE-U's "on" cycle. Besides, frame collisions could be mitigated by incorporating some form of LBT/CCA into LTE-U. Specifically, CCA should be performed before activating LTE-U's "on" cycle. If the channel is detected busy, LTE-U's "on" cycle is deferred.

7.2 LAA-LTE with Exponential Back-off

While LBT, as a general approach, can be a good basis for coexistence of LAA-LTE and Wi-Fi, the LBE LBT in its current form (as introduced by European regulations) which is adopted for LAA-LTE is still unfair to Wi-Fi. LAA-LTE nodes impact Wi-Fi nodes in terms collision rate and probability of successful channel access more than similar Wi-Fi nodes on the same carrier. This is not compliant with the objectives as listed in 3GPP LAA LTE Study Item [1]: "LAA should not impact Wi-Fi services (data, video and voice services) more than an additional Wi-Fi network on the same carrier; these metrics could include throughput, latency, jitter, etc.". One major and obvious reason is, that while Wi-Fi applies exponential back-off rule, LAA-LTE simply applies fixed-size back-off rule. In order to elaborate this observation, consider a typical example follows. It is assumed that $W^{\mathrm{LAA-LTE}} = 31$, $W_{\min}^{Wi-Fi} = 31$, and $W_{\max}^{\mathrm{Wi-Fi}} = 1023$. Then, as described in subsection **??**, LTE-U always back-offs with contention window $W^{\mathrm{LAA-LTE}} = 31$. For Wi-Fi, as described in subsection **??**, it back-offs with contention window $W(0) = 31$ for the initial transmission attempt. However, if collisions occur, it progressibly doubles its contention windows to reduce the probability of a subsequent collision: $W(1) = 63$ (the first re-transmission attempt), $W(2) = 127$ (the second re-transmission attempt), $W(3) = 255$ (the third

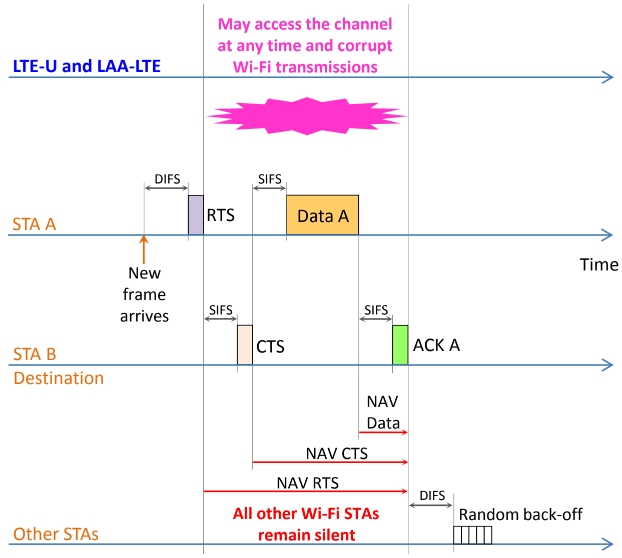

Fig. 7.2 U-LTE may cause channel collisions with Wi-Fi at any time.

re-transmission attempt), $W(4) = 511$, $W(5) = 1023$, $W(6) = 1023$, and etc. Fig. 7.1 compares contention windows of LAA-LTE and Wi-Fi.

At present, there is no existing work that studies how an exponential back-off can help to improve the fairness between LAA-LTE and Wi-Fi. It is important to note that, compared to Wi-Fi, designing an exponential back-off protocol for LAA-LTE that employs OFDMA-based MAC layer might not be straightforward. In details, Wi-Fi adopts OFDM in the PHY layer and allows only one user to occupy the whole channel at one time. Its contention window is scaled respectively to the outcome (success or failure) of a frame transmission to given user. For LTE, OFDMA devides the system bandwidth into a series of Physical Resource Blocks (PRBs). Each PRB is composed of 12 OFDM subcarriers. Different PRBs can be allocated to different users in a given subframe and multiple users can occupy the channel at the same time. This implies that the rule governing the adaptation of contention window of LAA-LTE is required to be more sophisticated than that of Wi-Fi. In adddition to back-off procedure design, there are two other interesting questions: (i) how exponential back-off could (negatively) affect the performance and efficiency of LAA-LTE; and (ii) what could be appropriate values for LAA-LTE's operation parameters.

A side note is that, according to [2], 3GPP is now having a working agreement to use a LBT mechanism with exponential back-off. At this moment, LAA-LTE standard is not yet finalized by 3GPP and no information is publicly available. ETSI is also devising a set of minimum "fairness" requirements as part of EN 301 893 standard for "5 GHz high performance wireless access systems" in Europe (scheduled to be completed by the end of 2015).

7.3 Wi-Fi-aware LTE-U and LAA-LTE

As addressed in subsection **??**, RTS/CTS and NAV are effective and important mechanisms employed by the IEEE 802.11 CSMA-CA protocol to reserve the channel and avoid collisions. However, since U-LTE and Wi-Fi are not collaborating, Wi-Fi's NAV information carried by RTS, CTS, and data frames is not known by U-LTE devices. In other words, while Wi-Fi STAs defer their transmissions until ongoing frame exchanges are done, U-LTE devices do not respect Wi-Fi reservation and may start their transmissions at any time, as shown in Fig. 7.2. This may result in a high rate of channel collisions and corrupt both Wi-Fi and U-LTE transmissions. As visualized Fig. 7.2, an U-LTE transmission could accidentally destroy the whole Wi-Fi transmission session composing of RTS, CTS, data, and ACK frames (at the same time, U-LTE frame is also corrupted by Wi-Fi frames). Mechanisms that provide U-LTE with information on Wi-Fi activities to avoid such transmission corruptions could be therefore very beneficial.

7.4 Collaborative U-LTE and Wi-Fi

As metioned so far, almost all existing works dealing with U-LTE and Wi-Fi coexistence assume non-cooperative approach which does not required any information exchange between these two networks. LTE is simply additionally equipped with some mechanisms to friendly share the same channel with existing Wi-Fi networks. The authors in [3, 4] carry out preliminiary investigations towards this direction. However, only conceptual network archirectures and mechanisms and are presented. Collaborative approaches is quite interesting since it may result in better coexistence by sharing information between different radio access technologies (RATs) and enabling global/local optimizations. Some benefits of such approaches has been outlined in subsections 7.1 and 7.3. This approach, on the other hand, may be challenging since it needs additional network infrastructure/entities and set of protocols for inter-RAT communications. They are required for discovery of neighboring radio systems, selecting operating channels/transmission power, etc., for radio systems, and providing some level of fair and/or efficient use of available channels.

7.5 Inter-operator U-LTE Coexistence

In addition to coexistence between U-LTE and Wi-Fi, coexistence among U-LTE systems deployed by different operators running in a shared band is also a critical concern. This concern is more pronounced in high density urban areas with a very large number of devices/system running different protocols. Work in [5] presents a preliminary study on this and the results show that LBT mechanisms can increase the network throughput since collisions can be mitigated. Work in [6] investigates the interactions between different LBT mechanisms when they are deployed in proximity of each other. Inter-operator U-LTE coexistence is especially important when multiple operators employ similar MAC protocols based on fixed contention windows that could be accidentally synchronized in channel access attemps and result in consecutive collisions. As a result, exponential back-off rules, inter-RAT communications, and collaborative inteference management protocols could be promising approaches.

7.6 Other Considerations on Coexistence

Operations, system performance, and coexistence of radio networks highly depend on deployment scenarios. This is the main reason why a number of existing work supports U-LTE technology while the others call for further investigations and developments before deploying this technology. Also, different coexistence mechanisms are recommended for different scenarios. For a complete understanding of U-LTE impacts on Wi-Fi, a wide range of node and load densities should be considered. Besides, performance of voice and video-related applications should be evaluated. For most of existing work, only throughput and channel access probability of Wi-Fi networks are evaluated. However, an insight to latency and jitter performance could be desirable. Besides, it would be interesting to take into account the operations and performance of recent Wi-Fi variants when coexisting with U-LTE.

7.7 Emerging Wi-Fi Technologies and U-LTE

With the currrent trends of future RANs including network densification, heterogeneous network (HetNet), Internet of Things (IoT), the explosion of various applications (smart homes/cities, smart transportations, automomous vehicles, etc.), and etc., numberous technological evolutions have been expecting. For time-sensitive applications (e.g., sensor and control for critical infrastructures and automomous vehicles), data communications is required to be extremely reliable, robust, energy-efficient while being able to guaratee latencies in millisecond or sub-millisecond scale. These requirements urge for the developments of collaborative, well-controlled, and synchronous Wi-Fi MAC protocols (instead of distributed, random-access-based, and asynchronous IEEE 802.11 CSMA/CA that have been widely deployed). To this end, PCF and HCCA operation schemes (specified in IEEE 802.11/802.11e standards but not widely used) should be re-visited.

Despite the fact that PCF and HCCA allocate the channel to STAs in a well-controlled manner, their performance (in terms of throughput, latency, and power consumption) is still questionable due to their complexities and signaling overheads, specially in highly dense networks with a vast number of battery-operated devices exchanging short and bursty messages. Furthermore, it is compelling to understand their interaction and coexistence with U-LTE. While CFP and CAP are desired for time-sensitive applications, the aggressive operation of U-LTE in the same frequency band may render them impossible. Finally, protocols and enabling technologies for collaborations and synchronizations between PCF-/HCCA-based Wi-Fi and U-LTE appear to be essential and thus could be very interesting working areas.

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