AMERICAN UNIVERSITY OF BEIRUT

A DESIGN AND IMPLEMENTATION FOR AN LTE-WIFI CARRIER AGGREGATION SCHEME FOR FUTURE 5G MULTI-RAT AND SMALL-CELL ENVIRONMENTS

by

RASHA MOHAMMAD ALKHANSA

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AN ABSTRACT OF THE THESIS OF

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Title: A Design and Implementation for an LTE-WiFi Carrier Aggregation Scheme for Future 5G Multi-RAT and Small-cell Environments

Multi-Radio Access Technology (multi–RAT) carrier aggregation (CA), also known as multi-Flow CA, is an envisioned future technique that allows channels from different RATs to be aggregated and allocated to the end user. This technique allows for an efficient utilization of the fragmented and crowded spectrum, as well as for coordination and load balancing between the different RATs. The concept of CA was introduced in 3GPP's Release 10 for the Long Term Evolution (LTE) systems, and the feasibility of LTE-LTE CA scenarios has been studied. In this work, we present a study of the feasibility of LTE-WiFi CA. We assume a CA mode where the LTE system borrows from the WiFi spectrum. Our study shows that this CA mode is compatible with the LTE-Advanced physical layer specifications, and is therefore theoretically achievable. This led us to propose a system design for achieving the LTE-WiFi CA mode, and to implement this design within the confines of the LTE and WiFi standards; that is, without introducing changes to these standards. Our scheme is suitable for small cell environments in which the LTE small base station and the WiFi Access Point are either collocated or are in close proximity, and provide cellular and WLAN access to a group of mobile users within a small geographical area. In the design, the LTE base station plays the role of a WiFi station that contends for accessing spectrum or requests access from the AP, and then aggregates this borrowed spectrum with the available LTE spectrum, thus increasing the cellular network throughput. We implemented the design using the OMNET++ network simulator, and generated results that highlight the performance of our scheme under different scenarios. The results show that about 40-50% of the LTE scheduling intervals can benefit from our scheme in using the WiFi channels under typical WiFi load scenarios. Given this and the underutilized WiFi channels in certain scenarios, our scheme efficiently achieves higher bandwidths and thus higher data rates using cognitive-radio-like logic that does not require changes to the LTE and WiFi standards. The significance of our work is that it provides throughput gains while using a simple distributed and fair approach. In particular, this work belongs to the framework of what is referred to as "LTE-Unlicensed", and it provides a fair solution for the coexistence problems that occur when licensed technologies use the unlicensed bands.

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LIST OF ABBREVIATIONS

3GPP: Third Generation Partnership Project
AC: Access Category
ACK: Acknowledgement
AIFS: Arbitration Inter-Frame Space
AMC: Adaptive Modulation and Coding
AP: Access Point
ARQ: Automatic Repeat Queuing
BSS: Basic Service Set
CA: Carrier Aggregation
CAP: Controlled Access Phase
CC: Carrier Component
CF: Contention Free
CFP: Contention Free Period
CM: Cubic Metric
CP: Cyclic Prefix
CQI: Channel Quality Information
CS: Carrier Sense
CSI: Channel State Information
CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance
CTS: Clear To Send
D2D: Device-to-Device
DCF: Distributed Coordination Function
DCI: Downlink Control Information
DFT: Discrete Fourier Transform
DIFS: DCF Inter-Frame Space
DLS: Direct Link Setup
DRACH: Downlink Random Access Channel
EDCA: Enhanced Distributed Channel Access
EDCA: Enhanced Distributed Channel Access Function
EIFS: Extended Inter-Frame Space
ESS: Extended Service Set
eNB: eNodeB
EPC: Evolved Packet Core
EPS: Evolved Packet System
E-UTRAN: Evolved – Universal Terrestrial Radio Access Network
FME: First Maximum Expansion
HCCA: HCF Controlled Channel Access
IBSS: Independent BSS
IFFT: Inverse Fast Fourier Transform
IMS: IP Multimedia Subsystem

IP: Internet Protocol
ISI: Inter-Symbol Interference
ISM: Industrial, Scientific, and Medical
ITU: International Telecommunications Union
LTE: Long Term Evolution
LTE-A: LTE – Advanced
LTE-U: LTE Unlicensed
MAC: Media Access Control
MBSS: Mesh BSS
MIB (in LTE context): Master Information Block
MIB (in WiFi context): Management Information Base
MIMO: Multiple Input Multiple Output
MLME: MAC Layer Management Entity
MSDU: Mac SDU
NAV: Network Allocation Vector
OFDM: Orthogonal Frequency Division Multiplexing
PAPR: Peak-to-Average Power Ratio
PBCH: Physical Broadcast Channel
PCF: Point Coordination Function
PCFICH: Physical Control Format Indicator CHannel
PDCCH: Physical Download Control CHannel
PDN: Packet Data Network
PDSCH: Physical Downlink Shared Channel
PF: Proportional Fairness
PHICH: Physical Hybrid ARQ Indicator CHannel
PHY: PHYsical
PIFS: PCF Inter-Frame Space
PLCP: Physical Layer Convergence Procedure
PLME: Physical Layer Management Entity
PMD: Physical Medium Dependent
PUCCH: Physical Uplink Control CHannel
PURACH: Physical Uplink Random Access CHannel
PUSCH: Physical Uplink Shared CHannel
QoS: Quality of Service
RAT: Radio Access Technology
RB: Resource Block
RE: Resource Element
RF: Radio Frequency
RIFS: Reduced Inter-Frame Space
RME: Recursive Maximum Expansion
RS: Reference Signal
RSN: Robust Security Network
RTS: Request to Send
SAP: Service Access Point
SC-FDMA: Single Carrier – Frequency Division Multiple Access

SDU: Service Data Unit
SIFS: Short Inter-Frame Space
SME: Station Management Entity
STA: STAtion
TBTT: Target Beacon transmission Time
TS: Traffic Stream
TSPEC: Traffic SPECifications
TTI: Transmission Time Interval
TU: Time Unit = 1024 μs
TXOP: Transmission OPportunity
UE: User Equipment
UP: User Priority
USRP: Universal Software Radio Peripheral
WiFi: Wireless Fidelity

CHAPTER I
INTRODUCTION

The Third Generation Partnership Project (3GPP) has been working on developing and standardizing techniques for LTE-Advanced (LTE- A) systems, which represent the evolution of LTE (Long Term Evolution) wireless communications systems that aims at meeting the International Telecommunications Union (ITU) performance requirements, such as higher peak rates and wider bandwidth. Carrier aggregation (CA) is one of the main techniques specified by 3GPP to achieve these performance requirements. It aims at providing wider bandwidth in the uplink and the downlink by aggregating multiple (LTE) component carriers (CCs), thus achieving a wider bandwidth, while maintaining backward compatibility with the existing LTE standard. Aggregation of up-to 5 20-MHz CCs are currently supported in the 3GPP specifications, therefore allowing for a 100 MHz achievable bandwidth for LTE- A users.

The carrier aggregation technique makes it easy to overcome the legacy issues and backward compatibility considerations for the existing LTE Release 8/9 deployments by aggregating the LTE Release 8/9 CCs. The crowded spectrum, however, renders it practically difficult to allocate a non-fragmented 100 MHz band for LTE-A users. Hence, non-contiguous CA is also supported, where CCs can be of different bandwidths and from the same or different bands. Muti-RATs (Radio Access Technologies) CA is another active research area, where the aggregation of CCs from bands belonging to different RATs is made possible. It is envisioned that in future LTE releases, CA will occur between different

3GPP and non-3GPP technologies such as WiFi, thus allowing for a more efficient utilization of the available spectrum and for load balancing made possible through coordination between different RATs.

It is worth mentioning that a Multi-RAT scheme is also known as a Multi-flow scheme, which is a concept employed for aggregating data flows of different RATs. A typical multi-flow scenario is when a device with multiple available interfaces maintains simultaneous connections and communication flows through different RATs. Although our scheme is not properly aggregating different data flows, it does use borrowed spectrum from WiFi, so it can be considered as multi-flow. However, we emphasize the fact that the aggregated spectrum is managed by the LTE-A technology for resource allocation, scheduling, and transmission. In this context, our scheme falls within the framework of what is referred to as LTE-Unlicensed (LTE-U), which is a very recent LTE research area. LTE-U concerns the extension of the LTE operation into the unlicensed spectrum in order to offload at least part of the exponentially growing mobile data traffic in the scarce and costly licensed spectrum. Currently two operating modes for LTE-U are under discussion: In the first mode, unlicensed spectrum is aggregated with the existing licensed channels, while in the second mode, the unlicensed spectrum acts as the only carrier for LTE-U where both data and control channels resides. As mentioned earlier, our scheme operates in the first mode as it aggregates the WiFi and the LTE spectrum, and regards the WiFi spectrum as an added carrier to the LTE system.

While LTE-U promises an estimated 2x to 5x higher throughput and spectral efficiency than WiFi [add reference to LTE-U conference], it also introduces coexistence challenges. The uncoordinated LTE and WiFi networks might experience interference when they operate on the same frequencies. On the other hand, fairness concerns are raised when LTE and WiFi use the same unlicensed spectrum. Particularly, the LTE traffic channels are designed to continuously transmit with minimum time gap even in the absence of data traffic, under the assumption that only one operator has control over the spectrum. WiFi, on the other hand is designed to coexist with other technologies through channel sensing and random backoff and through defined inter-frame spaces. Therefore, when operating on the same frequencies as those used by the LTE system, the WiFi STAs will have very little chance to access the medium.

In this work, we propose and evaluate an LTE-WiFi CA scheme, in which the LTE access point (eNodeB) behaves as a QoS-WiFi station (STA) to access the WiFi channels and aggregate them with the LTE channels. In our scheme, both performance and fairness are taken into account by utilizing the QoS facility of the WiFi standard which, on one hand, provides QoS guarantees, and on the other hand, imposes limits on the granted medium time based on traffic loads and admission capacity.

The remaining of this report is organized as follows: Chapter II describes the technologies involved in our design; namely LTE, LTE-A, and WiFi, in terms of their system design and specifications. Chapter III introduces the problem of LTE-WiFi CA in terms of feasibility considerations and research challenges. Chapter IV summarizes similar works, while Chapter V presents our CA scheme design. Chapter VI presents our implementation, and Chapter VII presents and analyzes the simulation results. Finally Chapter VIII concludes this thesis.

CHAPTER II

THE INVOLVED TECHNOLOGIES

As mentioned earlier, our work is mainly targeted to achieve higher throughput in LTE-A, and our approach is to extend the LTE operation into the unlicensed spectrum used by WiFi. Hence, our work involved an in-depth study of the specifications of the LTE and WiFi standards. In this section, we present a summary of these specifications, where we include all the details needed to understand our design. Particularly, in section A we present the LTE specifications; in B we describe LTE-A and the carrier aggregation technique; and finally in section C, we present the WiFi specifications.

A. LTE

In this section, we summarize the main components of the LTE network architecture. We then present the MAC and Physical layer specifications.

1. LTE System Architecture

The LTE system is designed to support packet switched services. It provides connectivity between a User Equipment (UE) and a Packet Data Network (PDN) with mobility support through access points (base stations) known as eNodeBs.

LTE, also known as the Evolved Packet System (EPS), includes the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the EPC (Evolved Packet

Core). The EPS uses bearers to route IP traffic from the PDN to the UE, where a bearer is an IP packet flow with a defined QoS, which is set up by the E-UTRAN and the EPC. LTE supports voice services over IP Multimedia Subsystem (IMS) using VoIP. It also supports interworking with traditional Circuit Switched Support.

Each eNodeB can manage multiple cells and be connected to more than one EPC. Coordination between the network components is made available through standardized interfaces. The X2 interface for example connects neighboring eNodeBs and performs multiple functions, including interference coordination and load balancing.

For Further details on LTE network design and interfaces, the interested reader can refer to [29].

2. LTE MAC Layer Design

The MAC Layer design includes most of the intelligence of the LTE system. LTE MAC functions include buffering packets from upper layers, encapsulating MAC Service Data Units (SDUs) and vice versa, Adaptive Modulation and Coding (AMC), and scheduling. As far as our design is concerned, we focus on the scheduler function at the MAC Layer.

The eNodeB scheduler runs within the MAC layer of the eNodeB and it is run at the beginning of each 1ms subframe, also known as Transmission Time Interval (TTI). At the start of the TTI, time-frequency Resource Blocks (RBs) are allocated to the UEs, and the scheduling decision cannot be changed until the end of the TTI. This constraint is taken into consideration in our scheme, as it will be illustrated Chapter V.

Scheduling decisions are based on channel feedback from UEs through Channel Quality Information (CQI) that report the channel quality that UEs experience on the different RBs. RBs are then allocated in a way that optimizes throughput. There is no one standard scheduling algorithm for LTE systems, and it is left to the operators to implement their algorithms. Several scheduling algorithms exist in the literature; these include the channel-aware algorithms which primarily focuses on optimizing throughput, such as First Maximum Expansion (FME) [33] and Recursive Maximum Expansion (RME) [33]; the Proportionally Fair algorithms (PF) [34] [35] which take fairness into account at the cost of decreased throughput; and the QoS-Aware algorithms [36] which account as well to QoS requirements. For our design, we are not concerned about the scheduling algorithm, but rather about the channel feedback computation and reporting. In particular, we aim at achieving carrier aggregation for an LTE-A UE, and for the sake of our study, we measure the throughput gain of one UE; thus, the way the RBs are distributed among multiple UEs is out of the scope of our study. On the other hand, we are concerned about the channel feedback model which depends on the frequency, because we are aggregating carrier frequencies that belong to different bands. Chapter V will present the channel model that we used.

Details on the LTE time-frequency grid and the structure of RBs are provided in the next subsection.

3. LTE PHY Layer Design

The following subsections present the PHY layer specifications of LTE; specifically, we present the access schemes and physical channels specifications.

a. <u>Access Schemes</u>

LTE adopts the Orthogonal Frequency Division Multiplexing (OFDM) and the Single Carrier-Frequency Division Multiple Access (SC-FDMA) schemes in the downlink and the uplink respectively. OFDM is a multicarrier transmission technique that divides the available transmission bandwidth into narrow subcarriers that are mutually orthogonal. Independent data streams can therefore be transmitted simultaneously on the different subcarriers, with theoretically no interference due to orthogonality. An OFDM transmitter uses an IFFT operation to generate the orthogonal subcarriers. A Cyclic Prefix (CP) is added to each set of simultaneous subcarriers in order to eliminate the remaining effect of Inter-Symbol Interference (ISI) caused by multipath propagation.

As mentioned above, the main advantage of OFDM lies in its robustness against Inter-Symbol Interference (ISI). This is due to the reduction in subcarrier bandwidth which reduces the frequency selectivity of the channel and consequently reduces ISI. Two other advantages of OFDM are its low complexity receivers and its flexible access technique as it allows for the transmission over variable number of different bandwidths. This flexibility is exploited in OFDMA (OFDM multiple Access), where multi-user scheduling is performed to assign the different subcarriers to different users. By contrast, the transmitter design of OFDM is more costly due to the high Peak to Average Power Ratio (PAPR) of the OFDM signal (due to the superposition of the symbol carriers in time domain) and which requires a highly linear RF power amplifier [3]. This limitation is not a concern in the downlink, due to the high capabilities of the transmitters at the eNodeB. In the uplink, however, the high PAPR of OFDM is difficult to tolerate for the transmitter of the mobile terminal, since it is necessary to compromise between the output power required for good outdoor coverage, the power consumption, and the cost of the power amplifier [3]. In order to overcome this limitation, LTE adopts SC-FDMA in the uplink.

SC-FDMA, also known as Discrete Fourier Transform-Spread- FDMA (DFT-S-FDMA), is a multiple access technique that has much in common with OFDM, but with the advantage of having a much lower PAPR. This is achieved by applying a DFT operation on the symbols before passing them with the null symbols as inputs to the IFFT block. The DFT insertion gives the SC-FDMA signal a single carrier-like nature. In particular, unlike OFDM, where the data symbols directly modulate each subcarrier independently, in SC-FDMA the signal modulated onto a given subcarrier is a linear combination of all the data symbols transmitted at the same time instant. Thus in each symbol period, all the transmitted subcarriers of an SC-FDMA signal carry a component of each modulated data symbol, giving the SC-FDMA signal its single-carrier nature. For further details on OFDM and SC-FDMA designs, the interested reader is referred to [3] and [4] respectively.

b. Downlink Physical Channels

In the downlink, 3GPP defines three Control channels, a shared data channel (PDSCH), a physical broadcast channel (PBCH), a random access channel (DRACH), and reference signals. The downlink control channels in LTE are transmitted in the control region which is located at the beginning of each sub-frame; namely, in the 1st 1, 2, or 3 OFDM symbols [5]. These three control channels are:

- PCFICH: the Physical Control Format Indicator Channel, which is an indicator showing the number of OFDM symbols used for control information.
- PDCCH: Physical Downlink Control Channel: carries the Downlink Control Information (DCI) (e.g. resource assignments, etc.) for a UE or group of UEs.
- PHICH: Physical Hybrid ARQ Indicator Channel: carries ACK/ NACK indicator to specify if the eNodeB has correctly received a transmission on the PUSCH (Physical Uplink Shared Channel)

The DSHCH on the other hand carries downlink data and can be used in a multiplexed mode for control information and random access (DRACH: Downlink Random Access Channel). The PBCH carries broadcast system information that are needed for UEs requiring to access the network. In particular, the PBCH carries the Master Information Block (MIB) messages which are mapped onto the central 72 subcarriers (6 RBs) of the available bandwidth.

Figure 1 illustrates how the mentioned logical channels are mapped onto the physical channels in a 20 MHz (100 RBs) bandwidth scenario. The dark grey regions are the control channels RBs, the blue (middle-horizontal) region carries the PBCH MIBs, while the yellow (lightest color) region carries the PDSCH data. Finally the green regions (vertical symbols at the end of slots 0 and 10) carry primary and secondary synchronization messages respectively (P-SS and S-SS) that are used for UE cell search and synchronization procedures. Note that in LTE, time is divided in 10-ms frames, each of which is divided into ten subframes, and each subframe is divided to two time slots. Finally, a slot is divided into 7 OFDM symbols (or 6 symbols in case of extended OFDM CP). Figure 1 shows the mappings for one frame, where these mappings are repeated for the following frames. In frequency domain, on the other hand, 100 frequency blocks are available within a 20 MHz bandwidth. Each frequency block is divided into 12 15kHz subcarriers and therefore occupies 180 kHz. A 180 KHz frequency block for a slot duration (0.5 ms) is termed as a resource block (RB). The details on the number of RBs available within each bandwidth are provided in Chapter IV.

Finally, within each RB, the reference signals are allocated to resource elements (REs) within a pattern that optimizes channel estimation and equalization. An RE is a 15kHz subcarrier x 1 OFDM symbol resource available for transmission. Each RB therefore includes 7x12 = 84 REs, in case of normal CP duration.

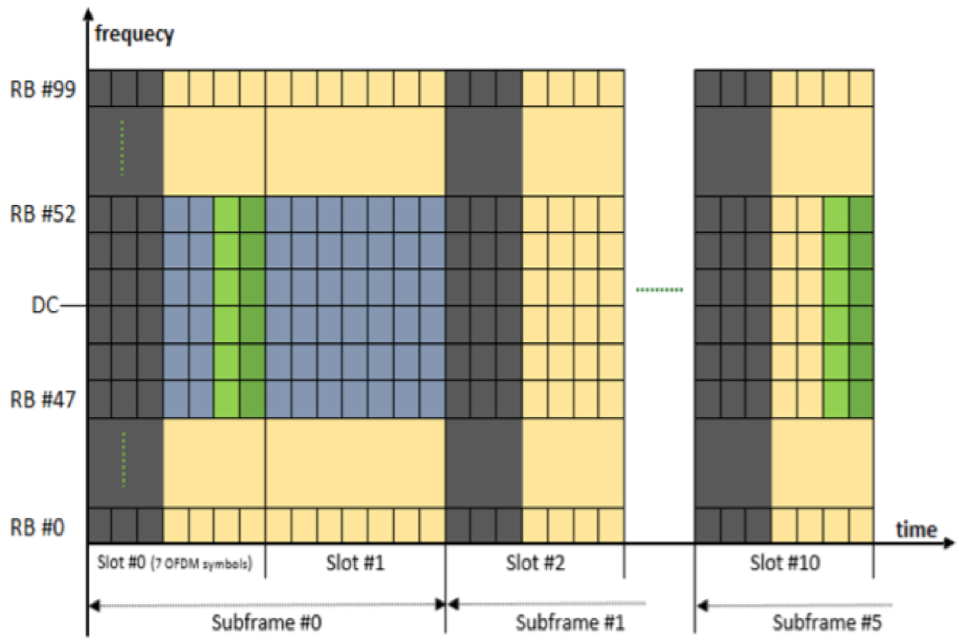

Figure 1. Downlink Logical-to-Physical channels mappings

c. Uplink Physical Channels

In the Uplink, 3GPP defines three physical channels and reference signals [16]:

- PUSCH: Physical Uplink Shared Channel: similar to the downlink channel but carries uplink user data.
- PUCCH: Physical Uplink Control channel: carries uplink control information (including channel state information). This channel is located at the edges of the band.
- PURACH: Physical Uplink Random Access Channel: for uplink random access. This channel is multiplexed with PUSCH.

The reference signals in the uplink are distributed among the REs in similar patterns as those in the downlink, and they are meant to measure the channel response on the different frequencies. This in turn is used by the eNodeBs for scheduling purposes by favoring UEs with the best channel conditions at the given frequencies.

B. LTE – Advanced

LTE Releases 8 and 9 satisfy to a large extent the ITU-R requirements [14]. LTE-A enhances LTE to fully satisfy these requirements and even exceed them in some aspects [21]. Carrier Aggregation (CA) is one of the main features of LTE-A [13]. The following subsections will present the concept of CA, its modes, and deployment scenarios. For information on other advanced techniques that were introduced in LTE-A such as Device-to-Device (D2D) and Multiple Input Multiple Output (MIMO) techniques, the interested reader is referred to [28], which summarizes these techniques and surveys the research challenges for LTE-A.

1. Carrier Aggregation in LTE-A

a. <u>Concepts and Techniques</u>

CA aims at achieving higher peak data rates and obtaining up to 100 MHz bandwidth for LTE-A users, while maintaining backward compatibility with the existing up to 20 MHz bandwidth for LTE users. Moreover, CA achieves better coverage for medium data rates by allowing the use of lower orders of modulation and lower code rates, which leads to a reduction in the required link budget, power consumption, and interference.

Carrier aggregation is the process of grouping multiple LTE component carriers (CCs) to allow LTE-Advanced devices to use them as one carrier to achieve higher bandwidth. For example, five LTE 20 MHz CCs can be grouped as one 100 MHz CC that can be used by an LTE-Advanced device. These grouped carriers can still be viewed as separate carriers by the LTE devices, thus achieving the compatibility requirement. As shown in Figures 2 through 4, CA can be achieved in a contiguous mode, non-contiguous single-band mode, and non-contiguous multiple bands mode. As the names indicate, in the contiguous mode, the aggregated CCs need to be adjacent in the frequency domain, while in the non-contiguous mode, they can be non-adjacent; additionally, they might belong to the same frequency band or to different bands.

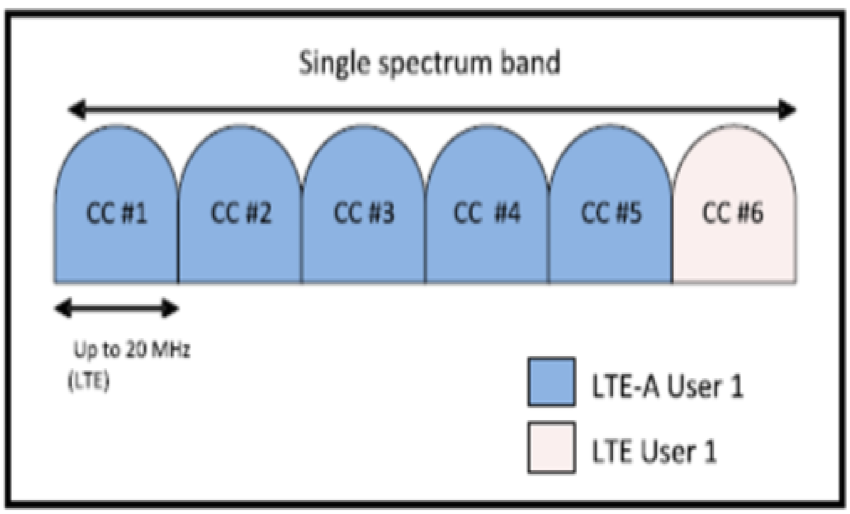

Figure 2. CA, contiguous mode [6]

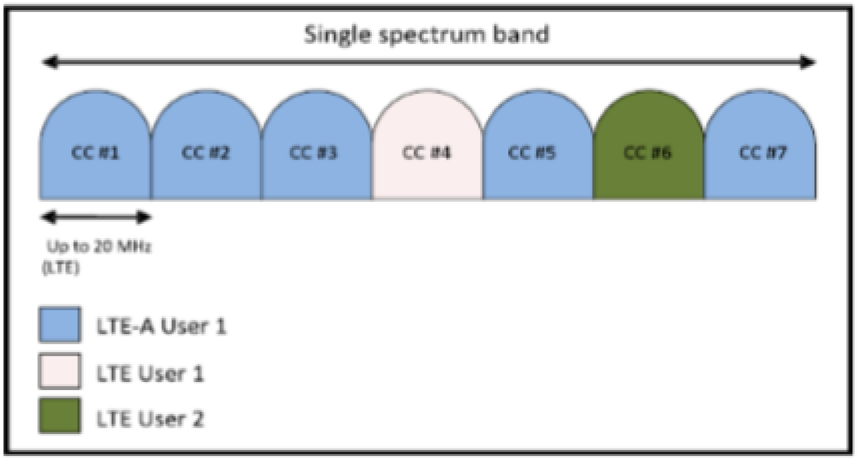

Figure 3. CA, non-contiguous single-band mode [6]

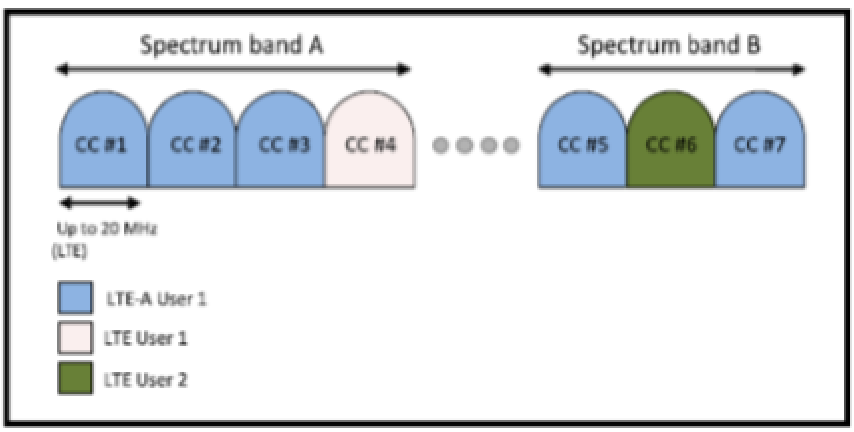

Figure 4. CA, non-contiguous multiple-bands mode [6]

Carrier aggregation maintains backward compatibility with LTE Releases 8 and 9 by requiring coexistence with the ‘legacy’ physical channels, and therefore the REs carrying the new UE-specific RSs (reference signals) have to avoid the cell-specific RSs and downlink control channels [7]. One consequence of this requirement is that a contiguous resource allocation of more than 20 MHz for an LTE-A user transmission is not possible, because this means that the user data transmission would occupy the control regions at the edges of the band. For this reason, the access scheme design for LTE-A includes clustering of the allocated bandwidth into 20 MHz blocks, as it will be illustrated in the following section.

b. Uplink Access Scheme for Supporting Carrier Aggregation

As mentioned earlier, the uplink multiple access schemes of LTE in Releases 8 and 9 are OFDM and SC-FDMA respectively. While OFDM is flexible and suitable for all modes of CA, SC-FDMA is not suitable for contiguous CA when the aggregated bandwidth is for bandwidths wider than 20 MHz. This is because an LTE-A user cannot use contiguous carriers for transmission in a wide bandwidth without breaking the backward compatibility requirement. In particular, the single-carrier properties need to be broken at the Release 8/9 CC edges, because these are reserved for the PUCCH control signaling as discussed earlier in Chapter II, and cannot be used for user transmission. For this reason, and in order to allow for additional flexibility and performance improvements, enhanced access schemes are being considered for LTE-A uplink. Figures 5 and 6 present the transmitter block diagrams for two candidate schemes, namely, clustered SC-FDMA and NxSC-FDMA, also known as multiple SC-FDMA [13].

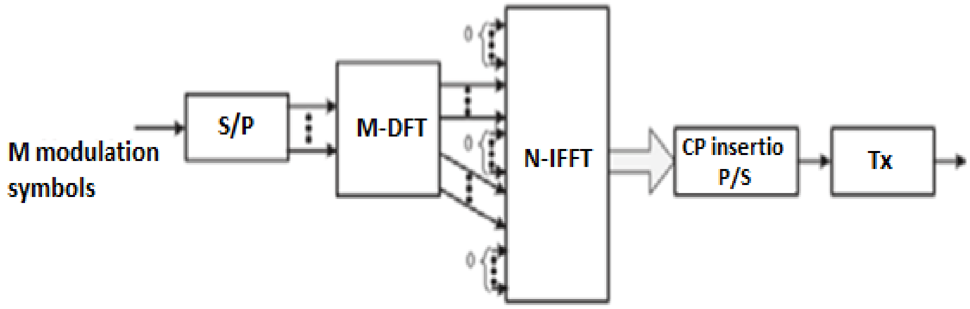

Figure 5. Transmitter diagram of clustered SC-FDMA [13]

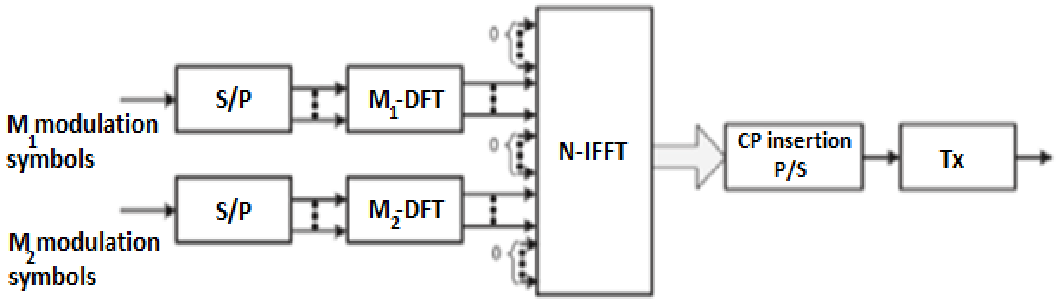

Figure 6. Transmitter diagram of NxSC-FDMA [13]

Clustered DFT-S-OFDM keeps a single (although larger) DFT operation but modifies the resource element mapping at the output of the DFT from a single cluster (as used for SC-FDMA) to multiple clusters. Clustering is performed so that a cluster width does not exceed 20 MHz. This solves the PUCCH compatibility constraint discussed previously. On the other hand, Multiple SC-FDMA (NxSC-FDMA) simply has multiple DFT operations.

The resulting waveforms from these schemes are no longer single carrier, and experience worse Cubic Metric (CM) than that of SC – FDMA, but still achieve much lower PAPR and CM than those of the OFDM scheme. The CM issue concerns the transmitter’s RF amplifier operating in the non-linear (saturation) region, thus causing distortion of the transmitted signal.

c. Feasibility of Carrier Aggregation

In theory, carrier aggregation can occur between any two different bands and between channels of different bandwidths. However, for practical deployment, several technical and non-technical constraints need to be addressed.

i. Non-Technical Constraints

Operators’ input is one consideration to be taken into account when selecting CA deployment scenarios. In LTE, 3GPP selected aggregation scenarios for feasibility study based on operators’ input and proposals, which are naturally affected by their specific needs and band-ownership [9].

ii. Intra-Band Technical Constraints

For a better understanding of the technical constraints, we first present an example of a candidate deployment scenario. Figure 7 shows a band plan and carrier aggregation scenarios that were under discussion for deployment in Europe [9].

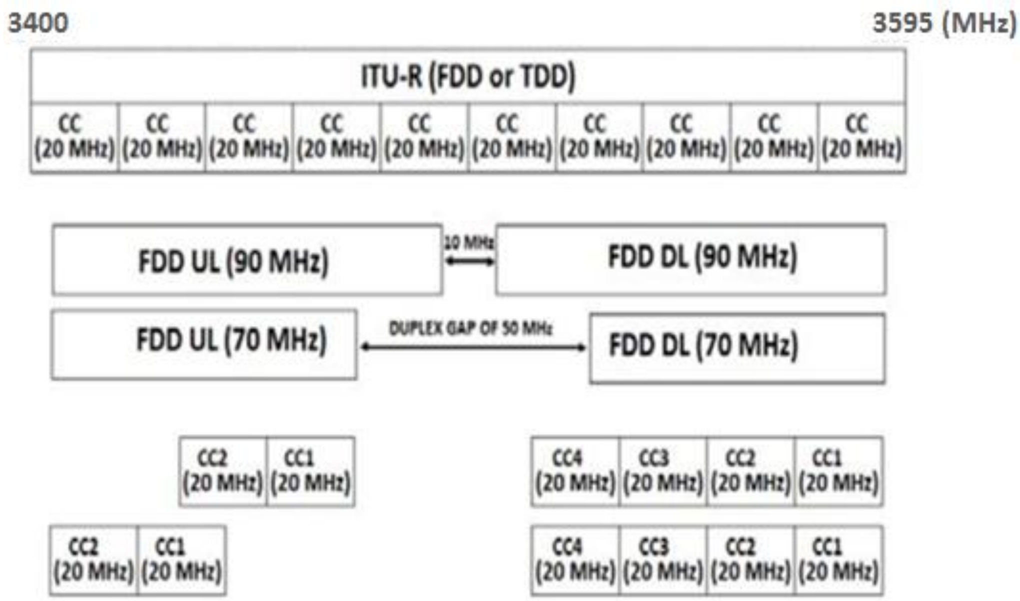

Figure 7. CA scenario deployment [9]

In Figure 7, the 3.5 200-MHz-wide GHz band is shown, and can therefore accommodate up to ten CCs of 20 MHz each. Two FDD scenarios chosen for this band are also shown: the first one provides two 90 MHz bands for uplink (UL) and downlink (DL) respectively with a 10 MHz spacing, whereas the second provides smaller UL and DL bands and a wider duplex gap. Finally, the figure presents different choices of CC positions and duplexer gaps that are considered for aggregation. These choices have implications on the performance as it will be illustrated next.

The first consideration to be taken into account is the duplexer complexity. A larger duplex gap implies a more complex duplexer. In [10], for example, it is shown that it is difficult to implement a duplexer based on the 10 MHz gap scenario described above, and the 2x70 MHz is suggested instead. On the other hand, the duplex gap should be sufficiently large to prevent or reduce self-interference between the transmitter and the receiver signal at the UE antenna. For example, in the figure above, there is high potential for self- interference between the transmission on CC1 in the UL and reception on CC4 in the DL, when the duplex gap is small. One observation is that the 10 MHz gap is not sufficient to avoid self-interference and that 50 MHz is better, although not sufficiently large enough either according to [9].

It is clear that the higher the number of aggregated CCs, the higher the spectral efficiency since more CCs imply more transmissions and receptions of user data on the specified frequencies. Thus, we see that there is a tradeoff between duplexer design and self-interference on one hand and spectral efficiency on the other hand. More specifically, a smaller duplexer gap increases spectral efficiency by allowing more CCs to be aggregated, but it also increases the duplexer complexity and the self-interference.

iii. Inter-Band Technical Constraints

In LTE, a distinction is made between channel bandwidth (in MHz) and channel bandwidth configuration (in resource blocks, or RBs). The former represents the total channel bandwidth and is used as a reference for transmitter and receiver RF requirements, while the latter signifies the allowed number of resource blocks that can be used for transmission. Figure 8 and Table 1 illustrate this concept.

The channel raster in LTE Release 8 is 100 kHz, which means that the carrier center frequency must be an integer multiple of 100 kHz. The same channel raster is expected for LTE–A. This requirement is a consequence of the channel bandwidth specifications discussed above and the need to maintain the orthogonality of the aggregated carriers. In order to efficiently meet the 100 kHz channel raster requirement in LTE–A, the difference between the center frequencies of contiguously aggregated CCs shall be a multiple of 300 kHz [9].

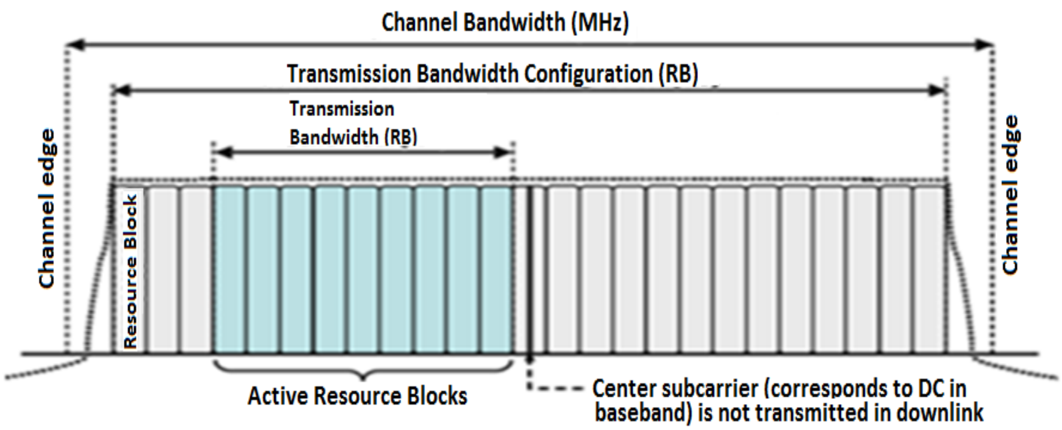

Figure 8. Channel/Transmission bandwidth specifications [9]

Channel Bandwidth (MHz)	**1.4**	**3**	**5**	**10**	**15**	**20**
Transmission bandwidth configurations (RBs)	6	15	25	50	75	100

Table 1. Bandwidth Configuration

d. Multi-RAT Carrier Aggregation

Multi-RAT CA is expected to be part of 3GPP Release 12 specifications for aggregating CCs from the 3GPP technologies bands, namely, from UMTS, LTE, and LTE-A bands. It is also envisioned that in future communication systems, carrier aggregation with non-3GPP technologies such as WiFi will be supported [8].

LTE-LTE CA scenarios:

Based on the above feasibility and efficiency considerations, 3GPP selected specific scenarios for carrier aggregation [9]. These are particular combinations of bands and bandwidths for aggregation. As summarized in [13], for intra-band carrier aggregation, the first supported carrier bandwidths are 15 and 20 MHz in E-UTRA Band 1 (2.11 GHz FDD band), and 10, 15 and 20 MHz in Band 40 (2.3 GHz TDD band). A maximum of two aggregated carriers are supported initially, as was determined in [9].

Aggregation scenarios have been defined for LTE-LTE aggregation as it will be detailed next:

For inter-band carrier aggregation, the first defined scenarios are likely to include:

- E-UTRA Bands 1 and 5 for 10 MHz CCs, one CC per band
- E-UTRA Bands 3 and 7 for 10, 15, and 20 MHz CCs, one CC per band
- E-UTRA Bands 4 and 13 for 10 MHz CCs, one CC per band
- E-UTRA Bands 4 and 17 for 10 MHz CCs, one CC per band

Refer to Appendix A for the List of E-UTRA bands.

Other combinations will be added in a release-independent manner, allowing for Release 10 and beyond UEs to support them.

Multi-RAT CA scenarios:

While CA scenarios have already been proposed for LTE-LTE CA, future research is required for aggregation between LTE and different non-3GPP access technologies, hence the importance of our work which seeks to propose an approach for aggregating spectrum from LTE and a different technology, namely WiFi.

C. WiFi

We conducted a study on the 802.11 standard physical layer design, band and bandwidth specifications. Our study was based on the 802.11-2012 version of the standard which incorporates more than ten WiFi amendments that were proposed before 2012 [24], and the study is only concerned with the OFDM specifications [11]. We assume the following CA mode: LTE and WiFi infrastructures coordinate, and when available, the LTE system can borrow spectrum from the WiFi bands and allocate them to LTE-A UEs for aggregation. More specifically, in an organizational setting (e.g., university campus), a small cell LTE-A base station (eNodeB) could coordinate with the WiFi access points (APs) in the covered area to request WiFi channels, thus appearing as a WiFi user. The borrowed channels will be used by the LTE-A cell as though they are part of the LTE-A spectrum. The coordination between the eNodeB and an AP may occur over the air interface, by having the eNodeB act just like any WiFi station, or via a wired interface that resembles the X2 interface used between eNodeBs. In another possible physical implementation, an integrated eNodeB-AP node will transfer WiFi spectrum for LTE-A usage based on the demand for both LTE-A and WiFi transmissions. This may be a more practical option as it is envisioned that communication systems will converge to 5G [8] in the future.

For considering the LTE-A-WiFi aggregation mode, it will be sufficient to study the WiFi spectrum and bandwidth specifications. However, for implementation and realization, we would need to consider the WiFi spectrum access scheme and how the LTE-A infrastructure would interface to the WiFi infrastructure.

We selected OFDM WiFi, first because of its similarity to the OFDM-based access schemes of LTE, and second and more importantly because it uses the unlicensed and underutilized 5.8 GHz ISM band. More details on WiFi OFDM PHY specifications will be provided in a following subsection.

In the following subsections, we present a summary of the WiFi architecture, MAC layer access schemes, management entities and protocols, and PHY layer specifications. This survey of the WiFi system design and specifications is essential for understanding the coexistence challenges that occur when two technologies, namely LTE and WiFi which are not only different but also incompatible, use the same unlicensed spectrum.

Note – *Throughout the presentation in the next subsection, the word "standard" refers to the 802.11-2012 WiFi standard [30].*

1. WiFi Architecture

The main component of the WiFi architecture is the WiFi Station (STA). WiFi STAs can be classified as: AP-STAs and non-AP STAs, with the former having additional access point capabilities. On the other hand, STAs are classified as QoS and non-QoS

STAs, depending on whether they support the enhanced QoS capabilities. Finally, STAs can be classified as mesh or non-mesh STAs, depending on whether they run the distributed mesh functions, which are out of the scope of our study.

STAs operate within what is called a Basic Service Set (BSS). A BSS is the basic building block of the WiFi system, and it can be thought as a coverage area within which the member STAs may remain in communication.

BSSs, as well, are classified into three types:

- Independent BSS (IBSS): also known as ad-hoc BSS, where STAs are able to communicate directly
- Infrastructure BSS: controlled by an AP-STA
- Mesh BSS (MBSS): with distributed control rather than centralized control at the AP

When the AP in an infrastructure BSS is a QoS-AP, the BSS under its control is referred to as a QoS-BSS. Both QoS and non-QoS STAs can join a QoS-BSS and associate with the QoS-AP, but only QoS-STAs will benefit from the enhanced QoS functions.

2. WiFi Layer Management Protocols

In this section, we give an overview of the WiFi layer management model and describe the management primitives that we will use in our design.

A WiFi station includes the following management entities:

- MLME: MAC Layer Management Entity
- PLME: PHY Layer Management Entity
- SME: Station Management Entity; a layer-independent entity

These entities perform management functions and interact with each other through specific protocols and primitives (functions) that run within Service Access Points (SAPs); however, the specific manner in which these MAC and PHY LMEs are integrated into the overall MAC sublayer and PHY is not specified within the standard.

Three management SAPs are present between the management entities:

- SME-MLME SAP
- SME-PLME SAP
- MLME-PLME SAP

The latter two SAPs can be regarded as a single SAP, referred to as the PLME SAP, as they support identical primitives.

Figure 9 illustrates the relationships between these different entities in addition to the MAC, PLPC and PMD layers. Note that MIB in the figure refers to the STA's *Management Information Base* which includes different management parameters that are configurable by the STA and potentially by external management entities. The LMEs, as illustrated in Figure 9, interact with this MIB through Get and Set primitives that allow the STA to read and write to the MIB.

Note – *Throughout this report, MIB parameters will be highlighted in bold and detailed descriptions of these parameters including their data types, default values and valid ranges are presented in Appendix B.*

In addition to the SET/GET primitives, each SAP supports a RESET primitive which allows the initialization of the LMEs and MIBs, not necessarily to default values.

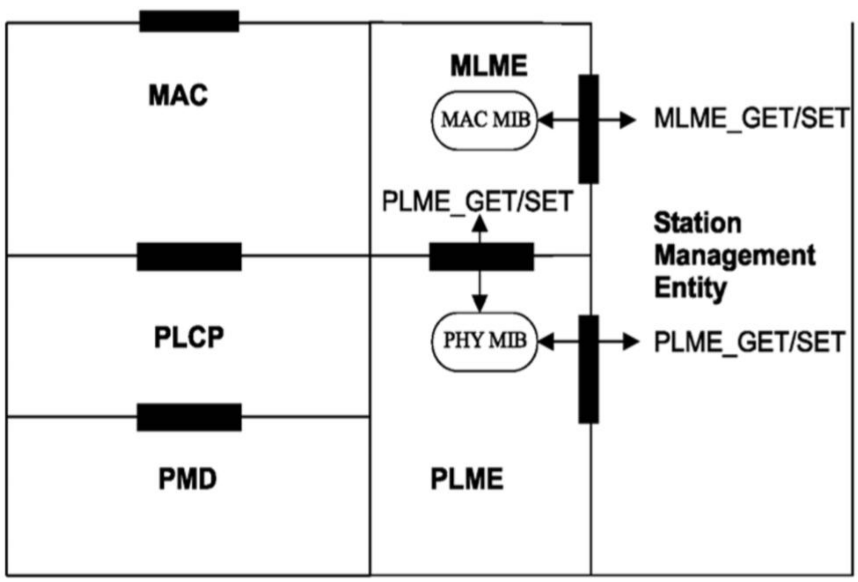

Figure 9. Station management entities [54]

As explained above, the SET, GET, and RESET primitives are common to the three SAPs. Other SAP-specific primitives exist for each SAP. For our purposes, we restrict our study to the MLME SAP primitives; because it is the MAC Layer specifications that define the time synchronization parameters and channel access methods that we need for our CA scheme.

The MLME SAP includes more than eighty different MAC Layer management functions including scanning, synchronization, and power management functions. In the following sections, we present the details of the functions that are most relevant to our purposes. For a complete presentation of the MLME SAP primitives and for detailed parameter tables, the interested reader is referred to section 6-3 of the standard [54].

a. <u>BSS Initiation and Termination</u>

A STA uses the MLME-START and MLME-STOP primitives in order to start and stop a BSS respectively.

<u>BSS Initiation:</u>

The Initiation of a BSS occurs using two primitives: MLME-START.request and MLME-START.confirm.

The MLME-START.request primitive is generated by the SME to request (from the MLME) that the MAC entity start a new BSS or become a member of an MBSS. The BSS can be one of the three BSSTypes mentioned earlier (Infrastructure, Independent, or Mesh).

The primitive specifies all the MAC and PHY layer management configuration parameters that need to be set by this STA at the initiation of the BSS (set by the AP in the case of infrastructure BSS). These parameters are returned in the scan results in the form of elements within the BSSDescription structure. The scan results are obtained through the MLME-SCAN primitives which will be presented in the next subsection.

The MLME-START.comfirm is returned by the MLME and contains the result of the BSS initiation procedure.

Details on the START primitives are found in section 6.3.11 of the standard [54].

In our design, the QoS-AP initiates an infrastructure QoS BSS and sets the MIB parameters and the capability information as it will be specified in the following subsection.

BSS Termination:

The MLME-STOP.request primitive is generated by the SME of the AP to terminate the infrastructure BSS it is controlling.

Before generating this request, the SME should notify all associated non-AP STAs. After generating the request, all the AP functions are stopped (e.g. beacon generation and access to the DS, etc.) In addition, all the STAs in the infrastructure BSS are deauthenticated.

Details about the STOP primitive are found in section 6.3.12 of the standard [54].

b. Scanning and Synchronization

The objective of the MLME scanning primitives is to obtain information about available BSSs. The STA uses two functions to perform scanning: MLME-SCAN.request and MLME-SCAN.confirm.

A STA that has previously obtained information about available BSSs from the scanning results, can select one of these BSSs and use the Join primitives (MLME-JOIN.request and MLME-JOIN.confirm) to synchronize with it.

The requests are generated by the SME, while the confirmations and results are issued by the MLME as shown in Figure 10.

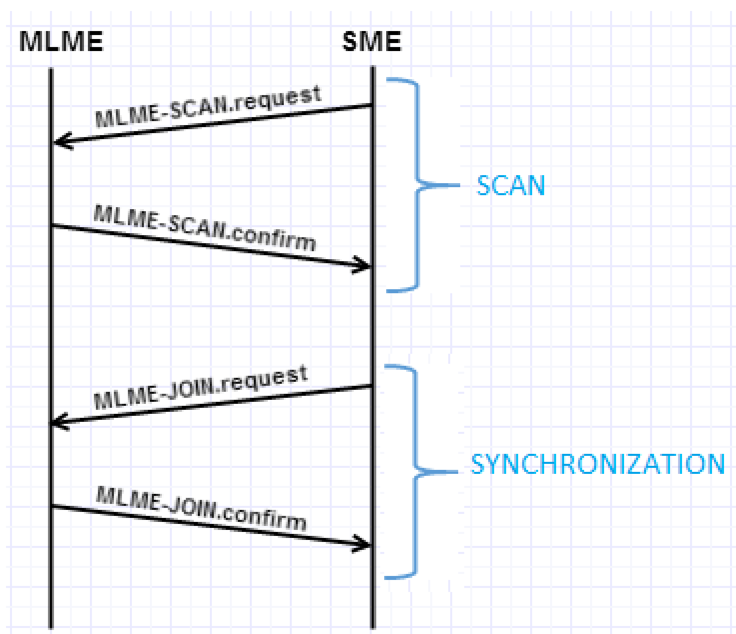

Figure 10. Scanning and synchronization primitives

The MLME-SCAN.request primitive:

A WiFi-STA uses the MLME-SCAN.request primitive each time it wishes to listen to Beacon frames from WiFi STAs. These aim at collecting information about available nearby BSSs.

The SME sends the MLME-SCAN.request to the MLME, and the request includes scanning-specific parameters including the following:

BSSType: An Enumeration of {INFRASTRUCTURE, INDEPENDENT, MESH, ANY_BSS} Through the BSSType input parameter, the STA specifies what kind of BSSs it should collect information about. For example, if the BSSType is INFRASTRUCTURE, the STA processes Beacon frames that refer to infrastructure APs and ignores other Beacon frames.

BSSID: which specifies the MAC address of the AP/STA(s) whose Beacon frames are of interest. For our CA scheme, the BSSID refers to the MAC address of a QoS-AP with whom the eNodeB will coordinate.

ChannelList: an ordered set of integers, each representing a channel number. Each channel is selected from the valid channel range for the appropriate PHY and carrier set. This parameter specifies a list of channels that are examined when scanning for a BSS.

MinChannelTime and MaxChannelTime: integers that specify the min/max amount of time to spend on each channel when scanning.

The MLME-SCAN.confirm primitive:

After receiving the MLME-SCAN.request, the MLME performs the requested scan. The scan results are sent to the SME through the MLME-SCAN.comfirm primitive.

In case of a successful scan, the MLME-SCAN.confirm includes a BSSDescriptionSet which is a set of BSSDescription structures, each referring to a single BSS.

A BSSDescription includes elements that are extracted from Beacon frame fields. In this subsection, we only present elements that are needed by our design. The interested reader can refer to Table 8-20 of the standard for a description of all fields within the Beacon frame body [55], in addition to the Table on pages 109 through 114 of the standard for details on BSSDescription elements [54].

Table 2 describes a subset of the elements included in the BSSDescription structure.

Name	**Type**	**Valid Range**	**Description**	**Significance in our design**
Beacon Period	Integer	N/A	This parameter is specified by the dot11BeaconPeriod**,** which is an MIB parameter that controls the time that elapses between target beacon transmission times. Any change in this attribute will require that any current BSS be dissolved and a new BSS started with the new beacon period. This parameter is therefore fixed throughout the lifetime of the BSS.	This parameter allows the eNodeB to know when to expect Beacon frames, and therefore, when to scan for obtaining BSS information.
Timestamp *(of AP)*	Integer	N/A	The timestamp of the received frame (probe response/beacon) from the found BSS.	This is needed for time synchronization between the WiFi and LTE systems.
Channel	Integer	N/A	This parameter contains	When the eNodeB gets

Number			the channel number on which the frame was received. Valid channel numbers are defined in the relevant PHY clause.	access to the WiFi medium, it forwards the channel information in this field to the MAC scheduler.
CF Parameter Set	CF Parameter Set element	As defined in a following subsection of this report.	The parameter set for the Contention Free (CF) periods, if found BSS supports CF mode.	This parameter includes information about the start times and durations of the Contention Periods (CP) and Contention Free Periods (CFP). Based on this information, the eNodeB can know which channel access method(s) it can use at a given time. The element is mainly used for supporting the PCF; however, it can also be used by the HCF to advertise the time duration when it will gain control over the shared medium. Within our design, this element will be utilized in the HCF context.
BSS Available Admission Capacity	BSS Available Admission Capacity element	As defined in a following subsection of this report.	The values from the BSS Available Admission Capacity element if such an element was present in the probe response or Beacon frame, else null.	This element allows the eNodeB to know the likelihood of being admitted to access the channel in the future. It will be used in our design when setting the TSPEC fields of the ADDTS request: the fields are set so that the needed medium time for the requested SPECs is less than the admission capacity.
Load	BSS Load element	As defined in a following subsection of this report.	The values from the BSS Load element if such an element was present in the probe response or Beacon frame, else null.	This element allows the eNodeB to know about the current load in the BSS in terms of number of associated STAs. Knowing the number of STAs in the BSS, the eNodeB can estimate the likelihood of collisions when attempting to access the medium.
Capability – Information	Capability Information field	As defined in a following subsection of this report.	The advertised capabilities of the BSS.	This element includes the capabilities supported by the WiFi STA that generated the Beacon frame (the AP in our

				case). The WiFi STA should verify that the AP is a QoS AP using the fields of this element.
EDCA - Parameter Set	EDCA Parameter Set element	As defined in a following subsection of this report.	The values from the EDCA Parameter Set element if such an element was present in the probe response or Beacon frame, else null.	This element includes the parameters needed for running the EDCA access method which we will use in our design for borrowing the WiFi channels.

Table 2. BSS Description Elements

Next, we present in more detail the formats of the elements mentioned in Table 2.

CFParameterSet

Reference: section 8.4.2.6 of the standard [55]

The CF Parameter Set element contains the set of parameters necessary to support the PCF. It contains the CFPCount, CFPPeriod, CFPMaxDuration, and CFPDurRemaining fields. The total length of the Information field is 6 octets. See Figure 11.

	Element ID	Length	CFP Count	CFP Period	CFPMaxDuration (TU)	CFPDurRemaining (TU)
Octets:	**1**	**1**	**1**	**1**	**2**	**2**

Figure 11. CF Parameter Set element format

CFPCount indicates the time duration left before the start of the next CFP.

CFPPeriod indicates the time interval between the start times of consecutive CFPs, and is based on the value of **dot11CFPPeriod** MIB parameter.

CFPMaxDuration indicates the maximum duration of the CFP that may be generated by this PCF. This value is used by STAs to set their Network Allocation Vector (NAV) at the Target Beacon Transmission Time (TBTT) of Beacon frames that begin CFPs; where the NAV is an indicator of the period of time that these STAs will defer from accessing the medium. The CFPMaxDuration is based on **dot11CFPMaxDuration** whose bounds are as follows:

- The minimum value for CFPMaxDuration should be sufficient time for the AP to send 1 data frame to a STA, and for the polled STA to respond with a data frame.
- The maximum value should be sufficient time to send at least 1 data frame during the CP

Finally the CFPDurRemaining indicates the maximum time remaining in the present CFP, and is set to 0 in CFP Parameter elements of Beacon frames transmitted during the CP. The value of CFPDurRemaining is referenced to the immediately previous TBTT. This value is used by all STAs to update their NAVs during CFPs.

As mentioned above, the CFParameterSet element is used for the PCF; however, it can also be used by the HCF (which is actually a variation of PCF) to indicate the time it will be controlling the medium. This can be done by setting the CFPDurRemaining as desired. More details on the HCF and the other access methods will be given in section C-3

BSS Available Admission Capacity element

Reference: sections 8.4.2.45 and 10.11.17 of the standard [55]

The BSS Available Admission Capacity element is helpful for roaming QoS STAs to select a QoS AP that is likely to accept future admission control requests, but it does not provide an assurance that the Hybrid Coordinator (HC) – which runs at the QoS-AP – will admit these requests. In our design, we assume that there is only one QoS-AP in range, and this element will be useful to allow the eNodeB to estimate the likelihood of being admitted by this AP to access the medium in the future, using explicit admission control. Chapter V will describe in more detail how we will use this element in our design.

The format of the BSS Available Admission Capacity element is shown in Figure 12.

	Element ID	Length	Available Admission Capacity Bitmask	Available Admission Capacity List
Octets:	**1**	**1**	**2**	**2 x (total number of nonzero bits in Available Admission Capacity Bitmask)**

Figure 12. BSS Available Admission Capacity element format

The Available Admission Capacity Bitmask is 16 bits long, each represents a specific User Priority (UP) or Access Category (AC), as follows:

- Bits 0 through 7 represent Ups 0 through 7 respectively.
- Bits 8 through 11 represent ACs 0 through 3
- Bits 12 through 15 are reserved

Each bit in the bitmask, if set to 1 indicates that an Available Admission Field corresponding to this UP or AC exists in the Available Admission Capacity List Field.

The Available Admission Capacity field is 2 octets long and contains an unsigned integer that specifies the amount of medium time available using explicit admission control for the corresponding UP or AC traffic, in units of 32 μs per 1 s.

More specifically, the transmitted BSS Available Admission Capacity value represents a proportion of time on the wireless medium scaled linearly in units of 32 μs/s from 0 (0% available time) to 31 250 (100% available time) (i.e. 31250 x 32 x 10^6 = 1 sec/sec => 100% available time). If an AP transmits a BSS Load element (to be described next), the values for any transmitted BSS Available Admission Capacity values shall be less than or equal to the Available Admission Capacity field value of the BSS Load value. If an AP transmits a BSS Available Admission Capacity element, the transmitted values should be current or recently calculated. The AP recalculates Available Admission Capacity values according to local policy. An Available Admission Capacity value of 0 transmitted in the BSS Available Admission Capacity element indicates that no admission capacity is available at the calculation time and that no explicit admissions can be granted by the AP for that UP or AC unless additional capacity becomes available. An AP that receives a Traffic SPECification (TSPEC) admission request for total medium time that is less than or equal to the current available admission capacity for the requested UP or AC local policy may apply additional local policy before admitting the requested TSPEC.

NOTE 1—Available Admission Capacity values are dynamic in a BSS and the transmitted values cannot always reflect the actual values currently used by the AP for explicit admission control. Thus an AP should recalculate the Available Admission Capacity values regularly or after changes in the environment or the admitted capacity.

NOTE 2—STAs are advised that requesting admission for any TSPEC at a UP or AC that requires more medium time than is reported as available for the requested UP or 3AC is possible yet unlikely to be successful.

Load element:

Reference: section 8.4.2.30 of the standard [55]

The BSS Load element contains information on the current STA population and traffic levels in the BSS. The element information format is defined in Figure 13.

	Element ID	Length (5)	Station Count	Channel Utilization	Available Admission Capacity
Octets:	**1**	**1**	**2**	**1**	**2**

Figure 13. Load element format

The STA Count Field is interpreted as an unsigned integer that indicates the total number of STAs currently associated with this BSS.

The Channel Utilization field is defined as the percentage of time, linearly scaled with 255 representing 100%, that the AP sensed the medium was busy, as indicated by either the physical or virtual carrier sense (CS) mechanism. When more than one channel is in use for the BSS, the Channel Utilization field value is calculated only for the primary channel. This percentage is computed using the formula,

$$\boldsymbol{Channel\ Utilization} =$$

$$\boldsymbol{Integer}\left(\left(\frac{channel\ \boldsymbol{busy}\ time}{\boldsymbol{dot11ChannelUtilizationBeaconIntervals} \times \quad dot11BeaconPeriod \times 1024}\right) * \ 255\right)$$

where,

channel busy time is defined to be the number of microseconds during which the CS mechanism – which will be described in a following subsection – has indicated a channel busy indication, **dot11ChannelUtilizationBeaconIntervals** represents the number of consecutive beacon intervals during which the channel busy time is measured.

The Available Admission Capacity is similar to that in the Admission Capacity element: it is 2 octets long and contains an unsigned integer that specifies the remaining amount of medium time available via explicit admission control, in units of 32 μs/s. The field is helpful for roaming STAs to select an AP that is likely to accept future admission control requests, but it does not represent an assurance that the HC admits these requests.

Capability Information Element

The first 2 bits of the Capability Information element represent the ESS and IBSS subfields. These subfields indicate the kind of STA transmitting the Beacon frame. Specifically:

An AP (as in our design) sets the ESS subfield to 1 and the IBSS subfield to 0 within transmitted Beacon or Probe Response management frames. A STA within an IBSS sets the ESS subfield to 0 and the IBSS subfield to 1. A mesh STA sets the ESS and IBSS subfields to 0.

On the other hand three bits: QoS, CF-Pollable, and CF-Poll Requests, are used to provide further information on the capabilities of the STA; as detailed in Table 3. The table shows how these three bits are encoded when the Beacon is sent by an AP. In our design, the AP is a QoS-AP and thus the QoS bit is set (this is verified by the WiFi submodule when it receives the Beacon frame). The CF-Poll bits are needed if HCCA is used, as it will be illustrated in Chapter V.

QoS	**CF-Pollable**	**CF-Poll Request**	**Meaning**
0	0	0	No PC at non-QoS AP
0	0	1	PC at non-QoS AP for delivery only (no polling)
0	1	0	PC at non-QoS AP for delivery and polling
0	1	1	Reserved
1	0	0	QoS AP (HC) does not use CFP for delivery of individually addressed data frames
1	0	1	QoS AP (HC) uses CFP for delivery, but does not send CF-Polls to non-QoS STAs
1	1	0	QoS AP (HC) uses CFP for delivery, and sends CF-Polls to non-QoS STAs

1	1	1	Reserved

Table 3. AP usage of QoS, CF-Pollable, and CF-Poll Requests subfields

For a complete presentation of the Capability Information Element Fields and format, the interested reader can refer to section 8.4.1.4 of the standard [55].

EDCA Parameter Set Element

The EDCA Parameter Set element provides information needed by STAs for proper operation of the QoS facility during the CP. The format of the EDCA Parameter Set element is defined in Figure 14.

	Element ID	**Length (18)**	**QoS Info**	**Reserved**	**AC_BE Parameter Record**	**AC_BK Parameter Record**	**AC_VI Parameter Record**	**AC_VO Parameter Record**
Octets:	**1**	**1**	**1**	**1**	**4**	**4**	**4**	**4**

Figure 14. EDCA Parameter Set Element

For an infrastructure BSS, the EDCA Parameter Set element is used by the AP to establish policy (by changing default MIB attribute values), to change policies when accepting new STAs or new traffic, or to adapt to changes in offered load. The most recent EDCA parameter set element received by a STA is used to update the appropriate MIB values.

The QoS Info field contains the EDCA Parameter Set Update Count subfield, which is initially set to 0 and is incremented each time any of the AC parameters changes. This allows the WiFi STA to know whether it has the most recent EDCA Parameters or not. The

QoS Info field also contains the TXOP Request subfield, which is a 1 bit field that indicates whether the sending STA (the QoS AP) supports non-zero TXOP durations to be requested. In our design, this bit is set to 1 in the Beacon frames sent by the QoS AP, meaning that we assume that the AP supports non-zero TXOP durations, because the eNodeB will try to reserve medium time using EDCA or HCCA TXOPs, as it will be illustrated in Chapter V.

The formats of AC_BE, AC_BK, AC_VI, and AC_VO Parameter Record fields are identical and are illustrated in Figure 15.

	ACI/AIFSN	ECWmin/ECWmax	TXOP Limit
Octets:	**1**	**1**	**2**

Figure 15. AC_BE, AC_BK, AC_VI, and AC_VO Parameter Record field format

The format of the ACI/AIFSN field is illustrated in Figure 16.

	B0 B3	B4	B5 B6	B7
	AIFSN	**ACM**	**ACI**	**Reserved**
Bits:	**4**	**1**	**2**	**1**

Figure 16. ACI/AIFSN field

The value of the AC index (ACI) references the AC to which all parameters in this record correspond. The mapping between ACI and AC is defined in Table 4. The ACM (admission control mandatory) subfield indicates that admission control is required for the

AC. If the ACM subfield is equal to 0, then there is no admission control for the corresponding AC. If the ACM subfield is set to 1, admission control has to be used prior to transmission using the access parameters specified for this AC. Admission Control requires that the STA sends an ADDTS request to the HC. Unless the request is admitted, the STA cannot use the EDCA priority parameters. The ADDTS primitives will be introduced in section in the following subsections, and further details on the ADDTS element formats will be provided in Chapter V.

The AIFSN subfield indicates the number of slots after a SIFS duration QoS-STA should defer before either invoking a backoff or starting a transmission. The minimum value for the AIFSN subfield is 2.

ACI	**AC**	**Description**
00	AC_BE	Best Effort
01	AC_BK	Background
10	AC_VI	Video
11	AC_VO	Voice

Table 4. ACI-to-AC coding

The ECWmin and ECWmax fields are illustrated in Figure 17.

	B0 B3	**B4 B7**
	ECWmin	**ECWmax**
Bits:	**4**	**4**

Figure 17. ECWmin and ECWmax fields

The ECWmin and ECWmax fields encode the values of CWmin and CWmax, respectively, in an exponent form. The ECWmin and ECWmax values are defined so that

- $CWmin = 2^{ECWmin} - 1$
- $CWmax = 2^{ECWmax} - 1$

Hence the minimum encoded value of CWmin and CWmax is 0, and the maximum value is 32 767.

The value of the TXOP Limit field is specified as an unsigned integer, with the least significant octet transmitted first, in units of 32 μs.

Table 5 defines the default EDCA parameter values used by a non-AP STA if dot11OCBActivated is false.

Note 1: we are not interested in the case where dot11OCBActivated is true, because in that case TXOP limit will always be zero); this is because the eNodeB will use the TXOP to reserve the medium time for the LTE system.

Note 2: In the table, “Clause 18” corresponds to the OFDM PHY specifications; thus, we are concerned with the corresponding TXOP limits which are highlighted in gray in the table.

AC	CWmin	CWmax	AIFSN	TXOP limit		
				For PHYs defined in Clause 16 and Clause 17	For PHYs defined in Clause 18, Clause 19, and Clause 20	Other PHYs
AC_BK	aCWmin	aCWmax	7	0	0	0
AC_BE	aCWmin	aCWmax	3	0	0	0
AC_VI	(aCWmin+1)/2-1	aCWmin	2	6.016 ms	3.008 ms	0
AC_VO	(aCWmin+1)/4 - 1	(aCWmin+1)/2 – 1	2	3.264 ms	1.504 ms	0

Table 5. Default EDCA Parameter Set element parameter values if OCBA is not activated.

By the EDCA Parameter Set element, we conclude the set of scan elements that are of interest in our design. Next, we present a brief summary of the Join primitives.

The MLME.JOIN.request and MLME.JOIN.confirm primitives:

The Join primitives are generated for synchronization purposes, where the SME generates the MLME-JOIN.request to join one selected BSS. The SelectedBSS parameter of the MLME-JOIN.request primitive refers to the BSSDescription of the selected BSS that the STA wishes to join. Refer to the scanning and synchronization section above for a description of the BSSDescription structure.

After receiving the join request, the MLME runs the synchronization function and returns the results to the SME via the MLME-JOIN.confirm primitive. The join result includes a status code that specifies whether the synchronization was successful or not. In case of a successful join procedure, the synchronization time offset is also reported.

c. Authentication and Association

Each WiFi STA maintains four different authentication/association states corresponding to the authentication/association status between it and another peer STA.

- State 1: Initial start state, unauthenticated, unassociated.
- State 2: Authenticated, not associated.
- State 3: Authenticated and associated (Pending RSN Authentication).
- State 4: Authenticated and associated.

The states above are used for filtering frames at the STAs' transceivers as follows:

In State 1, only Class 1 frames are allowed. In State 2, either Class 1 or Class 2 frames are allowed. In State 3 and State 4, all frames are allowed (Classes 1, 2, and 3), where:

Class 1 frames include:

- the *RTS*, *CTS*, *ACK*, *CF-End+ACK*, and *CF-End* control frames
- the *Beacon*, *Authentication*, and *Deauthentication* management frames
- and data frames between IBSS and DLS peers

Class 2 frames include the association, reassociation, and disassociation management frames.

Class 3 frames include:

- Data frames between STAs in an infrastructure BSS

- Management frames within an infrastructure BSS or an MBSS, all Action and Action No Ack frames except those that are declared to be Class 1 or Class 2 frames.

- PS Poll and control frames and control frames within an infrastructure BSS

Based on the above, it is necessary that the eNodeB:

- First, establish an authentication relationship with the WiFi AP
- Then associate with the WiFi AP

This is so that the eNodeB can send the frames that are necessary for reserving the medium time.

More details on authentication and association are presented in the following subsections.

<u>The Authentication Primitives:</u>

Considering the fact that authentication is required for infrastructure BSSs and the fact that APs do not initiate authentication requests, it is necessary that our WiFi submodule initiate an authentication relationship with the selected AP. In an authentication procedure, a requester STA initiates an authentication sequence in order to authenticate a peer STA. A successful authentication example sequence is shown in the Figure 18 below. Once authenticated successfully, the STA moves to State 2.

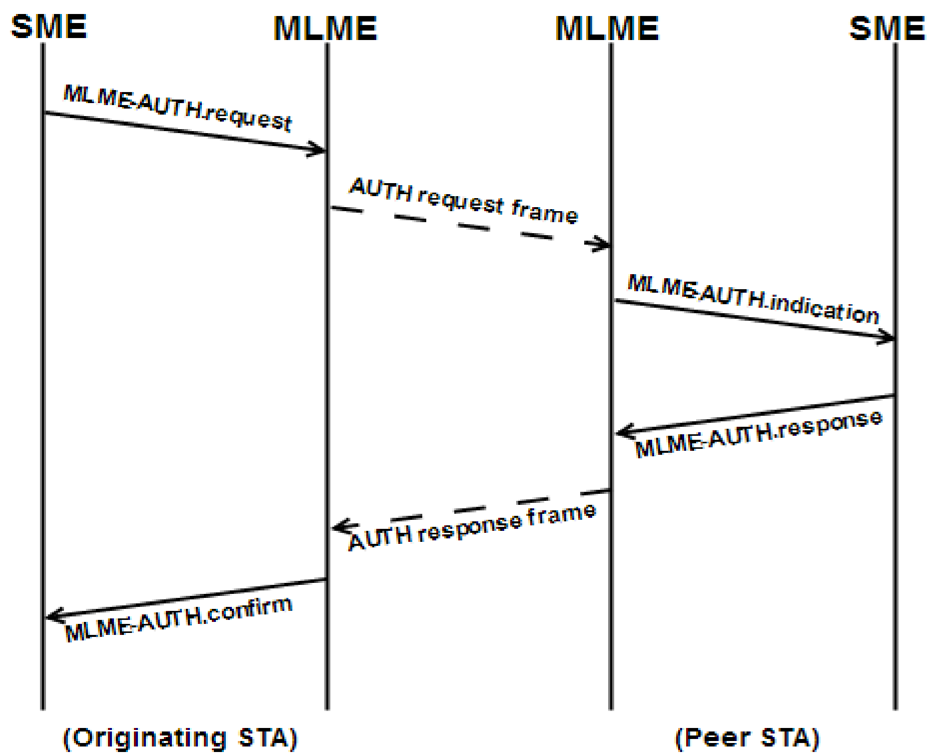

Figure 18. Successful authentication sequence

As shown in the figure, four different MLME primitives are used in this authentication sequence.

In the request primitive, the authentication algorithm is specified, where four different algorithms are defined: OPEN_SYSTEM, SHARED_KEY, FAST_BSS_TRANSITION, and SAE.

On the other hand, the authentication Request and Response frames are management frames of the format presented in Figure 19 assuming an OPEN_SYSTEM authentication algorithm; otherwise, 12 additional fields are required: refer to section 8.3.3.11 and tables 8-28 and 8-29 in the standard for further details [55].

Authentication Algorithm number	Authentication transaction sequence number	Status Code (2 Octets)

Figure 19. Authentication Frame Format

As the name indicates, the first field holds the authentication algorithm number. This is set to 1 if the authentication algorithm used is OPEN_SYSTEM.

The authentication sequence number is set to 1 if this is the request frame, and is set to 2 if this is the response frame.

Finally, the Status Code is reserved in the request frame, and it carries the result of the authentication in the response frame (e.g. SUCCESSFUL).

Further details on the authentication primitives and parameters are detailed in section 6.3.5 of the standard [54]. Clause 11 [56], on the other hand, presents the security algorithms and protocols in the WiFi standard including detailed description of the four security algorithms mentioned above.

The Deauthentication Primitives:

A STA may deauthenticate a peer STA at any time, for any reason, in which case the STA gets back to State 1.

Three MLME primitives are used for completing a deauthentication procedure as shown in Figure 20. Details on these primitives and their parameters are found in section 6.3.6 of the standard [54].

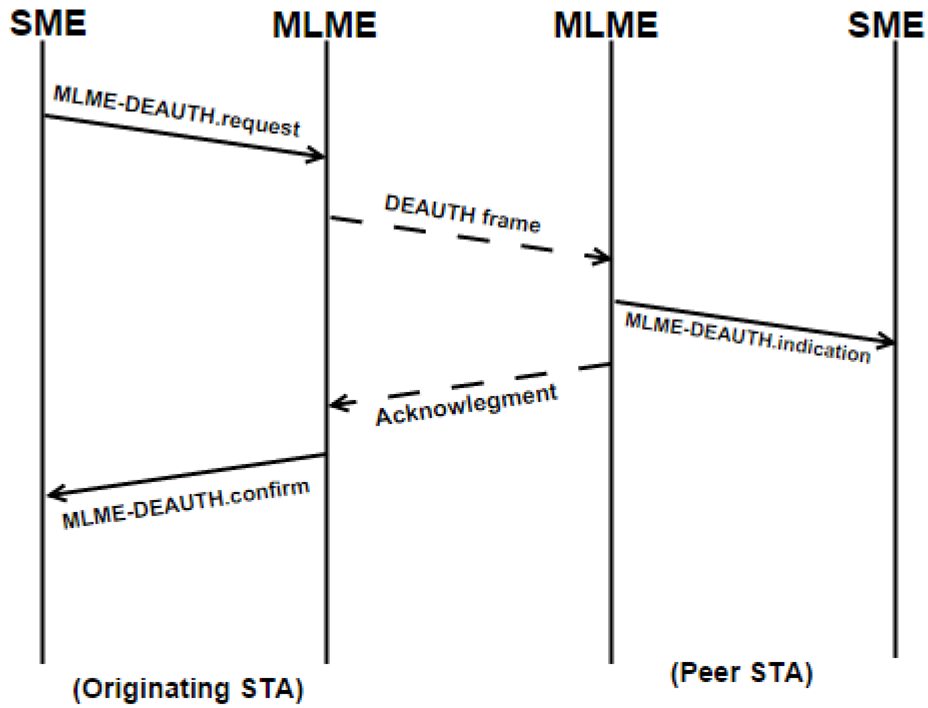

Figure 20. Deauthentication primitives

<u>The Association Primitives:</u>

Once authenticated with an AP, a non-AP STA can request association with the AP using the primitives described in this section.

The association transaction sequence is similar to that of the authentication sequence, where four kinds of primitives (MLME-ASSOCIATE.request, MLME-ASSOCIATE.confirm, MLME-ASSOCIATE.indication, and MLME-ASSOCIATE.response) are used in addition to request and response frame exchange between the non-AP STA (initiator) and the AP (responder).

The request primitive requests association with a specified peer MAC entity that is within an AP, and the response frame includes a status code that indicates the success or failure of the association attempt. Association failure may be caused by any misconfiguration or parameter mismatch, e.g., data rates required as basic rates that the STA did not indicate as supported in the STA's Supported Rates element, shall be corrected before the SME issues an MLME-ASSOCIATE.request primitive for the same AP.

Similar to the capability information element in Beacon frames – which advertise the AP's capabilities – the association request includes a capability information element that informs the AP of the capabilities of the STA. If a STA wishes to use the HCCA access method, then it should make sure to set the CF-Pollable subfield of the capability information element of the association request frame, so that the HC at the AP adds it to the list of STAs to be polled for HCCA admission.

Further details on the association primitives and their parameters are found in section 6.3.7 of the standard [54].

The Disassociation Primitives:

The disassociation primitives terminate the association relationship between the AP and the associated STA. The disassociation procedure occurs via three primitives: MLME-DISASSOCIATE.request, MLME-DISASSOCIATE.confirm, and MLME-DISASSOCIATE.indication. These are very similar to the deauthentication primitives, and follow a similar sequence. The disassociation procedure can be requested by the non-AP STA, or can be initiated by the AP that may decide to disassociate the non-AP.

A comprehensive description with further details on all the authentication and association primitives mentioned in this section are found in section 10.3 of the standard [57], and further details on the disassociation primitives and their parameters are found in section 6.3.9 of the standard [54].

d. TS Management Interface

The Traffic Stream management primitives will be used in our design in the context of explicit admission control that is used under HCF operation, as it will be detailed in section Chapter V. In this subsection, we describe these primitives. More specifically, we present the primitives used to add or delete what is called a Traffic Stream. Where a Traffic Stream (TS) is a set of medium access control (MAC) service data units (MSDUs) to be delivered subject to the quality-of-service (QoS) parameter values provided to the MAC in a particular traffic specification (TSPEC). TSs are meaningful only to MAC entities that support QoS within the MAC data service. These MAC entities determine the TSPEC applicable for delivery of MSDUs belonging to a particular TS using the priority parameter provided with those MSDUs at the MAC service access point (MAC_SAP). In our design, the TSPEC fields will be set so that they meet the LTE medium time requirements, rather than the traffic specifications.

The TS primitives

Similar to the authentication and association primitives, four TS primitives are used for adding a TS: MLME-ADDTS.xxx primitives, where xxx denotes: request, confirm, indication, or response. On the other hand two primitives are used for deleting a TS: MLME-DELTS.request and MLME-DELTS.indication; where a TS, as mentioned above, is a traffic stream associated with a STA and having specified QoS guarantees. The TS management interface is controlled by a HC that exists within a QoS-AP.

The TSPEC element and other optional elements are transported on the air by the ADDTS Request frame and the ADDTS Response frame, and across the MLME SAP by the MLME-ADDTS primitives.

Following a successful negotiation, a TS is created, identified within the non-AP STA by its TSID and direction, and identified within the HC by a combination of TSID, direction, and STA address.

It is always the responsibility of the non-AP STA to initiate the creation of a TS regardless of its direction.

A STA may simultaneously support up to eight TSs from the HC to itself and up to eight TSs from itself to other STAs, including the HC. The actual number it supports may be less due to implementation restrictions.

A HC may simultaneously support up to eight downlink TSs and up to eight uplink TSs per associated STA. The actual number it supports may be less due to implementation restrictions.

TSPECs are constructed at the SME, from application requirements supplied via the SME, and with information specific to the MAC layer.

An active TS may become suspended if no activity is detected for a duration of a suspension interval. Upon detection of activity, the TS may be reinstated. While the TS is in the suspended state, the HC shall not reclaim the resources assigned to the TS.

Figure 21 shows the primitives and frame sequences used for a TS setup. The non-AP STA's SME decides that a TS needs to be created. How it does this, and how it selects the TSPEC parameters, is beyond the scope of the WiFi standard. The SME generates an MLME-ADDTS.request primitive containing a TSPEC. The SME may take the resource/timing requirements of the TS in the accepted state into consideration before assigning any further resources to any other admitted or accepted TS, and in calculating the available admission capacity for the BSS Load element.

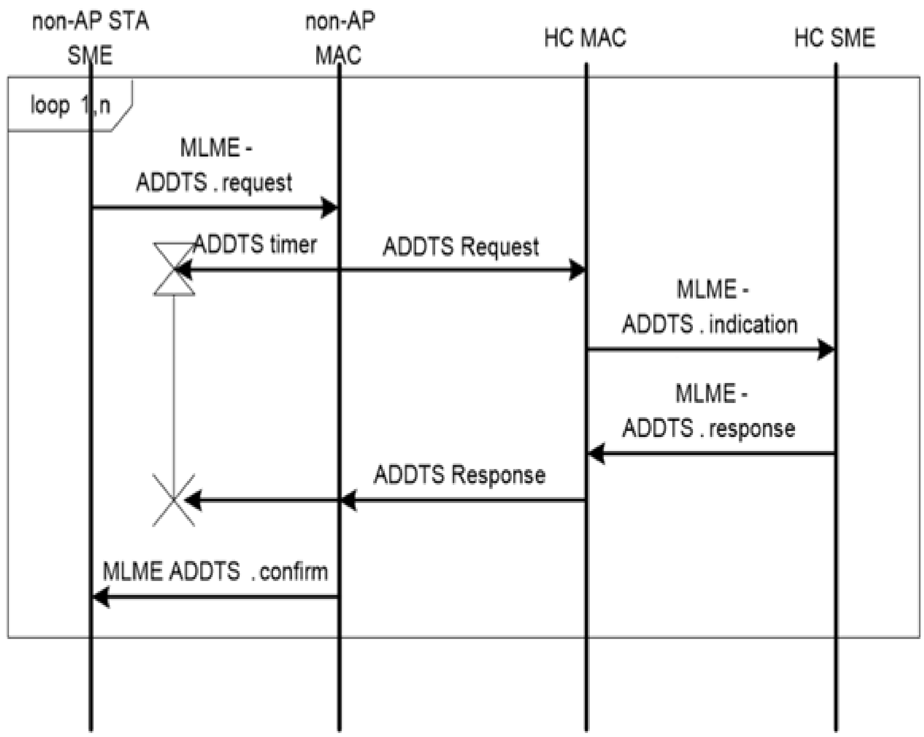

Figure 21. TS Setup [57]

The TS remains active until it is deleted by the DELTS primitives described next, or when the current CAP terminates; where CAP is a time period when the HC maintains control of the medium after gaining medium access by sensing the channel to be idle for a PIFS duration. It might scan multiple TXOPs (Transmission Opportunities) and can contain polled TXOPs.

A CAP may occur within a CP or CFP as shown in the Figure 22.

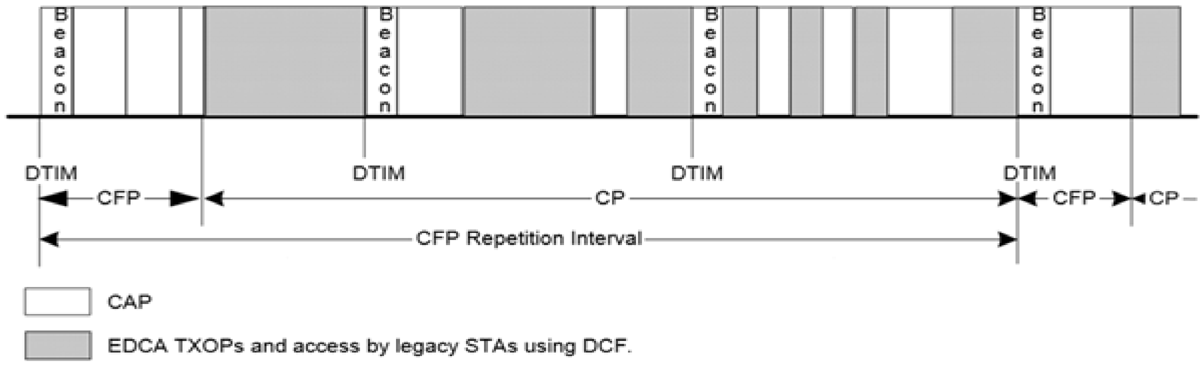

Figure 22. CAP/CFP/CP Periods

The relationship between TXOPs and the admitted TS characteristics will be illustrated further in Chapter V.

Deleting a TS:

The MLME-DELTS.request and MLME-DELTS.indication primitives are used to delete an active TS.

THE MLME-DELTS.request requests the deletion of a TS with a specified peer MAC and may be generated by either the AP or the non-AP STA. It is generated by the SME at the STA to initiate the deletion when a higher layer protocol or mechanism signals the STA to initiate such a deletion.

In effect, a TS deletion procedure is initiated causing the local MAC entity to send out a DELTS frame containing the specified parameters. If this primitive was generated at the HC, the frame is sent to the specified STA's MAC address. If this primitive was generated at the non-AP STA, the frame is sent to its HC. In either case, the DELTS frame does not solicit a response from the recipient frame other than an acknowledgment to receipt of the frame.

The MLME-DELTS.indication, on the other hand, reports the deletion of a TS by a specified peer MAC entity or deletion of the TS due to an inactivity timeout. This primitive runs at the HC only.

Details on the parameters of the ADDTS and DELTS primitives are found in section 6.3.26 of the standard [54]. On the other hand, a comprehensive description of the TS management specifications is found in section 10.4 of the standard [57].

3. *WiFi MAC Design: The Channel Access methods*

In this subsection, we summarize the WiFi MAC Layer specifications in terms of the defined channel access methods.

a. The Distributed Coordination Function

The Distributed Coordination Function (DCF) is the fundamental channel access function in the WiFi standard. This function should be implemented in all WiFi STAs and is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol.

In particular, a STA under the DCF operation tries to access the wireless medium using the following procedure:

- It uses a carrier sense procedure to sense the medium and check for activity

- If the medium is free, it waits for a DIFS and transmits if the medium is still free

- If the medium is busy, it backs off for a random number of time slots (minimum 15, and maximum 1023). When the random duration passes, and given that the medium is still free, it transmits, and if the transmission fails due to a collision, it backs off again with a larger random window, up to a preconfigured upper limit

Where DIFS is the DCF Inter-Frame Space, and it is one of six IFSs defined in WiFi:

- RIFS: Reduced Inter-Frame Space
- SIFS: Short Inter-Frame Space
- PIFS: PCF Inter-Frame Space
- DIFS: DCF Inter-Frame Space
- AIFS: Arbitration Inter-Frame Space (used by the QoS facility)
- EIFS: Extended Inter-Frame Space

Such that, RIFS<SIFS< PIFS < DIFS < AIFS<EIFS

Two carrier sense mechanisms are used to detect activity in the medium:

1. A physical carrier sense (CS) mechanism which shall be provided by the PHY
2. A virtual CS mechanism which shall be provided by the MAC. This method is based on setting what is referred to as the Network Allocation Vector (NAV), which represents a duration of time during which the STA defers from accessing the medium based on a *prediction* that the medium will be busy. This prediction is based on the duration information that is declared in the “Request-To-Send” and “Clear-To-Send” (RTS/CTS) frames that are sent when a STA attempts to reserve the medium before sending its actual traffic.

In our design, the PHY CS will be able to detect LTE traffic that is occurring on the WiFi channels, and will let the WiFi STAs defer from using the medium during LTE activity; thus preventing any interference between the LTE and the WiFi traffic.

On the other hand, the virtual CS cannot predict the LTE traffic, unless this is explicitly advertised.

b. The Point Coordination Function

The Point Coordination Function is required for Contention-Free services for non-QoS STAs and is optional otherwise. It is usually collocated with the AP. Thus, it is a centralized priority that gains control over the medium because it waits for a duration less than DIFS, namely for a PIFS duration.

The Point Coordinator (PC) maintains control over the medium during the Contention Free Period (CFP) for a maximum of CFPMaxDuration, which was presented earlier earlier within the description of the CFParameterSet element. During the CFP, and as the name indicates, no contention activities will be successful due to the PCs control over the medium. Instead, contention-free access to the medium can be given to a CF-Pollable STA. More specifically, the PC acts as a polling master and maintains a list of CF-Pollable STA to be polled and given permission to transmit.

c. The Hybrid Coordination Function

The QoS facility includes an additional coordination function called HCF that is only usable in QoS network configurations. The HCF shall be implemented in all QoS STAs except mesh STAs. Instead, mesh STAs implement the MCF. The HCF combines functions from the DCF and PCF with some enhanced, QoS-specific mechanisms and frame subtypes to allow a uniform set of frame exchange sequences to be used for QoS data transfers during both the CP and CFP. The HCF uses both a contention-based channel access method, called the enhanced distributed channel access (EDCA) mechanism for contention-based transfer and a controlled channel access, referred to as the HCF controlled channel access (HCCA) mechanism, for contention-free transfer.

i. HCF Contention-free Channel Access (HCCA)

The HCCA function provides parameterized QoS and it is contention-free, as TXOPs are polled. More specifically, the HC provides CF-Poll to the QoS station. After being polled, the QoS-STA can send an ADDTS request for requesting medium time. The ADDTS primitives were introduced in the Layer Management Protocols section above, and further details on the HCCA access method will be provided in Chapter V.

ii. HCF contention-based channel access (EDCA)

The EDCA mechanism provides differentiated, distributed access to the wireless medium for STAs using eight different UPs. The EDCA mechanism defines four access categories (ACs) that provide support for the delivery of traffic with User Priorities (UPs) at the STAs.

In order to use EDCA, QoS-APs implement four EDCA Functions (EDCAFs) corresponding to the four ACs. Each EDCAF is associated with a priority traffic queue containing data that belongs to the corresponding AC.

The EDCAF is a variation of the DCF; that is, when data is available for transmission, the EDCAF function contends for accessing the medium in a DCF standard manner; however, it uses the EDCA back-off and defer durations instead of those specified for DCF.

After gaining access to the medium, the QoS-STA is said to have won an instance of EDCA TXOP. During the TXOP, the QoS-AP will have uninterrupted access to the medium.

The EDCA parameters specifying the random window size and TXOP limits for each AC are set at the AP and advertised via the EDCA Parameter Set of Beacon frames. The EDCA Parameter Set format and the default EDCA settings were presented in section layer management subsection above. One can see that priority is given by smaller AIFS durations and back-off window sizes.

More details on the EDCA access method will be given in Chapter V.

4. WiFi PHY Layer Design

As mentioned earlier, we assume an OFDM PHY operation in the 5.8 GHz ISM band. Due to their high frequencies, the signals transmitted onto the 5.8 GHz band carriers experience high path-loss attenuation, which decreases their coverage capabilities. However, compared to the widely used and crowded 2.4 GHz band, the 5.8 GHz band is often underutilized, which justifies our choice.

Our choice was also based on the similarity between OFDM WiFi and the LTE PHY specifications whose access schemes are also OFDM-based; although, it is not necessary that WiFi shall use the same PHY access scheme for our system to work. More specifically - and as explained in the introduction of this thesis – our scheme is not aggregating simultaneous data flows from different technologies; hence, we don't need a transceiver design that is suitable for both LTE and WiFi PHY specifications. Instead, we are only borrowing spectrum, and the ultimate usage will be purely based on the LTE PHY specifications. Therefore, the only requirement for our design is to make sure that the structure of channels within the WiFi spectrum is consistent with the LTE PHY specifications, regardless of the access scheme used in WiFi transceivers.

In this regard, our study revealed many similarities between WiFi and LTE in terms channel bandwidth specifications, which further motivates the application of CA on these two standards.

a. Band, Bandwidth and Access Scheme Compatibility

In terms of band and bandwidth specifications, we found that the set of defined WiFi bandwidths is a subset of the LTE bandwidth set. In particular in LTE, the following bandwidths are defined: 1.4, 3, 5, 10, 15, 20 MHz, while in WiFi OFDM specifications 5, 10, and 20 MHz bandwidths are defined as basic bandwidths.

Thus, carrier aggregation as defined in the LTE specifications is compatible with the WiFi specifications. Particularly, the NxSC-FDMA approach can be applied for LTE-WiFi aggregation. This comes as a no surprise as both WiFi and NxSC-FDMA are based on the OFDM access scheme.

b. Channel Raster Compatibility

In terms of channel raster, aggregating LTE and WiFi channels should be compatible with the LTE-A 300 kHz channel raster as explained above. In our proposed CA mode, the aggregation is simple, as we are not integrating two standards together. We are simply borrowing spectrum and are still applying one standard: LTE-A. Thus, in theory the only restriction to take into account is channel raster: the center frequencies of the aggregated bands should satisfy the channel raster separation requirement. Reference [12] presents the band specifications for the WiFi standard. Channels from this band should be chosen so that their center frequencies are multiples of 100 kHz to satisfy LTE's channel raster requirements. The channel center frequencies in the 802.11 standard are defined as:

CCF = CSF + 5 x nCH, where

- CCF is the Channel center frequency
- CSF is the Channel starting frequency, which is defined as dot11ChannelStartingFactor × 500 kHz, or is defined as 5 GHz for systems where dot11OperatingClassesRequired is false or not defined.
- nCH is the channel number (ranges from 1 to 200 MHz)

The dot11ChannelStartingFactor attribute is implementation dependent, and being an integer, the WiFi channel center frequencies satisfy the 100 kHz channel raster.

CHAPTER III

FEASIBILITY CONSIDERATIONS AND RESEARCH CHALLENGES OF LTE-WIFI CA

Before presenting our design, we present in this section the main feasibility considerations and challenges when designing a coordinated LTE-WiFi system.

A. Coexistence Challenges and Fairness considerations

As it was stated earlier, coexistence challenges need to be considered when two different technologies use the same unlicensed bands. One of the main challenges is the degradation of performance due collisions and interference, which are expected to increase due to the incompatibility between the different specifications. This is mainly a concern for WiFi performance, as WiFi uses increasing random backoffs and inter frame spacing to avoid collisions. The WiFi STAs with such specifications will have little chance to access the medium when coexisting with the LTE system, not to mention that the LTE uses continuous traffic generation with minimum time gaps even in the absence of mobile data traffic, which makes the performance degradation of the WiFi system even more severe.

A solution to the problem stated above can be through one of two approaches: a coordinated approach through which the WiFi and LTE systems coordinate to manage the interference and fairness issue; and an uncoordinated approach, where the two technologies remain independent and take measures to avoid accessing the channels that might be in use with coexisting technologies. WiFi’s channel sensing and random backoff procedures are examples of uncoordinated measures. Dynamic frequency selection is another uncoordinated approach.

In our design, we use a coordinated approach that can be easily deployed without requiring any changes to the WiFi or LTE standards. In this approach the LTE system coordinates with the WiFi system to get information on the available spectrum and channel access methods.

B. LTE-WiFi Integration through HetNets

Generally speaking, the existing advances in the cellular systems technologies allow for multi-RAT integrated network architectures, through which coordination between the different RATs is made possible. These advances include the existing deployments of heterogeneous networks (HetNets) and small cells [17].

A network combining regular LTE cells, called macrocells, and small cells, is referred to as a heterogeneous network (HetNet). Small cells are similar to macrocells, but they have smaller coverage. Small cells can be generally classified into two kinds: picocells and femtocells. Table 6 summarizes the differences between these two kinds.

By referring to Table 6, we see that the femtocell deployment can be applied to a WiFi cell. In this option, a WiFi access point can be deployed as a HeNB, as it shares the same characteristics presented in Table 6. Given this, in addition to the 3GPP specifications for small-cell-macrocell coordination, LTE-WiFi coordination can be facilitated using small cell architectures. Another option, is that the coordination takes place between an

LTE pico-eNB and a regular WiFi AP; the importance of this option is that, unlike the macro-eNB, a pico-eNB has limited coverage, and hence less LTE-WiFi interference problems will occur when the pico-eNB borrows WiFi spectrum. More specifically, a macro LTE cell typically covers a significant number of WiFi APs, which introduces serious coordination and interference challenges. One or both options mentioned above can be taken into consideration in an LTE-WiFi CA design.

	Small Cells	
	Picocells	**Femtocells**
Controlled by	Pico-eNB	Home-eNB (HeNB)
Number of cells	Multiple small cells	One cell
Deployed/planned by	Network operator	The registered customer
Power (typically)	Higher	Lower
Network interfaces	Same interfaces of the regular eNodeB	Can be different from the regular eNodeB interfaces
Typical deployment coverage	An enterprise, mall, et. (hotzones)	A house or apartment

Table 6. Small Cells: picocells versus femtocells

C. Research Challenges for the LTE-WiFi Coordinated Scheme

The application of LTE-WiFi CA through multi-RAT coordination requires detailed network and MAC layer protocol design for the coordination between the two systems. The protocols are needed for WiFi AP discovery, connection establishment, interference coordination, and time synchronization. In subsections 1-3, we provide more details on these challenges. In subsection 4, we present another research challenge related to UE limited capabilities that constrain the selection of LTE-WiFi CA scenarios.

1. AP Discovery and Connection Configuration

Obviously, the first needed step in an LTE-WiFi coordinated CA system is for the eNodeB to be aware of the available WiFi APs in its proximity. After AP discovery, proper connection establishment protocol between the LTE and WiFi systems is needed.

AP Discovery:

In WiFi infrastructure-based systems, the WiFi stations STAs use Beacon request/report pairs for collecting information about available nearby WiFi APs. Beacon requests are sent from a STA to request from another STA a list of APs whose beacons it can receive on a specified set of channels [26]. It follows that an LTE eNodeB that needs to borrow spectrum from the WiFi system should simply behave as another WiFi STA by using similar beacon requests to discover nearby WiFi APs to interact with.

As we have mentioned earlier, another alternative is for the eNodeB of a small cell and the WiFi AP are wired (i.e., as part of a future standard), or collocated within an integrated physical element. In this case discovery may not be necessary as the two channel access units can communicate through a dedicated interface.

Connection Establishment:

After detecting available WiFi APs, the eNodeB needs to establish a connection with each AP it wishes to coordinate with. One approach is to design an X2-like interface between the eNodeB and the WiFi AP. This interface can be used for coordination and for the exchange of CA requests and replies. As mentioned earlier, the X2 interface connects eNodeBs together and is used for load-balancing, handover, and interference coordination functions.

The initiation of an X2 connection consists of three steps:

- Identification of a suitable neighbor. This is done by configuration or a self-organization process known as Automatic Neighbor Relation Function. This function can be replicated for the LTE-WiFi connection establishment and modified to include the beacon request messages and reports, as discussed earlier.

- Setting up the Transport Network Layer by the initiating eNodeB using the transport layer address of this neighbor as retrieved from the network or local configuration. The network addresses are also obtained from the network or the configuration.

- X2 set-up procedure, triggered by the initiating eNodeB. This allows for the exchange of application level configuration data including information about each of the cells managed by these eNodeBs. This kind of exchange is essential for LTE-WiFi CA, as it includes band and frequency information for each cell.

We believe that the functions of the X2 interface can be employed effectively in an LTE-WiFi integrated system. Further research is required to design the detailed protocol for such an X2-like interface.

2. Interference Coordination

As mentioned earlier, interference is another critical challenge for the application of the coordinated aggregation scheme, and it is more severe in the macro-cell scenario. The eNodeB will borrow spectrum from the WiFi bands which may already be occupied by WiFi STAs in nearby cells. Thus, interference detection (i.e., sensing) and mitigation is needed between the two systems to prevent the LTE-A UE transmissions from interfering with the WiFi STAs, and this can be a function within the X2-like interface, discussed previously.

3. MAC Layer Time Synchronization

As detailed in section C-3, the architecture of the WiFi MAC sublayer includes two basic functions: the Distributed Coordination Function DCF and the Point Coordination Function PCF. The DCF is used for contention-based services, where stations contend for accessing the radio channel based on the CSMA/CA access scheme. The stations must verify that the medium is idle for a period of time, after which it uses a pseudo-random back-off period before it accesses the channel, given that the channel remains idle. On the other hand, the PCF is collocated with the Access Point (AP) and provides contention-free services, where the AP acts as a polling master for granting permissions to stations in the range to transmit. For Quality-of-Service (QoS) networks (providing differentiated services), the counterparts of DCF and PCF are EDCA (Enhanced Distributed Channel Access) and HCCA (HCF Control Channel Access), respectively.

The WiFi MAC divides time into constant-length superframes, each containing an optional CFP (Contention-free Period) followed by a CP (Contention Period). Hence, the PCF and DCF access methods alternate in time, where the CFP stretches or shrinks based on demand for transmissions given there is enough time to transmit at least one MAC frame [27].

On the other hand, and as mentioned in Chapter II, the LTE system divides time into 1ms subframes, each containing two 0.5ms time slots, occupied by two resource blocks in time. The eNodeB scheduler runs every subframe, also known as Transmission Time Interval (TTI), and allocates RBs to the UEs.

It follows that proper LTE-WiFi time synchronization is required to avoid interference between the LTE and WiFi traffic. Particularly, when the eNodeB gets access to the WiFi channels, using the WiFi channel access protocols, it has to make sure that the borrowed channel(s) will be available to the LTE system for the entire subframe, because the eNodeB cannot grant WiFi resources unless it knows that the WiFi channel will remain available till the end of the resource allocation time.

4. Complexity and Power Considerations

The complexity and power considerations of the UEs are additional concerns. 3GPP defined five different UE categories for LTE [21] based on their cost and capabilities [25]. Three additional UE categories (6, 7, and 8) were added in LTE Release 10, and additional ones are expected in the future. The choice of the carrier aggregation scenario should take into consideration these UE categories and their capabilities. Tables 7 and 8 show the detailed capabilities of the 8 UE categories [21] [22].

	UE Category				
	1	2	3	4	5
Supported downlink data rate (Mbps)	10	50	100	150	300
Supported uplink data rate (Mbps)	5	25	50	50	75
Number of receive antennas required	2	2	2	2	4
Number of downlink MIMO layers supported	1	2	2	2	4
Support for 64QAM modulation in downlink	Y	Y	Y	Y	Y
Support for 64QAM modulation in uplink	N	N	N	N	Y
Relative memory requirement for physical layer processing (normalized to cat 1 level)	1	4.9	4.9	7.3	14.6

Table 7. LTE Release 8 and 9 UE categories

	UE Category		
	6	7	8
Approximate supported DL data rate (Mbps)	300	300	3000
Approximate supported UL data rate (Mbps)	50	100	1500
Number of downlink MIMO layers supported	2 or 4	2 or 4	8
Number of uplink MIMO layers supported	1, 2 or 4	1, 2 or 4	4
Support for 64QAM modulation in downlink	Y	Y	Y
Support for 64QAM modulation in uplink	N	N	Y
Relative memory requirement for Downlink HARQ processing (normalized to cat 1 level)	14.6	14.6	144

Table 8. LTE Release 10 UE categories

As shown, each UE category supports a specific data rate which restricts the bandwidth allocation for this UE. A category 3 UE, for example, can be re-used in Release 8 to support the aggregation of 2 CCs of up-to 10 MHz bandwidth each. In addition, it is possible for LTE-A UEs (i.e. category 6, 7, or 8) to signal a category 1 through 5 UE to support backward compatibility in networks which do not support Release 10. Therefore, in addition to the RF constraints mentioned in section B-1-c, specific UE categories need to be chosen before selecting an aggregation scenario. The CA scenario should provide an aggregation scheme that can be supported by the UE.

In the following chapter, we present our literature review, and next we present our proposed design for the LTE-WiFi CA system. In our design, we only focus on the WiFi channel access methods and the timing synchronization matters. Further research is required for addressing the remaining challenges summarized above.

CHAPTER IV
LITERATURE REVIEW

Multi-RAT carrier aggregation (CA) is a recent and active research area, as it is envisioned that in future 5G systems, Carrier Components (CCs) from different technologies will be aggregated and allocated to the end user. Particularly, CCs from different 3GPP technologies (UMTS, LTE, and LTE-A) and non-3GPP technologies such as WiFi, are expected to be used for LTE-A CA. In this section, we present the state of art in this research area with emphasis on the existing challenges and how we addressed them.

A. Multi-RAT CA

The authors in [38] propose a setup for modeling the downlink transmission according to the LTE Release 12 PHY specifications, and use this setup to assess the performance of different CA scenarios. The authors present the three CA modes; namely, the contiguous mode, the non-contiguous single-band (or intra-band) mode, and the non-contiguous multi-band (or inter-band) mode. Moreover, they describe the different CA deployment scenarios which vary in terms of carrier frequency coverage of the aggregated CCs, the base stations' antenna directions, and the presence of remote radio heads. Finally, the authors evaluate and compare – via simulations – the performance of different CA scenarios in terms of bit error rates (BERs). Table 9 presents the three sets of simulated scenarios with summaries of the results for each.

	Description	Summary of Results
1st set of scenarios	The inter-band non-contiguous CA scenarios defined by 3GPP Release 10 CA specifications [14].	In this experiment, the CA scenarios varied in terms of CC bandwidths. Obviously, wider aggregated BWs provided less BERs.
2nd set of scenarios	Intra-band CA scenarios.	In this experiment, two CA scenarios we tested, which varied in terms of center carrier frequency of the aggregated CCs (within the same licensed band). The two scenarios showed the same performance results in terms of BER.
3rd set of scenarios	CA scenarios utilizing the unlicensed band.	In this experiment, a 900 MHz – 5 GHz unlicensed CA scenario was compared to a the CA(1,5) licensed scenario (see [14] for a description of the CA(1,5) scenario). Same BER performance was reported for the unlicensed and licensed scenarios.

Table 9. BER comparison between different CA scenarios

As shown in Table 9, CA in the unlicensed band can provide comparable performance to that of the licensed band, which motivates unlicensed CA deployment. This study however, and as noted by the authors, does not take into consideration the hardware complexity challenges which concern the power and cost requirements of the UE using the aggregated CCs; nor does it tackle the coexistence challenges that are raised when using the unlicensed bands. More specifically, the considered unlicensed bands are currently used by other technologies, namely 802.11 a/n, and using them for LTE-A CA will cause interference to these technologies; such interference can severely degrade the performance of these coexisting technologies.

Based on the above, coexistence challenges need to be considered when two different technologies use the same unlicensed bands. One of the main challenges is the degradation of performance due collisions and interference, which are expected to increase due to the incompatibility between the different specifications. This is mainly a concern for WiFi performance which uses increasing random backoffs and inter frame spacing to avoid collisions. The WiFi STAs with such specifications will have little chance to access the medium when coexisting with the LTE system, not to mention that the LTE uses continuous traffic generation with minimum time gaps even in the absence of mobile data traffic, which makes the performance degradation of the WiFi system even more severe.

The authors in [37] and [41] illustrate this problem by measuring the throughput degradation in LTE-WiFi coexisting networks under different deployment scenarios and STA densities. Figure 23 shows the results of an experiment reporting LTE and Wi-Fi average user throughput relative to Wi-Fi low AP density for indoor scenario [37]. The involved deployments are: low AP density (4 APs per technology) and high AP density (10 APs per technology) with an average STA density of 2.5 per AP for both cases. The LTE and Wi-Fi evaluations are made under two cases: isolated (LTE, Wi-Fi) and in coexistence (LTE (Coex) and Wi-Fi (Coex)). As shown in the figure, both LTE and WiFi experience degradation in performance; however, the degradation in LTE performance is insignificant, while that of WiFi is severe.

Of course, in this experiment, the LTE system is using a shared unlicensed spectrum instead of the licensed LTE bands. In our design, however, we do not replace the licensed spectrum; instead, we keep it and aggregate with it WiFi channels. Thus, the LTE system will experience higher throughput. Our main challenge therefore is to account for the degradation in the throughput of the coexisting WiFi network.

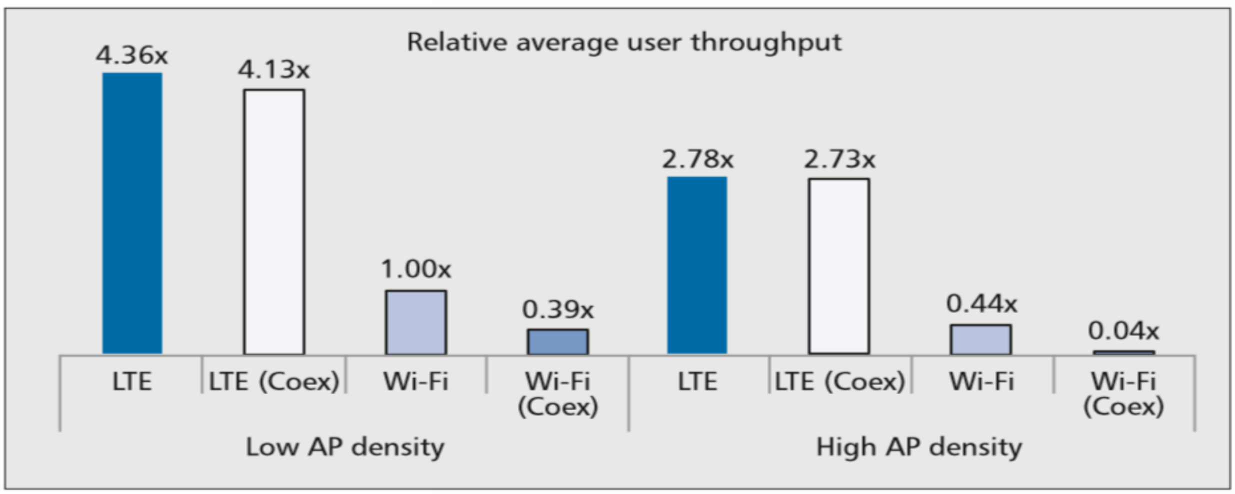

Figure 23. Throughput degradation due to LTE-WiFi co-existence [37].

Similar results were reported in [41], which shows that WiFi is almost blocked by LTE traffic in coexistence scenarios, where WiFi STAs stay in the LISTEN mode for more than 96% of the time, and their throughput decreases by 70 to 100% depending on the scenario.

In the next subsection, we present a summary of the main techniques that exist in the literature to solve the coexistence problem.

B. Multi-RAT Coexistence Techniques

A solution to the coexistence problem can be through one of two approaches: a coordinated approach through which the WiFi and LTE systems coordinate to manage the interference and fairness issue; and an uncoordinated approach, where the two technologies remain independent and take measures to avoid accessing the channels that might be in use with coexisting technologies. WiFi's channel sensing and random backoff procedures are examples of uncoordinated measures. Dynamic frequency selection is another uncoordinated approach. In this subsection, we summarize existing works that aim at solving the coexistence problem using one or both approaches.

1. The Cognitive Radio and Channel-Selection uncoordinated techniques

In cognitive-radio networks, secondary users utilize fragments of the spectrum used by other primary users in a way that minimizes interference with the primary traffic. Interference control is achieved by sensing the primary traffic at the secondary nodes. More specifically, in an LTE-Unlicensed cognitive-radio network, the LTE system senses the traffic on the unlicensed frequencies and uses these frequencies only when they are detected to be free.

The authors in [42] summarize the cognitive-radio literature and classify the sensing techniques used in the literature into two types: a "type 1" sensing method where sensing is performed before transmission, and a "type 2" sensing method where sensing is performed during transmission. Since type 2 sensing provides more efficient sensing than type 1, the authors propose a system model for type 2 sensing and discuss it with different energy detection methods; namely, beamforming based energy detection (ED-BF) [43] and reference signal cancellation based energy detection. The simulation results show acceptable sensing performance for a wide range of SNRs in different scenarios, including LTE-A CA scenarios.

Channel-selection is another technique proposed in the literature, and it can be considered as a special type of cognitive-radio. The authors in [44] propose a design and implementation of a dynamic channel-selection scheme for controlling the interference among sectorized WiFi cells, in which the least congested channels are selected by the Aps to reduce interference. Thus, in this work, coexistence between different RATs is not discussed, however similar schemes can be utilized in LTE-WiFi coexistence scenarios. In a channel selection scheme, the WiFi AP intelligently chooses the channels that minimize interference with the LTE traffic.

The importance of the cognitive-radio approach lies in its simplicity and low complexity implementations, where no coordination is required for reducing interference. However, this uncoordinated approach suffers from energy-detection inaccuracies due to the uncertainties of noise variance.

2. *Transmission power control uncoordinated techniques*

Transmission power control is another uncoordinated technique that can be used to enable LTE-WiFi coexistence. Particularly, LTE base stations (eNodeBs) limit their transmission power to reduce interference with the WiFi traffic.

The authors in [45] propose the use of LTE-UL power control to improve LTE-WiFi coexistence. The proposed technique is flexible with configuration parameters that can be adjusted to favor LTE or WiFi performances. The proposed technique adds a factor to the power control specifications of 3GPP [48], a factor that is based on interference measurements. In the conventional scheme, the power operating point is calculated as a function of pathloss only. The authors argue that is not sufficient for LTE-WiFi coexistence scenarios and propose adding an interference factor to the power operating point calculation. The interference factor is based on eNodeB interference power measurements.

Similar to cognitive-radio techniques, the transmission power control techniques suffer from potential inaccuracies.

3. Multi-RAT coordination techniques

As mentioned earlier, an alternative to the uncoordinated techniques is to build a coordinated system, where coordination between the coexisting technologies is used to reduce interference. In such coordinated systems, system parameters are typically negotiated between the coexisting technologies to achieve optimal performance.

The authors in [37] summarize literature on multi-RAT coordination techniques and describe the common features that are typically present in all coordinated schemes. Figure 24 shows a generalized procedure that most collaborative schemes follow. As shown the coexisting technologies typically switch between regular and coexistence modes, and within the coexistence mode, they negotiate system parameters for optimizing performance.

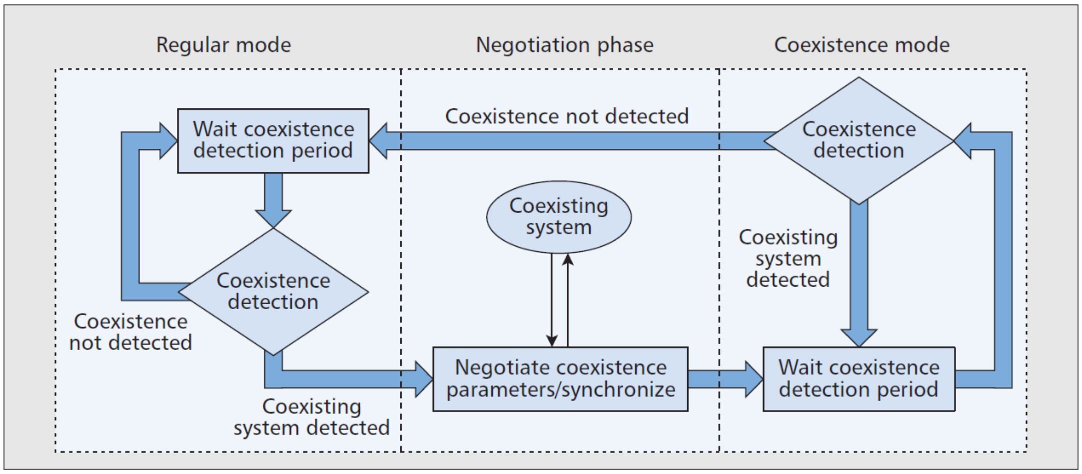

Figure 23. Generalized coordinated coexistence algorithm [37].

Examples of particular collaborative schemes are provided in [37]. These schemes include measures to avoid interference within coexisting networks. However, to the best of our knowledge (and as indicated in [37]), there is no design yet nor an implementation in the literature for an integrated and coordinated LTE-WiFi scheme; hence the significance of our work which seeks to propose such a design and implementation.

C. The LTE-WiFi Proposed Scheme as Compared to the State of Art

Our proposed scheme utilizes methods from both collaborative and non-collaborative techniques. In particular, we propose that the LTE base station eNodeB behave as a WiFi STA to access the WiFi spectrum; this is achieved by adding a WiFi submodule to the eNodeB that runs in parallel with the eNodeB functions. Within this approach, the WiFi and LTE functions will be running independently and hence, our scheme will resemble an uncoordinated scheme. In other words, from the WiFi system point of view, the LTE system will appear as any other regular WiFi STA; and on the other hand, from the LTE system point of view the WiFi spectrum resources are used as regular LTE resources.

On the other hand, we utilize a simple coordination technique, where the WiFi and the eNodeB submodules coordinate to achieve timing synchronization and exchange information on the transmission opportunities that were granted or gained by the WiFi submodule. Moreover, we utilize the different coordinated and QoS negotiation techniques that exist in the WiFi standard and which occur between a QoS STA and an AP. More details on the design will be presented in the design section next.

CHAPTER V

LTE-WIFI CA SYSTEM DESIGN

We propose a simple and efficient scheme for an LTE-WiFi coordinated CA system. In our scheme, the eNodeB behaves as a WiFi STA to access the WiFi channels and to borrow them for LTE Carrier Aggregation (CA) purposes. We assume a small cell scenario in which only one WiFi AP is within the transmission range of the eNodeB. For future work, we shall consider the macrocell scenario where multiple WiFi BSSs exist within the LTE cell range, in which case, complex interference problems need to be considered, as explained earlier.

Thus, in this design, the eNodeB needs to coordinate with one WiFi AP. For this purpose, we propose a hybrid model that includes two submodules that run in parallel:

1. eNodeB submodule: responsible for running the eNodeB functions within the LTE small cell
2. WiFi submodule: responsible for running the WiFi channel access functions within the WiFi BSS

The two submodules extend their functionalities beyond the standard eNodeB and WiFi functions and exchange information in order to achieve proper LTE-WiFi CA.

Figure 25 illustrates our hybrid model. The WiFi submodule shown in the figure is the interface through which the eNodeB communicates with the WiFi AP.

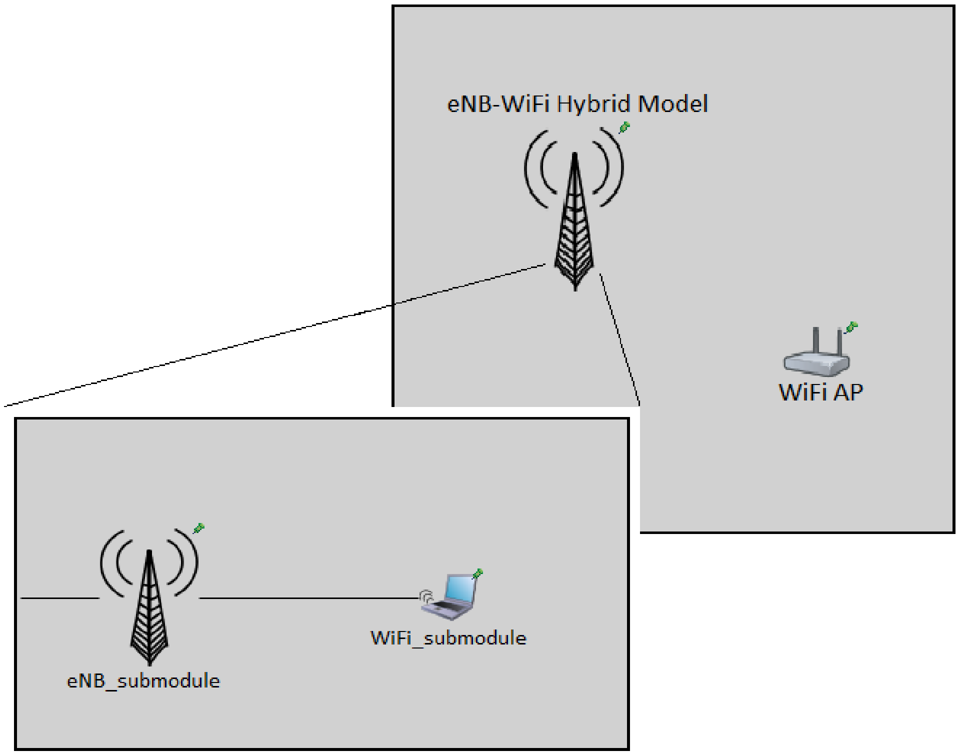

Figure 24. eNB-WiFi Hybrid Model

In our design, the WiFi submodule is a QoS-non-AP STA, and is assumed to belong to a QoS BSS; that is, the WiFi submodule is within the range of a QoS-AP. We selected the QoS BSS type so that we can utilize the EDCA and HCCA functions which, to the best of our knowledge, are the most suitable and efficient channel access methods for our system. These access methods and their corresponding management primitives were detailed in Chapter II. We selected HCF in order to limit the LTE's traffic interference with the WiFi traffic by imposing the HCF standardized medium time limits, and at the same time provide the LTE system with some medium time guarantees through EDCA's priority method and HCCA's QoS parameterized method.

The sequence of events that occur within our scheme can be summarized as follows:

- The WiFi submodule scans and reads the Beacon frames sent by the AP
- The WiFi submodule joins the WiFi BSS under the control of the AP, using the synchronization information in the Beacon frame
- The WiFi submodule initiates an authentication sequence to become authenticated by the AP
- Assuming successful joining and authentication, the WiFi submodule initiates an association sequence to associate with the AP. In the association request, it sets the CF-Pollable subfield of the capabilities element into 1 to indicate that it wants to be added to the AP's Polling list (assuming that the WiFi AP is a QoS-AP: this is similarly indicated in a capabilities information element in the beacon frame)
- While in the associated state, the WiFi submodule periodically scans for Beacon frames in order to remain up-to-date with all the BSS configurations. In this state as well, it utilizes the HCF access methods using one or both HCF functions; namely, EDCA and/or HCCA, in attempt to gain Transmission Opportunities (TXOPs)
    - If HCCA is to be used, the WiFi submodule waits for a QoS-Poll, and when it is polled, it sends an ADDTS (ADD-Traffic Stream) request to request TXOPs. The Traffic SPECifications (TSPECs) within the ADDTS request are set so that the corresponding needed medium time is less than the available channel capacity that is advertised in the Beacon frame. Otherwise, if the requested TSPECs require medium time that is larger than the channel capacity, then it is unlikely that TXOPs will be granted. Moreover, the inactivity interval and suspension interval are set to their maximum values to prevent the suspension of the TS in case of undetected traffic activity. The WiFi submodule is informed of the admission request result in the ADDTS response frame that is returned by the AP. If the TS is admitted, the response includes a schedule element that indicates TXOP start times and durations.

- If EDCA is to be used, the WiFi submodule checks the Admission Control Mandatory (ACM) bit of the EDCA Parameter Set element of the Beacon frame for the Access Category (AC) of the highest priority. If this bit is set, then admission control is required, and the WiFi submodule needs to send an ADDTS request as in the HCCA case. On the other hand, if ACM is not set, then no admission control is required, and the WiFi submodule can use the EDCA Function (EDCAF) corresponding to the selected AC to contend for accessing the medium and acquiring an EDCA TXOP. The EDCAF backoff, defer, and TXOP durations, as well as the priorities of the different ACs are advertised in the EDCA Parameter Set of Beacon frames.

- For each gained TXOP, whether gained by HCCA or EDCA, the following sequence of events follow:

  - The WiFi STA sends an EDCA frame that lets the other WiFi STAs reset their NAVs and regard the channel as busy till the end of the TXOP.

  - The WiFi submodule sends a timestamp and the remaining TXOP duration to the eNodeB submodule, along with WiFi channel information (bandwidth and carrier frequency)

  - The eNodeB uses the WiFi channel during the TTIs that fully belong to the TXOP timespan. The WiFi channel is aggregated with the LTE channel and allocated to the LTE-A UE.

  - In case the remaining TXOP duration is more than 0.5 ms and less than 1ms (not sufficient for the TTI), the eNodeB will not be able to use the WiFi channel. In this case, the eNodeB submodule notifies the WiFi submodule to inform it that the eNodeB will not use the remaining TXOP time. In this case, the WiFi submodule sends a CF-End frame which causes a NAV-reset at the WiFi STAs and hence allows them to use the TXOP duration that is left.

More details on the events listed above are provided in the following subsections.

A. WiFi submodule Authentication/Association FSM

Figure 26 presents the four authentication/association states of the WiFi submodule. These states were described in Chapter II. Initially, the WiFi submodule is in STATE 1. Using the standard procedures described earlier, the WiFi scans then synchronizes with the QoS-AP. It then initializes the authentication and association sequences. After a successful association, the WiFi submodule is in STATE 3 and is therefore ready to use the channel access methods.

Note that STATE 4 is concerned with Robust Security Network Authentication, which is out of the scope of our work; i.e. for the completeness of our design, it is sufficient to reach in STATE 3.

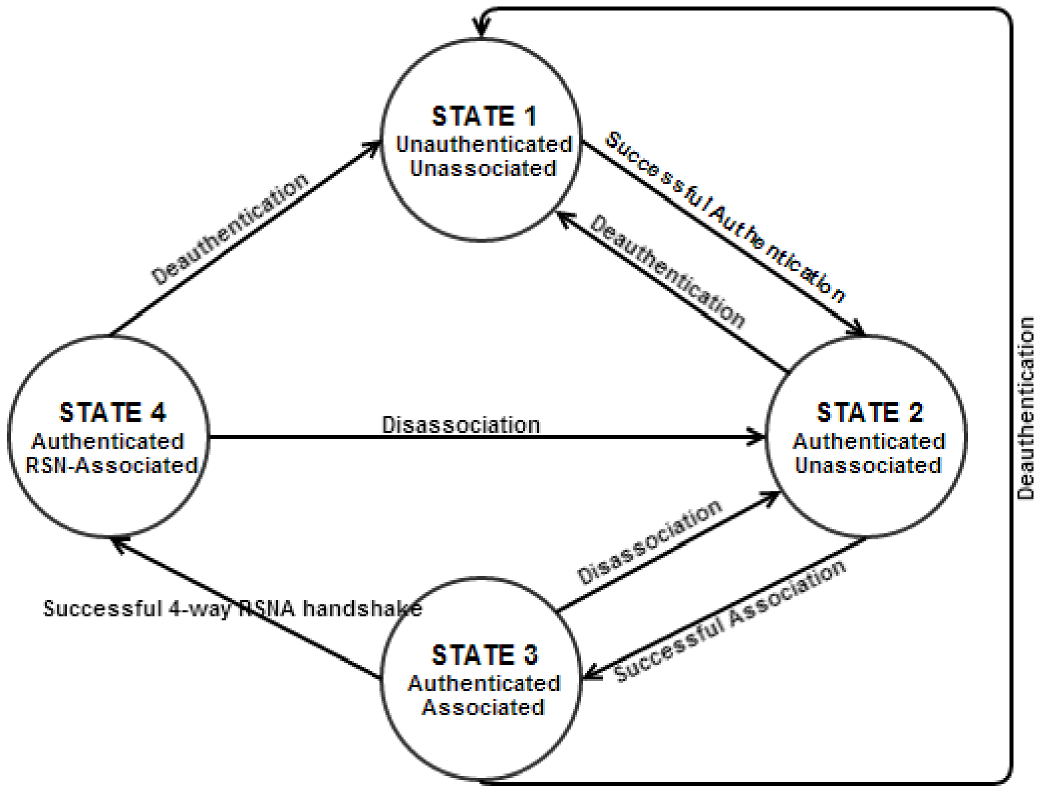

Figure 25. WiFi submodule auth/assoc FSM

B. LTE-WiFi timeline in STATE 3

While in STATE 3, the WiFi submodule will try to reserve medium time for CA purposes, using the HCF methods.

For This purpose, we propose two alternatives corresponding to each HCF access method; namely, HCCA and EDCA. These alternatives can be used separately or together. In the following subsections, we describe the sequence of events that occur for achieving CA on the LTE and WiFi timelines. The events include the sequence of messages exchanged between the WiFi submodule and the QoS-AP on one hand; and between the WiFi submodule and the eNodeB submodule on the other hand.

In both alternatives, the WiFi submodule will try to obtain a TXOP, which as mentioned earlier is a time duration during which it can get uninterrupted access to the medium; and whenever it wins a TXOP instant, it forwards the information to the eNodeB submodule to allow it to use the WiFi channel(s) during the TXOP duration.

1. HCCA design timeline

As mentioned above, the ADDTS MLME primitives are needed to obtain HCCA TXOPs. Namely, the WiFi submodule sends an ADDTS request frame to the QoS-AP. If it receives a response indicating a non-zero granted medium time, then the requested TS is admitted; meaning that the WiFi submodule will receive polled TXOPs. When the WiFi submodule is granted a polled-TXOP, it forwards this information to the eNodeB submodule so that it can use the WiFi channel for CA. This is illustrated in Figure 27.

As mentioned earlier, in order for the WiFi submodule to be polled (i.e. added to the polling list at the HC), it should indicate that it is CF-Pollable in the Capability Information element of the association request.

As shown in Figure 27, a beacon frame is received from the QoS-AP every Beacon Period (at TBTTs) and a CFP is started every CFPPeriod. Within both CP and CFP, the HC in the QoS-AP can gain control over the medium by contention. Specifically, the HC senses the medium to be idle for a PIFS duration, and if it gains access, it maintains control over the medium for a period of time called the Controlled Access Phase (CAP). During CAPs that start with a beacon frame, the CAP duration is advertised to the WiFi STAs in the

CFParameterSet element whose format was presented in Chapter II, in the same way by which a CFP duration is advertised. Thus the WiFi submodule scans every BeaconPeriod (at TBTTs) and obtains information about the CAP start times and durations, using the scanning primitives that were also described in Chapter II. Only during a CAP, the WiFi submodule can be polled and hence can use the HCCA access method. Similarly, only during CPs, it can use the EDCA access method.

Note on CP, CFP, and CAP durations – *Refer to Appendix B for details of CFPPeriod, CFPMaxDuration, and BeaconPeriod default and maximum values. By referring to Appendix B and keeping in mind that the CAP is similar to a CFP (that is, its duration cannot exceed the advertised CFPMaxDuration), we see that the CP and CAP durations are in the order of 100's to 1000's of TUs, where 1 TU is 1.024 ms. Thus, they overlap with 100's to 1000's of LTE subframes (or TTIs).*

During a TXOP that was granted by a successful ADDTS operation (i.e. with non-zero medium time), the eNodeB can use the WiFi channel only if the remaining TXOP duration completely covers a TTI. In the example of Figure 27, the TXOP is about 3 ms and it covers two TTIs. The eNodeB starts using the channel for CA at the beginning of TTI_{k+1}. That is: during the LTE scheduling process at the beginning of TTI_{k+1}, the eNodeB aggregates the WiFi channel with the available LTE channels. This is repeated for TTI_{k+2}. At the start of TTI_{k+3}, the remaining TXOP time is less than the TTI duration, which means that the WiFi channel will not be available for the entire scheduling interval.

Since the eNodeB does not perform new scheduling until the start of the next TTI, then it cannot use the WiFi resources for the current TTI. Therefore, the CA process ends at the end of TTI_{k+3}, and because of the early finish of the TXOP utilization, a TXOP truncation is performed by the WiFi submodule at the start of TTI_{k+3} using the CF-End frame, by which the TXOP is declared to be truncated so that other WiFi STAs can benefit from the remaining TXOP time.

The detailed operations for all these events are presented in the following subsections.

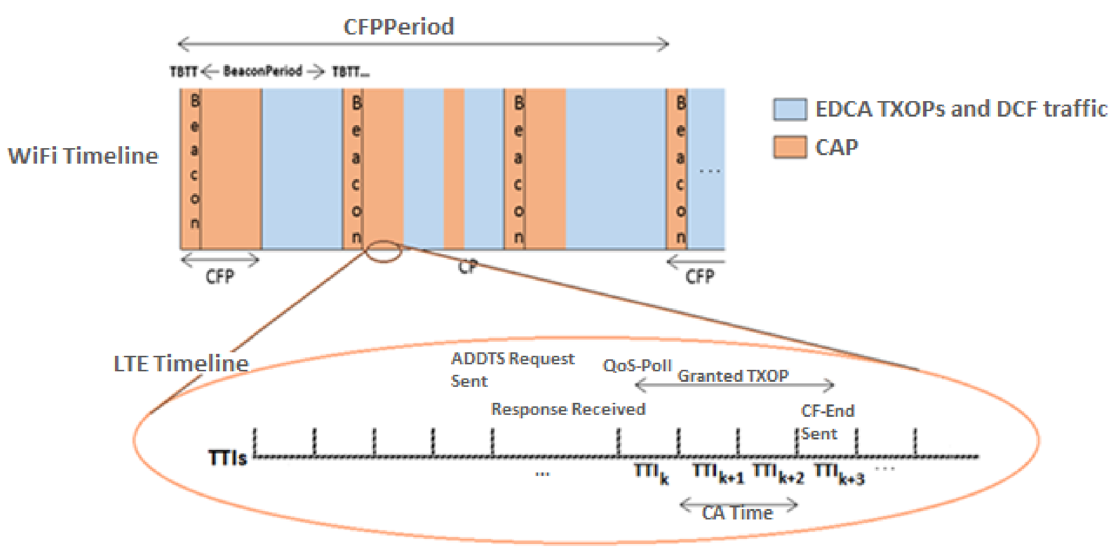

Figure 26. HCCA LTE/WiFi timelines

a. <u>The ADDTS request and response</u>

In Chapter II, we introduced the ADDTS primitives that are used for adding a TS of specified QoS parameters. In this subsection, we detail our proposed QoS parameter values.

As mentioned earlier, the WiFi submodule should initialize the ADDTS sequence by generating an ADDTS.request primitive. The request includes a TSPEC element describing the requested traffic specifications. Based on these specifications, the AP specifies the needed medium time and potentially grants it to the requesting STA.

In this section, we detail how the WiFi submodule uses the TSPEC element to get the medium time as needed by the LTE system.

The format of the TSPEC element is shown in Figure 28. In the figure, the fields highlighted in light gray color indicate the required fields. Other fields are optional and can be set to zero in case the STA does not have the corresponding information. In addition to the required fields, we will use the Inactivity and the Suspension Interval fields to make sure that the HC at the AP does not remove any granted medium time in case an inactivity was detected. This is because the LTE traffic might be detected via PHY carrier sense; however, if virtual carrier sense is used, it will not be detected, an inactivity might be assumed and the HC might delete the TS using the DELTS primitives that were presented in Chapter II.

The Medium Time field is not used by the WiFi submodule in the ADDTS request, because this field is set by the AP and is sent in the TSPEC element of the ADDTS response frame.

We present next the description of the fields and our proposed values for each.

	El. ID	L	TS Info	Nom. MSDU Size	Max. MSDU Size	Min. Ser. Inter.	Max. Servi ce Inter.	In-activity Inter.	Suspen -sion Inter.
Octs.	1	1	3	2	2	4	4	4	4

	Service Start Time	Min. Data Rate	Mean Data Rate	Peak Data Rate	Bur-st Size	Delay Bou-nd	Min. PHY Rate	Sur-plus BW Allow.	Medium Time
Octs:	4	4	4	4	4	4	4	2	2

Figure 27. TSPEC element Format

<u>TS Info Fields:</u>

Traffic Type – 1 bit: 1 --> periodic traffic pattern

0 --> aperiodic, unspecified traffic pattern

We propose setting this bit to 0 in order not to constrain the kind of traffic (LTE traffic in our case) that will be generated during the granted medium time.

TSID – 4 bits that contain a value that is a TSID. Note that the MSB (bit 4 in TS Info field) of the TSID subfield is always set to 1

Direction – 2 bits: 00 --> UL

10 --> DL

01 --> Direct Link

11 --> Bidirectional

We need to set this field to 00 because we do not expect any data to be downloaded from the AP to the WiFi submodule. Moreover, the borrowed spectrum will be utilized in the LTE UL RBs and TXOPs are the UL direction (remember TXOP stands for Transmission opportunity).

Access Policy – 2 bits that define the access policy to be used for the TS.

00 --> reserved

10 --> EDCA

01 --> HCCA

11 --> HEMM (HCCA, EDCA mixed mode)

In this case we will need to set this to HCCA (01)

Aggregation – 1 bit which indicates if aggregation of multiple TSs is requested.

We assume that this field is set to 0 because aggregation of multiple TSs is out of the scope of our study.

APSD – 1 bit which indicates that automatic PS delivery is to be used for the traffic

This is also out of the scope of our study and thus we assume it is set to 0.

User Priority – 3 bits that indicate the actual value of the UP to be used for the transport.

We set this to 7 which is the highest UP

TSInfo

Ack Policy – 2 bits that indicate whether MAC acknowledgments are required for MPDUs or A-MSDUs belonging to this TID and the desired form of those acknowledgments.

00 --> Normal IEEE 802.11 Acknowledgment

10 --> No Ack

01 --> Reserved

11 --> Block Ack

We set this field to “No Ack” because we are not expecting any acknowledgments for data frames.

Schedule – *1 bit that Specifies the requested type of schedule. This subfield in reserved in case of HCCA access method; thus, it will not be used in our context.*

Nominal MSDU Size

2 octets long, contains an unsigned integer that specifies the nominal size, in octets, of MSDUs or A-MSDUs belonging to the TS under this TSPEC.

This filed is divided into a 1-bit “Fixed” subfield and a 15-bits “Size” subfield.

If the Fixed subfield is equal to 1, then the size of the MSDU or A-MSDU is fixed and is indicated by the Size subfield. If the Fixed subfield is equal to 0, then the size of the MSDU or A-MSDU might not be fixed and the Size subfield indicates the nominal MSDU size. If both the Fixed and Size subfields are equal to 0, then the nominal MSDU size is unspecified.

This subfield along with the data rate subfields presented next will be set so that the calculated medium time at the AP is less than the Available Admission Capacity, in order to increase the probability of being admitted. This will be detailed in the medium time subfield description.

Inactivity Interval field:

4 octets long; contains an unsigned integer that specifies the minimum amount of time, in microseconds, that may elapse without arrival or transfer of an MPDU belonging to the TS before this TS is deleted by the MAC entity at the HC.

We set this subfield to *4 294 967 295* $(2^{32} - 1)$. In the standard this value indicates that inactivity will not stop the HCCA operations and grants for this STA. This is necessary because, the LTE traffic will not be detected if virtual carrier sense is used, and an inactivity might be assumed.

Suspension Interval

4 octets long; contains an unsigned integer that specifies the minimum amount of time, in microseconds, that may elapse without arrival or transfer of an MSDU belonging to the TS before the generation of successive QoS(+)CF-Poll is stopped for this TS.

Similarly, a value of 4 294 967 295 disables the suspension interval, indicating that polling for the TS is not to be interrupted based on inactivity. The value of the suspension interval is always less than or equal to the inactivity interval.

Mean Data Rate

4 octets long and contains an unsigned integer that specifies the average data rate specified at the MAC_SAP, in bits per second, for transport of MSDUs or A-MSDUs belonging to this TS within the bounds of this TSPEC. The mean data rate does not include the MAC and PHY overheads incurred in transferring the MSDUs or A-MSDUs.

Minimum PHY Rate

4 octets long; contains an unsigned integer that specifies the desired minimum PHY rate to use for this TS, in bits per second; that is required for transport of the MSDUs or A-MSDUs belonging to the TS in this TSPEC.

Surplus Bandwidth Allowance

2 octets long; specifies the excess allocation of time (and bandwidth) over and above the stated application rates required to transport an MSDU or A-MSDU belonging to the TS in this TSPEC. This field is represented as an unsigned binary number and, when specified, is greater than 0. The 13 least significant bits (LSBs) indicate the decimal part while the three MSBs indicate the integer part of the number. This field takes into account the retransmissions, as the rate information does not include retransmissions. It represents the ratio of over-the-air bandwidth (i.e., time that the scheduler allocates for the transmission of MSDUs or A-MSDUs at the required rates) to bandwidth of the transported

MSDUs or A-MSDUs required for successful transmission (i.e., time that would be necessary at the minimum PHY rate if there were no errors on the channel) to meet throughput and delay bounds under this TSPEC, when specified. As such, it should be greater than unity. A value of 1 indicates that no additional allocation of time is requested.

Medium Time

16-bit unsigned integer; contains the amount of time admitted to access the medium, in units of 32 μs/s.

This field is not set at the WiFi STA when sending the ADDTS request. Instead it is calculated at the AP based on the QoS specifications in the received TSPEC element. An example medium time calculation is as follows [58]:

$$Medium\ Time\ =\ Surplus\ Bandwidth\ Allowance\ \times\ pps\ \times\ MPDUExchangeTime$$

where:

$$pps\ =\ Ceiling\left(\frac{Mean\ Data\ Rate}{8 * Nominal\ MSDU\ Size}\right)$$

$$MPDUExchangeTime\ =$$

$$duration(Nominal\ MSDU\ Size, Minimum\ PHY\ Rate)\ +\ SIFS\ +\ ACK\ duration$$

Based on the above, we propose that the Mean Data Rate, Nominal MSDU Size, and Minimum PHY Rate fields be set so that the calculated Medium Time value is less than the Available Admission Capacity for the desired UP. Of course, the values will not reflect the real rates and data size the MSDUs because no WiFi traffic will actually be generated.

The admission capacity can be known from the BSS Admission Capacity element read from Beacon frames as it was detailed in Chapter II.

Thus, if medium time is less than the admission capacity, then it is likely that the stream will be admitted.

The ADDTS Response:

After receiving the ADDTS request, the WiFi AP calculates the required medium time as per the example provided above. If the current admission capacity is sufficient to admit the requested stream, a positive value of medium time is specified in the Medium Time field of the response TSPEC. The response is sent back to the WiFi submodule specifying the admitted SPECs in a TSPEC element of the same format as that in the request frame. In case of successful admission, a schedule element will be included in the response.

The schedule element lets the WiFi submodule know when it will get the TXOP grants (polls). The format of the schedule element is shown in Figure 29.

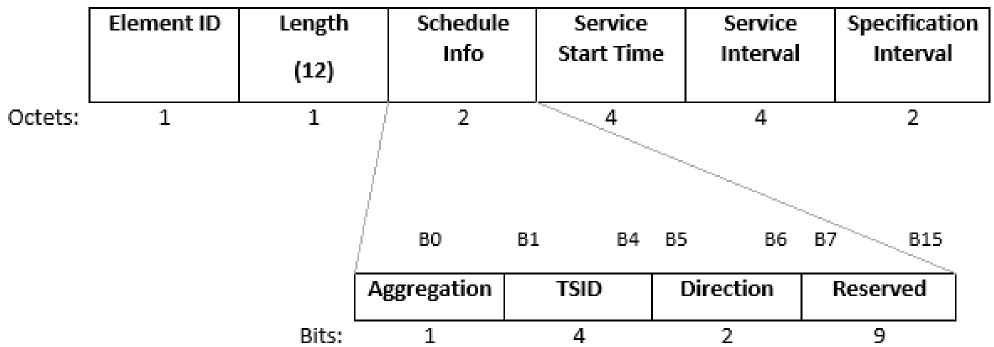

Figure 28. Schedule Element Format

The Aggregation subfield is set to 1 if the schedule is an aggregate schedule for all TSIDs associated with the STA to which the frame is directed (because a STA might have multiple TSs). It is set to 0 otherwise.

The TSID subfield indicates the TSID for which this schedule applies. The direction subfield defines the direction (UL, DL, Direct-link, or Bidirectional) of the TSPEC associated with the schedule.

The TSID and Direction subfields are valid only when the Aggregation subfield is 0. If the Aggregation subfield is 1, the TSID and Direction subfields are reserved.

The Service Start Time field is 4 octets and indicates the anticipated time, expressed in microseconds, when service starts and represents the lower order 4 octets of the TSF timer value at the start of the first SP (Service Period). The AP uses this field to confirm or modify the service start time indicated in the TSPEC request.

Where SP is a contiguous time during which one or more downlink individually addressed frames are transmitted to a quality-of-service (QoS) station (STA) and/or one or more transmission opportunities (TXOPs) are granted to the same STA. SPs are either scheduled or unscheduled. For a non-access-point (non-AP) STA, there can be at most one SP active at any time.

The Service Interval field is 4 octets and indicates the time, expressed in microseconds, between two successive SPs and represents the measured time from the start of one SP to the start of the next SP.

The Specification Interval field is 2 octets long and contains an unsigned integer that specifies the time interval, in TUs, to verify schedule conformance.

Therefore, in our scenario the schedule will indicate the TXOP times and durations (because we specified the UL direction). Figure 30 illustrates an UL schedule admitted to a STA. As shown in the figure, TXOPs are separated by Service Intervals (SIs).

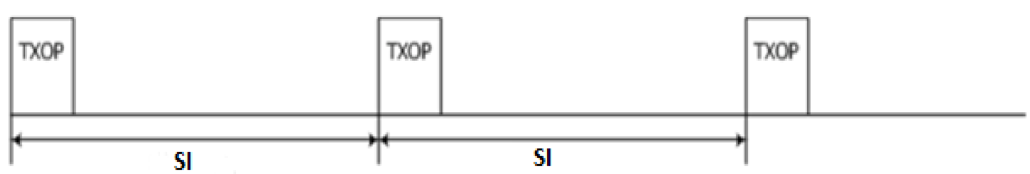

Figure 29. Sample UL schedule

During TXOPs that medium time will be reserved and can be used for the CA purposes.

b. LTE-WiFi synchronization during a TXOP

The logic that occurs on the eNodeB side for performing CA during a TXOP and the details of the information exchanged between the eNodeB and the WiFi submodules are the same for HCCA and EDCA alternatives. That is, the difference between the HCCA and EDCA methods is in the mechanism the TXOP is obtained; but once it is obtained, there is no difference between HCCA or EDCA TXOP.

The logic that runs at our hybrid LTE-WiFi model after gaining an instance of TXOP will be explained in Chapter V.

2. EDCA design timeline

The EDCA timeline is similar to that of the HCCA timeline, except that the WiFi submodule contends for EDCA TXOPs during CPs instead of sending an ADDTS request during CAPs. When the WiFi submodule gains an instance of EDCA TXOP and uses it for CA. This is illustrated in Figure 31.

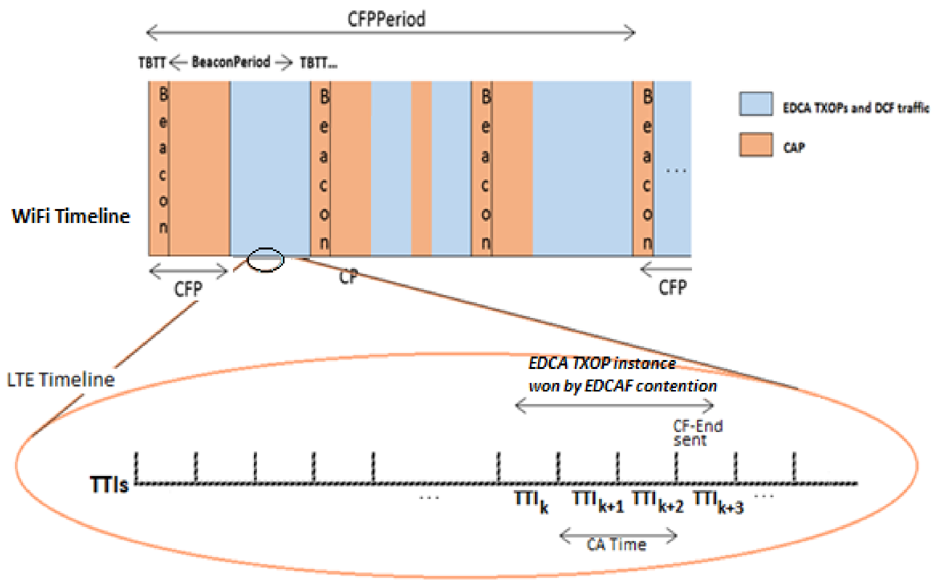

Figure 30. EDCA LTE/WiFi timelines

Note that if the ACM (Admission Control Mandatory) in the EDCAParameterSet element is set to 1 for the Access Category of interest, then it is required that the WiFi submodule send an ADDTS request in same way as presented in section B-1, but specifying EDCA instead of HCCA in the access method subfield. In what follows, it is assumed that the WiFi submodule is admitted to use EDCA for the desired AC (or ACM is not set).

a. <u>Obtaining an EDCA TXOP</u>

As explained in Chapter II, the EDCA function is a variation DCF with differentiated services based on traffic types. The differentiation is based on the Access Category (AC) of the traffic to be sent.

A regular QoS-WiFi STA maintains four traffic queues with four EDCAFs (EDCA Functions), one EDCAF for each. Each queue corresponds to one of the four ACs that were presented in the EDCA Parameter Set. Whenever there is traffic in one of the queues, the corresponding EDCAF contends to access the medium, and ACs of higher priority are favored by having smaller AIFS durations and random window size and larger TXOP durations, as it was illustrated in Table 5 which presented the default EDCA parameters for the four ACs.

In our scheme, the WiFi submodule uses the highest priority EDCAF and contends to access the medium using the corresponding EDCA parameter values, as they were advertised in the EDCA Parameter Set element. Particularly, our WiFi submodule uses the EDCA parameters corresponding to the AC that has the largest TXOP limit (AC_VI if the default values are used, in which case TXOP limit is 3.008 ms).

For this, the WiFi submodule:

- Creates a Request-to-Send (RTS) frame with Duration Field equal to the TXOP limit corresponding to the selected AC
- Inserts the RTS frame in the traffic queue corresponding to the selected AC
- Contends using the corresponding EDCA parameters
- If it gains access to the medium, it sends the RTS frame and specifies a TXOP duration that is equal to the TXOP limit advertised in the EDCA Parameter set

In regular WiFi STAs, the actual TXOP duration is not necessarily equal to the TXOP limit advertised in the EDCA Parameter Set, but instead, it depends on the size of traffic inside the queue. More specifically, the EDCAF specifies a TXOP duration that is equal to the minimum of TXOP limit and queue size needed time. In our design, however, the EDCAF uses the TXOP limit regardless of the queue size (which only has an RTS or equivalent EDCA frame!) Table 10 illustrates the difference between the regular EDCA settings and our EDCA settings.

	Regular EDCA Settings	**WiFi submodule EDCA Settings**
Access Categories Used (AC)	Four different ACs referring to the four traffic types (BE, BK, VI, VO).	Only one AC ($AC_{selected}$) is used, corresponding to the AC with highest TXOP limit value.
Window Size	As specified in the advertised window size EDCA parameters values for the corresponding AC.	As specified in the advertised window size EDCA parameter values for $AC_{selected}$.
AIFS	As specified in the advertised AIFS EDCA Parameter value for the corresponding AC.	As specified in the advertised AIFS EDCA Parameter value for $AC_{selected}$.
TXOP duration	= **min** (**time**(AC queue size), advertised TXOP limit)	= advertised TXOP limit for $AC_{selected}$

Table 10. Comparison between regular EDCA settings and our EDCA settings

b. <u>LTE-WiFi synchronization during a TXOP</u>

After winning an EDCA TXOP instance, the WiFi submodule sends the RTS frame and waits for an acknowledgment. This is needed so that the other WiFi STAs set their NAVs to the TXOP duration. In fact, any data frame sent from an EDCA TXOP winning

STA can lead to this NAV reset; but we selected the RTS frame because of no WiFi data frames are available in our WiFi submodule and an RTS subframe is sufficient.

More specifically, all STAs in the WiFi network maintain the address of the TXOP holder, which is the Transmitter Address of the first frame that was sent during the TXOP. The duration field in the transmitted frame is used to start a TXNAV timer. The STAs shall consider the medium as busy until the expiry of this time. For this reason, in our design, the WiFi submodule will send a RTS frame with duration field equal to the TXOP duration.

When the CTS and ACK frames are received, the WiFi submodule sends the following information to the eNodeB submodule:

- **Timestamp** representing the current time
- **Remaining TXOP duration** = TXOP limit – time to transmit RTS and receive ACK
- **Channel Information** corresponding to the WiFi channel characteristics: BW and carrier frequency

The eNodeB on the other hand maintains a timestamp, Remaining TXOP, and Channel Info variables and whenever it receives information from the WiFi submodule, it updates these values. The remaining TXOP duration is initially set to zero, and when the information is received it is updated as follows:

$$\boldsymbol{remainingTXOPDuration} = (\boldsymbol{received\ remainingTXOPDuration}) - (\boldsymbol{current\ time} - \boldsymbol{received\ timestamp})$$

This assumes that the eNodeB and WiFi submodule clocks are synchronized. This is a reasonable assumption as the two submodules are within the same hybrid model and they are connected via a fast wired link. The equation above is essentially removing the data rate delay of this link.

By referring to EDCA Parameter Set presented in Chapter II, we see that the size of TXOP limit is 2 Octets. The time, on the other hand, can be represented as a 64 bit integer and channel information (in Hz) can can also be presented with a maximum of 64 bits each. Assuming a 1 Gbps link connecting the WiFi and eNodeB submodules, the data rate delay for sending the information will therefore be of the order of a fraction of a microsecond.

At the start time of each TTI, and before performing the scheduling, the eNodeB runs the following logic:

```
If (remainingTXOPDuration ≥ 0.001) {    // if ≥ 1 ms
        remainingTXOPDuration = remainingTXOPDuration – 0.001;
        Perform LTE-WiFi CA …
}  else {
        If (remainingTXOPDuration ≥ 0.0005 )  //if it is worth performing a TXOP truncation
                Notify WiFi submodule of the need to perform TXOP truncation;
        Perform regular LTE scheduling …
}
```

TXOP truncation:

TXOP truncation is a procedure that is defined in the WiFi standard that allows a TXOP holder to declare the early end of TXOP utilization. The procedure occurs by sending a CF-End frame of the format shown in Figure 32.

	Frame Control	Duration	RA	BSSID (TA)	FCS
Octets:	**2**	**2**	**6**	**6**	**4**

Figure 31. CF-End Format

The BSSID field is the address of the STA contained in the AP. The RA (Receiver Address) field is the broadcast group address.

The Duration field is set to 0.

The WiFi STAs receiving this frame will interpret it as a NAV-reset. Thus, the STAs will be able to use the remaining unused time of the TXOP.

TXOP truncation is illustrated in Figure 33.

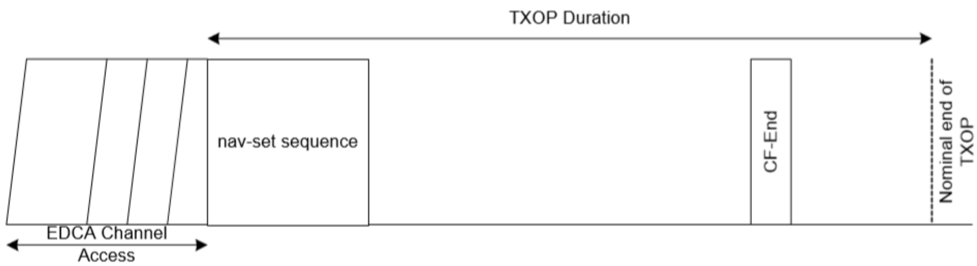

Figure 32. TXOP truncation [30].

With the TXOP Truncation, we conclude our design description. We present next our simulation framework and analyze the performance of our system based on simulation results that were obtained under different scenarios.

CHAPTER VI
IMPLEMENTATION

In this section, we present our implementation of the CA aggregation scheme within the Omnet++ simulation environment.

A. The simulation environment

Omnet++ is a simulation framework that allows for the modelling of different kinds of nodes, connections, and behaviors. Particularly, Omnet++ can be used to model communication networks.

As summarized in [51], “the basic Omnet++ building blocks are modules, which can be either simple or compound. Modules communicate through messages, which are usually sent and received through a connection linking the modules’ gates, which act as interfaces. A network is a particular compound module, with no gates to the outside world, which sits at the top of the hierarchy. Connections are characterized by a bit rate, delay and loss rate, and cannot bypass module hierarchy: with reference to Figure 34, simple module 3 cannot connect to 2, but must instead pass through the compound module gate. Simple modules implement model behavior. Although each simple module can run as an independent coroutine, the most common approach is to provide them with event handlers, which are called by the simulation kernel when modules receive a message. In addition to handlers, simple modules have an initialization function and a finalization function, often used to write results to a file at the end of the simulation. The kernel includes an event queue, whose events correspond to messages (including those a module sends to itself).

OMNeT++ allows one to keep a model's implementation, description and parameter values separate. The implementation (or behavior) is coded in C++. The description (i.e., gates, connections and parameter definition) is expressed in files written in Network Description (NED) language. The parameter values are written in initialization (INI) files. NED is a declarative language, which exploits inheritance and interfaces, and it is fully convertible (back and forth) into XML. NED allows one to write parametric topologies, e.g. a ring or tree of variable size. NED files can be edited both textually and graphically (through a Graphic User Interface, GUI), switching between the two views at any time. INI files contain the values of the parameters that will be used to initialize the model. For the same parameter, multiple values or intervals can be specified.

As far as coding is concerned, OMNeT++ comes with an IDE, derived from Eclipse, which facilitates debugging. In fact, modules can be inspected, textual output of single modules can be turned on/off during execution, and the flow of messages can be visualized in an animation, all of which occurs automatically. Events can be logged and displayed on a time chart, which makes it easy to pinpoint the causes or consequences of any given event.

As for workflow automation, OMNeT++ clearly separates models (i.e., C++ and NED files) from studies. Studies are generated from INI files, by automatically making the Cartesian product of all the parameter values and, possibly, generating replicas of the same instance with different seeds for the random number generators. Note that the IDE allows one to launch and manage multiple runs in parallel, exploiting multiple CPUs or cores, so as to reduce the execution time of a simulation study. Finally, data analysis is rule-based: the user only needs to specify the files and folders she wants to extract data from, and the recipe to filter and/or aggregate data. The IDE automatically updates and re-draws graphs when simulations are rerun or new data become available. The performance of OMNeT++ has been compared to that of other simulators, notably ns-3, [32]. The result is that the two are comparable as for run time and memory usage, with ns-3 faring marginally better within the limits of the analyzed scenarios."

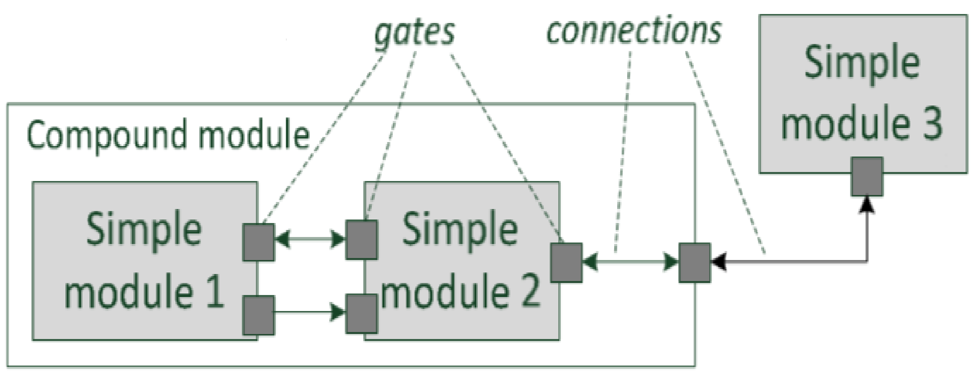

Figure 33. Omnet++ module connection [51]

B. CA scheme implementation

1. Implementation of the WiFi network using the INET framework

We used the INET framework [49] to model the WiFi network.

INET is built in omnet++, and it models different wired and wireless protocols including IPv4, IPv6, TCP, SCTP, and UDP. Moreover, INET provides implementation for several application models in addition to an MPLS model with RSVP-TE and LDP signaling. Finally, INET provides three link layer models; namely PPP, Ethernet, and 802.11.

a. INET Architecture

In the INET framework, protocols are modeled using Omnet++ simple modules. As mentioned earlier, a simple module implements different kinds of behaviors such as message sending and handling using the C++ language. These simple protocol modules can be combined to form different kinds of network nodes and interfaces. INET already provides implementation to some kinds of nodes and interfaces, such as the StandardHost and Router nodes, and the Ethernet and 802.11 interfaces. A network interface is usually composed of a queue, a MAC, and possibly other simple modules.

In addition to nodes and interfaces, INET provides compound modules that do not use the protocols, but rather provide functions that are common to different network nodes and configurations. For example, the RoutingTable module is provided for holding data, the NotificationBoard module is provided to facilitate communication between different network nodes, and the ChannelControl module is required for wireless simulations and keeps track of which nodes are within interference distance of other nodes.

We used INET's "wirelessHost" module to model a WiFi STA. By changing the configurations of the module parameters, we were able to configure different types of WiFi

STAs (i.e. access point, non-AP, QoS, non-QoS, etc.). More details on the 802.11 implementation within the INET framework are provided in the following subsection.

b. IEEE 802.11 implementation within the INET framework

As mentioned in the previous subsection, the INET framework provides an implementation of the IEEE 802.11 interface (NIC). The IEEE 802.11 NIC comes in several flavors differing in their role (ad-hoc STA, infrastructure mode STA, or access point) and level of detail.

NICs consist of four Layers: agent, management, MAC, and physical layer (radio). The descriptions of these layers are presented in Table 11 and are extracted from INET's IEEE 802.11 model documentation.

Layer	**Description**
Physical	The physical layer modules (Ieee80211Radio) deal with modelling transmission and reception of frames. They model the characteristics of the radio channel, and determine if a frame was received correctly (that is, it did not suffer bit errors due to low signal power or interference in the radio channel). Frames received correctly are passed up to the MAC. The implementation of these modules is based on the Mobility Framework.
MAC	The MAC layer (Ieee80211Mac) performs transmission of frames according to the CSMA/CA protocol. It receives data and management frames from the upper layers, and transmits them. Encapsulation/decapsulation must be done in the upper layers. (It is typically in the 802.11 management module, see in Ieee80211Nic). The base class for 802.11 frame messages is Ieee80211Frame, but this module expects Ieee80211DataOrMgmtFrame (a subclass) from upper layers (the management module). This module will assign the transmitter address (address 2) and the frame sequence number/fragment number fields in the frames; all other

	fields must already be filled when this module gets the frame for transmission. The module has an internal queue, but usually it is to be used with an external passive queue module. The passive queue module is a simple module whose C++ class implements the IPassiveQueue interface.
Management	The management layer performs encapsulation and decapsulation of data packets for the MAC, and exchanges management frames via the MAC with its peer management entities in other STAs and APs. Beacon, Probe Request/Response, Authentication, Association Request/Response etc frames are generated and interpreted by management entities, and transmitted/received via the MAC layer. During scanning, it is the management entity that periodically switches channels, and collects information from received beacons and probe responses. The management layer has several implementations which differ in their role (STA/AP/ad-hoc) and level of detail: - Ieee80211MgmtAdhoc - Ieee80211MgmtAP - Ieee80211MgmtAPSimplified - Ieee80211MgmtSTA, - Ieee80211MgmtSTASimplified. The simplified ones differ from the others in that they do not model the scan-authenticate-associate process, so they cannot be used in experiments involving handover.
Agent	The agent is what instructs the management layer to perform scanning, authentication and association. The management layer itself just carries out these commands by performing the scanning, authentication and association procedures, and reports back the results to the agent. The agent layer is currently only present in the Ieee80211Nic with mgmtType = Ieee80211MgmtSTA NIC module, as an Ieee80211AgentSTA module. The management entities in other NIC variants do not have as much freedom as to need an agent to control them. By modifying or replacing the agent, one can alter the dynamic behavior of STAs in the network, for example implement different handover strategies.

Table 11. IEEE 802.11 model layers' description from INET documentation

We used the Ieee80211MgmtSTA and Ieee80211MgmtAP management types for modeling the management layers of a WiFi STA and the WiFi AP respectively.

MAC model limitations:

The IEEE 802.11 MAC model of INET does not support the following features:

- Fragmentation
- Power management
- Polling (PCF and HCCA)

In addition, physical Layer algorithms such as frequency hopping and direct sequence spread spectrum are not implemented directly.

Thus, fields related to the above unsupported features are omitted in the management frame formats (such as the CF parameter set).

Due to the mentioned limitations, we only implemented and evaluated the EDCA design, and we leave the evaluation of the HCCA design for future work. Also our implementation does not include the CF-End frame that is sent at the end for TXOP truncation.

2. *Implementation of the LTE network using the simuLTE framework*

We used the simuLTE framework [50] [51] for implementing the LTE network.

simuLTE is built over the INET framework. It implements the data plane of the LTE Radio Access Network (RAN) and provides an omnet++ simulation framework for simulating LTE and LTE-A systems in the FDD duplexing mode.

The implementation includes the models for the LTE architectural nodes and interfaces: UE, eNodeB, X2 interface, etc.

The LTE implementation is mainly included within the NIC module which implements the LTE stack. The NIC submodule is common between the eNodeB and UE modules, and it includes the following layers, with function implementations varying depending on whether the module is a UE or an eNodeB:

- **PDCP-RRC:** performs header compression/decompression and logical connection establishment and maintenance.

- **RLC:** performs Multiplexing/Demultiplexing of MAC SDUs, and implements the three RLC modes: Transparent Mode (TM), Unacknowledged Mode (UM), and Acknowledged Mode (AM).

- **MAC:** performs RLC PDUs buffering, HARQ functionalities with multi-codeword support, allocation management, Adaptive Modulation and Coding (AMC), and scheduling.

- **PHY:** provides HetNets support: macro, micro, and pico eNodeBs. Channel feedback management, dummy channel model, and a realistic channel model.

The NIC submodule in the UE module is connected to an IP Layer, which in turn is connected to the TCP/UDP and application layers. The Application, transport, and IP layers are inherited from the INET framework. The NIC has another connection that links it to the eNodeB's NIC.

The NIC submodule in the eNodeB is similarly connected to an IP layer which is connected to a PPP layer.

Scheduling algorithm and Channel Model:

Three scheduling algorithms are provided within the eNodeB MAC: MAX C/I, Proportional Fair, and Deficit-Round-Robin (DRR). As mentioned earlier, we are not concerned about the scheduling algorithm because we are only investigating the CA gains that one LTE-A UE can achieve by aggregating LTE and WiFi channels. The channel model implementation on the other hand, is of concern to us because the channel characteristics vary between the LTE and the WiFi frequencies. We used simuLTE's *Realistic Channel Model*. Details on this model can be provided in [51]. As far as we are concerned, we only mention that the implementation of this channel model takes the frequencies on an RB-by-RB basis, when calculating the channel errors (i.e. the pathloss and fast fading). In other words, the channel error is modeled for each RB independently, and therefore, the channel model is suitable for our scheme were RBs from different bands will be aggregated.

3. LTE-WiFi interoperability

Although simuLTE is built over the INET framework, it does not support yet LTE-WiFi interoperability. More specifically, the LTE nodes are not able to handle the WiFi packets, and thus the simulation crashes each time they receive such packets. We implemented a "dummy" fix for this problem, by updating the message handlers at the UE and eNodeB modules to ignore the WiFi packets. We say "dummy" because this is not the proper fix: the LTE modules should be updated to ignore any traffic received at a different frequency from different technologies. We believe – to the best of our knowledge of the simulators' implementations – that the origin of the interoperability problem is that the frequency implementation in simuLTE is different than that in INET. Further investigation on this problem is left for future work.

4. eNB-WiFi Hybrid model implementation

We already explained in Chapter V that our design replaces the eNodeB with a hybrid eNodeB_WiFi base station. The hybrid base station includes a WiFi interface through with the eNodeB can run WiFi functions in parallel with the LTE functions. Figure 35 shows the high level implementation of the hybrid module. As shown, the hybrid model includes two submodules connected by a 1 Gbps wired connection.

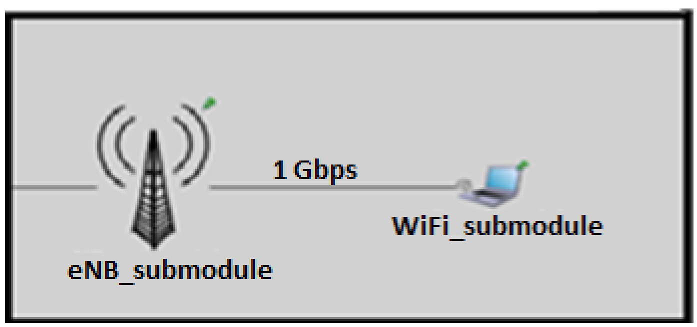

Figure 34. eNB-WiFi Hybrid module.

a. <u>eNodeB Submodule Implementation</u>

Figure 36 shows the implementation of the eNB_submodule.

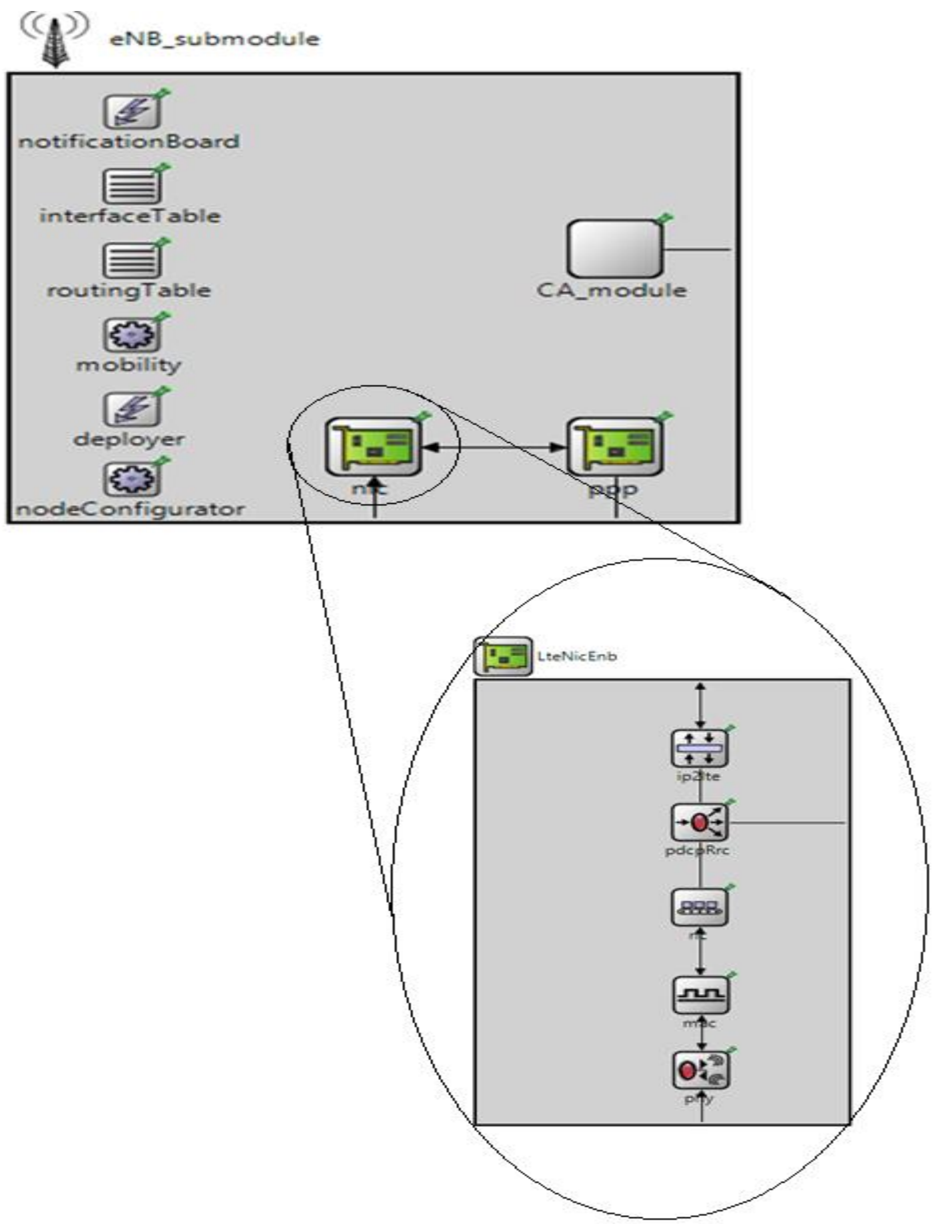

Figure 35.eNodeB submodule implementation

Our eNB_submodule is basically an extension to the existing eNodeB module in simuLTE. Namely, we added the new “CA_module” submodule which is shown in the

Figure. Moreover, we extended the "mac" submodule functionality, as it will be detailed next.

i. The ENB CA module

The CA_module is an instance of a new simple module that we created; namely, the "ENB_CA_submodule.ned" simple module. This module is responsible for communication with the WiFi_submodule on one hand and the mac submodule within the eNodeB on the other hand. This module can be similarly implemented as a process (or Thread) within the mac submodule; however, we prefer the simple module approach because it provides a logical separation between the mac functions and the LTE-WiFi communication functions, which makes it easier to understand or extend our logic in future work.

As mentioned earlier, while compound modules are combinations of simple modules, simple modules model behaviors and are implemented with C++ code. Thus, we created the "ENB_CA_submodule.h" and "ENB_CA_submodule.cc" files to define and implement the CA functions. In particular, we implemented the *initialize* and *handleMessage* functions, and we added the *BwToRbs* and *aggregate* functions:

- **initialize:** is a method of the simple module class, used for initialization of all the variables and parameters.

- **handleMessage:** also a method of the simple module class which is called each time a message arrives to the module. In this method, we implemented the handler for the message arriving from the WiFi submodule through the wired link. Whenever a txop is gained by the WiFi_submodule, it sends the timing and frequency information to the eNB_submodule through the wired link which is connected to the ENB_CA_module. When the latter receives the information, it extracts the information and decides to either use them for carrier aggregation or ignore them. It ignores them in cases where for example txop duration is negative or the bandwidth is very small (smaller than the smallest LTE bandwidth configuration). More details on the information was provided in Chapter V.

- **bwToRbs:** a simple method for calculating the number of RBs that can be used from the available WiFi BW. This is equal to the maximum BW configuration that is less than the borrowed BW.

- **aggregate:** called if a decision for aggregation is taken. This function updates the timing and frequency information that are needed by the mac module for carrier aggregation purposes. The information includes a flag that indicates whether we are currently within a TXOP or not.

ii. MAC extension

In addition to the CA_module, we extended the eNodeB mac simple module; namely, we created the mac_extension.ned simple module which extends the standarad eNodB module, and we implemented the CA logic in the C++ files that also inherit the standard files. Note that this module is able to access the variables in the CA_module; moreover, it can communicate with the CA_module through direct message sending. Direct message sending is a method provided by Omnet++ which allows direct communication between modules (i.e. with no need for gates, connections, or delays).

In the extended model, we added the CA logic which was presented in Chapter V; namely, we modified the main mac loop, which runs at the beginning of each TTI, according to the brief pseudo code shown below. Note that the remaining TXOP duration takes into account the data rate delay of the link as it was explained in Chapter V. Thus, if there is available TXOP time that will cover at least 1 TTI, carrier aggregation will take place by adding a band corresponding to the borrowed RBs (done using the bandLimit structure in simuLTE) with a BW and frequency as extracted from the information sent by the WiFi submodule; and then scheduling resources from both the original LTE band and the WiFi band to the end user. Also note that at the beginning of each TTI, the number of available RBs for scheduling is read from LTE configuration files, thus it is not affected by any modifications made on this number in previous TTIs; that’s why there is no need to remove any subbands that were added due to previous carrier aggregation operations.

The UF count shown in the pseudo code denotes the Utilization Factor. It is used for counting the number of TTIs that benefit from our scheme.

```
If (remainingTXOPDuration ≥ 0.001) {    // if ≥ 1 ms
        remainingTXOPDuration = remainingTXOPDuration – 0.001;
        perform carrier aggregation
        increment the UF count
}  else {
        remainingTXOPDuration = 0;
        Perform regular LTE scheduling …
```

b. WiFi_submodule Implementation

Figure 37 presents the WiFi submodule architecture. Similarly, this module is an extension to the standard WirelessHost module of INET, where we added a CA_module and extended the mac module.

i. The WiFi CA module

Similar to the ENB_CA_module, the WiFi_CA_module is a simple module that is responsible for communication between the WiFi mac on one side and the eNB_submodule on the other side. Whenever the mac extension indicates that a TXOP is started, it sends (via direct sending) the corresponding information to the WiFi_CA_module, which in turn forwards it to the eNodeB submodule through the wired link.

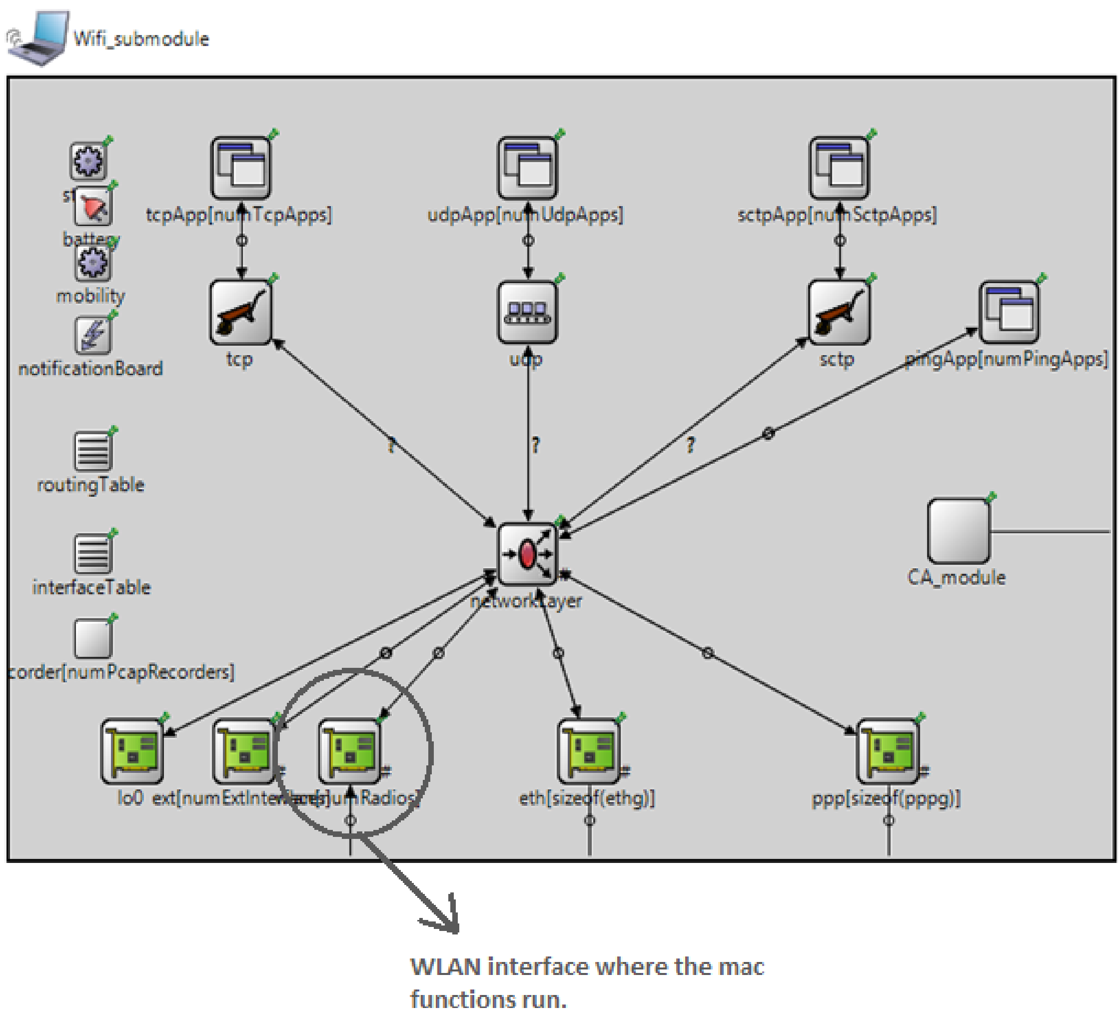

Figure 36. WiFi submodule implementation

ii. The mac extension

As shown in Figure 37, the mac functions run within the WLAN interface of the wirelessHost module. We extended the mac class by modifying the EDCA parameters. Namely, we modeled an “always full” EDCA traffic queue corresponding to the Voice traffic category. This is modeled by a virtual VoIP application with the following configurations:

- VoIP packet length = 1000 B
- Packetization interval = 0.01 ms (tries to send a VoIP packet every 0.01 ms)

In effect, and due to the small packetization interval and large data size, the mac will be almost continuously contending, and the TXOP duration will be almost equal to the maximum TXOP duration specified in the EDCA Parameter Set, as explained earlier. Whenever a TXOP is gained, the information is sent to the WiFi_CA_module which in turn forwards it to the ENB_CA_module, as mentioned earlier.

As indicated above, this is a virtual VoIP application that is used for simulation purposes only. In real physical implementation; however, no VoIP applications will run at the WiFi submodule, instead the maximum EDCA values are directly used and the medium is acquired by contention with only one EDCA frame. This EDCA frame is used to inform other WiFi STAs of the TXOP duration so that they set their NAVs accordingly, as detailed in Chapter V. After this frame is sent, the WiFi submodule sends the information to the eNB_submodule so that it can use the remaining TXOP time.

We already mentioned the interoperability problem between the INET and simuLTE frameworks, where the frequencies are implemented differently. Due to this limitation, the LTE network can use the WiFi frequencies at any time with no interference detected by the simulator. This is why we used the VoIP application that runs throughout the entire TXOP duration to model a busy WiFi channel that the WiFi STAs will not be able to use, because during this time, the eNodeB will be using RBs from this channel and hence it should be detected as busy using both the physical and virtual sense mechanisms.

We present next our simulation experimental scenarios and results.

CHAPTER VII

EXPERIMENTAL SCENARIOS AND RESULTS

Figure 38 shows the network setup that we used for our experiments. As shown the WiFi network is represented by a WiFi AP connected with a wire to a stationary host, which acts as a server to the application clients running at the WiFi STAs. The LTE network similarly is modeled by an eNodeB, a server, and UEs. The hybrid module implementation is also shown, and the omnet++ models used for each node are as presented in the previous section.

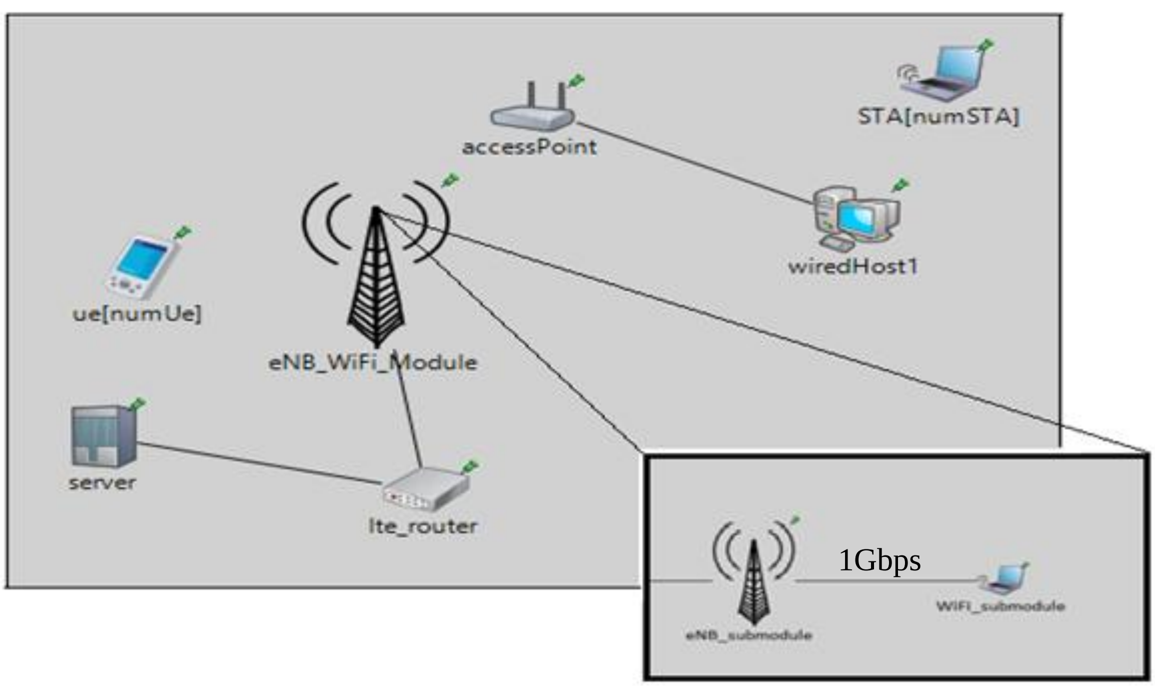

Figure 37. Network set-up

The following subsections present the different scenarios and experiments that we conducted in addition to their results.

A. The Utilization Factor (UF)

In this experiment, we measured the Utilization Factor (UF) relative to the number of won TXOP instances. In particular, in this experiment, the WiFi submodule does not contend continuously, but rather, it contends at random time instances; we varied these time instances and the frequency of their occurrence (i.e. how often it contends) to obtain different number of gained EDCA TXOPs (in other words, we varied the VoIP application configurations).

Configurations:

TXOP Limit = 3.008 ms
Total TTIs (simulation time) =100 (i.e. 100 ms)
numSTAs = 0

Total TXOP Time = *numTXOPs * 3.008*

UF *= number of TTIs that used the WiFi Channel*

Figure 39 shows the variation of total TXOP time and the UF versus the number of gained TXOPs.

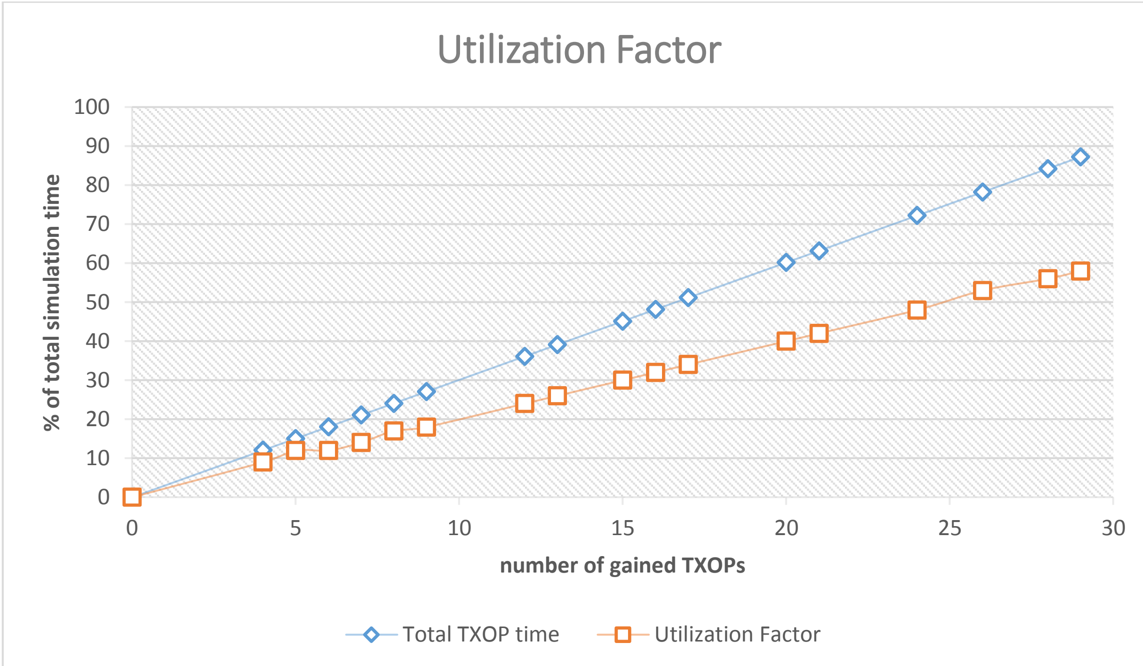

Figure 38. Utilization Factor

Based on Figure 39: $\boldsymbol{UF \approx \frac{2}{3} * TXOP\ Time}$

This result is expected, because each TXOP is 3.008 ms and is expected to cover 2 TTIs, as illustrated in Figure 40.

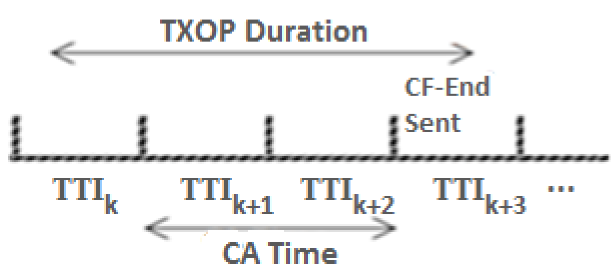

Figure 39. TXOP duration of 3 ms is expected to cover 2 TTIs

B. TXOP time versus the WiFi network Load

In this experiment, we varied the number of WiFi STAs and the kind of traffic generated by them. The WiFi STAs are assumed to QoS WiFi STAs and therefore their MAC modules are set to support EDCA:

Configuration: STA[*].wlan[*].mac.EDCA = true

We conducted three experiments:

1. A worst-case experiment that models extreme network load
2. A Typical VoIP Load experiment
3. A Typical Data Load experiment

Details on each of these three experiments and their results are presented in the following subsections.

1. Worst-case scenario

In this experiment, the worst-case scenario is studied. Namely, the traffic Load is maximized, where the WiFi STAs support EDCA and continuously contend for the highest priority traffic. This is modeled by a VoIP application running at each WiFi STA with the following configurations:

Application Type running at each WiFi STA: ***SimpleVoIPSender***

This is a VoIP application provided by the **inet** framework for generating VoIP traffic.

The application parameters are set as follows:

- **talkPacketSize** = 1000 B
  which represents the size of each VoIP packet
- **packetizationInterval =** 0.01 ms
- **destAddress =** “wiredHost1”

Thus all WiFi STAs continuously (every 0.01 ms) send 1000-byte VoIP traffic to wiredHost1, which runs a sink application that destroys these packet.

We measured the total TXOP time gained by the eNodeB as we increase the number of WiFi STAs; the results are shown in Figure 41. Note that these results are averaged results, where every instance was generated multiple times (equal to the number of WiFi STAs), and the average of the obtained values is reported.

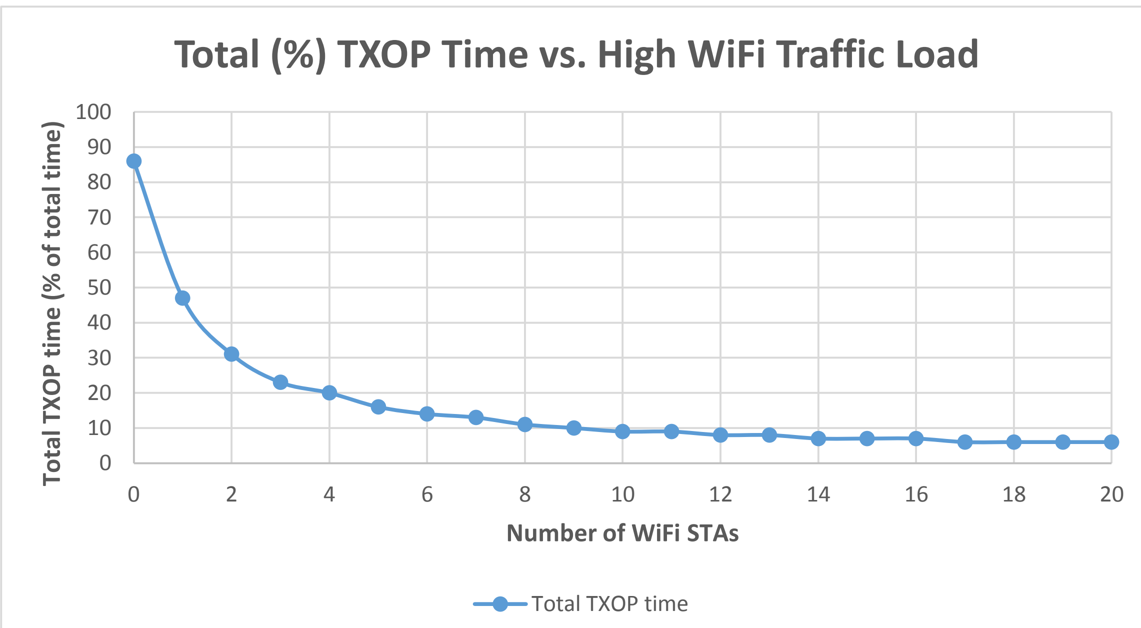

Figure 40. UF versus the number of WiFi STAs.

As expected, the average TXOP time gained by the eNodeB decreases as the number of WiFi STAs increase.

Moreover, the proportion of gained medium time is approximately **100/(number of STAs + 1)**, as expected because similar to the eNodeB, the WiFi STAs are continuously contending with the highest TXOP values and therefore have equal chances to gain the medium time.

2. Typical Load scenario

Since the extreme case is not what we expect in real life, we conducted another experiment to model typical VoIP and data traffic.

Thus, we repeated the VoIP experiment however with changed configurations:

- **talkPacketSize** = 40 B
  which represents the size of each VoIP packet
- **packetizationInterval = (uniform(**0.5,1.5**))*(**20 ms)

A packet size of 40 B and packetization interval of 20 ms are typical VoIP parameters according to inet documentation. We introduced a random factor on the packetization interval in order to randomize the packet generation instances, and since the random number is selected from a uniform distribution in the range between 0.5 and 1.5, then the average (mean) packetiztion interval will be equal to the typical interval of 1x20 = 20 ms.

The results after applying these VoIP configurations are shown in the lower curve of Figure 42. Also as expected, the gained medium time decreases as the number of WiFi STAs increases.

We conducted a third load experiment to model data traffic. For this, we used **inet**'s ***TCPBasicApp*** to model http traffic. The configurations are as follows:

Configurations at the WiFi STAs:

- **requestLength** = truncnormal(350,20)
- **replyLength** = exponential(2000)
- **thinkTime** = uniform(2,7)*(1s)
- **idleInterval** = uniform(1,5)*(1s)

where,

The request length is chosen from a truncated normal distribution with mean = 350 and standard deviation 20.

The thinkTime is the time gap between requests

The idleInterval is the time gap between sessions.

The above configurations are based on inet documentation, which states that these are typical http application values.

In addition wiredHost1 runs a ***TCPSrvApp*** which runs the http server application.

The results of the data-traffic experiment are shown in the upper curve of Figure 42. We can see that as expected, data traffic is less demanding and does not occupy a large portion of the medium time.

Even under a STA load of 20 STAs, the eNodeB will be able to gain around 57 % of the medium time under mixed-traffic load (the average of 63% and 51% values corresponding to data load and VoIP load respectively).

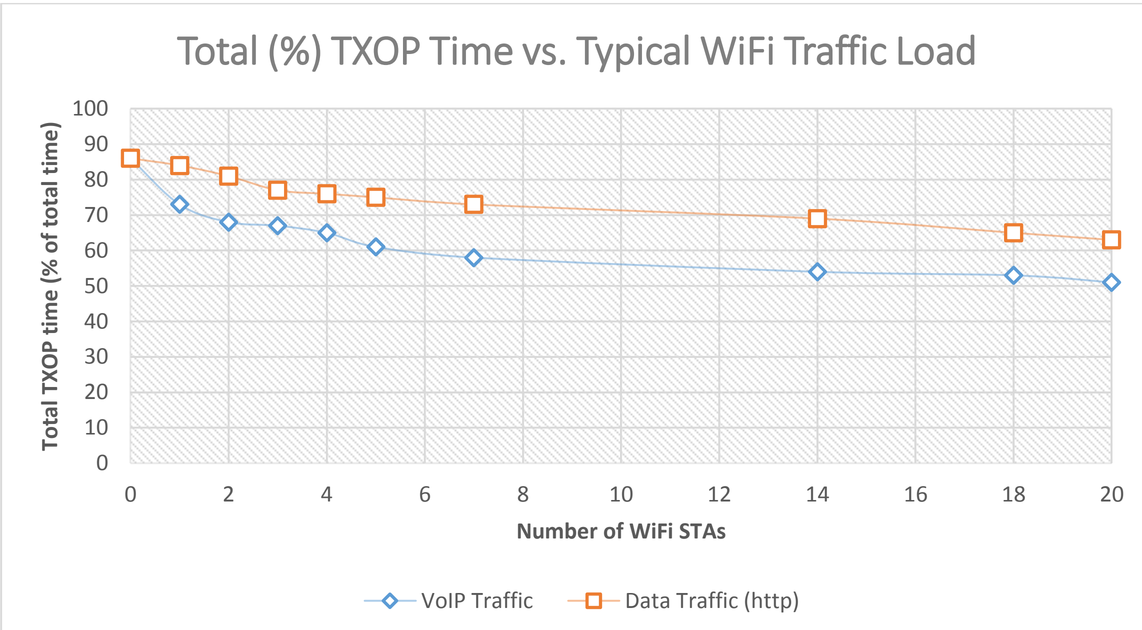

Figure 41. TXOP gained time vs. typical WiFi traffic.

C. Bit rate Gain

Based on the above results, we calculated the bitrate gains that the eNodeB can achieve in our scheme, under typical mixed data and VoIP traffic (the average of the values shown in Figure 42).

In the calculation we took both, the bandwidth configurations in the LTE standard (shown below) and the utilization factor (representing the percentage of LTE subframes benefiting from the scheme).

- 1.4 MHz corresponds to 6-180 kHz RBs
- 3 MHz corresponds to 15-180 kHz RBs
- 5 MHz corresponds to 25-180 kHz RBs
- 10 MHz corresponds to 50-180 kHz RBs
- 15 MHz corresponds to 75-180 kHz RBs
- 20 MHz corresponds to 100-180 kHz RBs

The bitrate gain is calculated as follows:

$$\boldsymbol{Bitrate\ Gain} = \frac{\mathbf{2}}{\mathbf{3}} * (\%\ \boldsymbol{of\ gained\ Time}) * (\mathbf{6}) * (\boldsymbol{number\ of\ RBs}) * (\mathbf{180}\ \boldsymbol{kHz}) * \frac{\mathbf{1}}{\mathbf{3}}$$

Where,

(2/3) is due to the utilization factor, where the eNodeB can use about 2/3 of the gained time as discussed earlier (because each 3ms TXOP covers 2 LTE subframes).

(6) corresponds to 6 bits per symbol corresponding to an assumed 64QAM modulation.

(number of RBs) is as defined in the BW configuration presented above

And **(1/3)** is the assumed coding rate

Figure 43 shows the bitrate gain for the six BW configurations defined in LTE and under varied load. For example, the upper curve presents the bitrate gain when the borrowed WiFi channel is of 20 MHz BW. Obviously, as the borrowed BW increases the bitrate gain increases. As shown in the results, when the borrowed BW is sufficiently large (10 MHz and above), significant bitrate gain can be achieved even under high STA density. Namely, when the borrowed BW is 20 MHz wide, the LTE-A UE is able to achieve 14 to 21 Mbps bitrate gain.

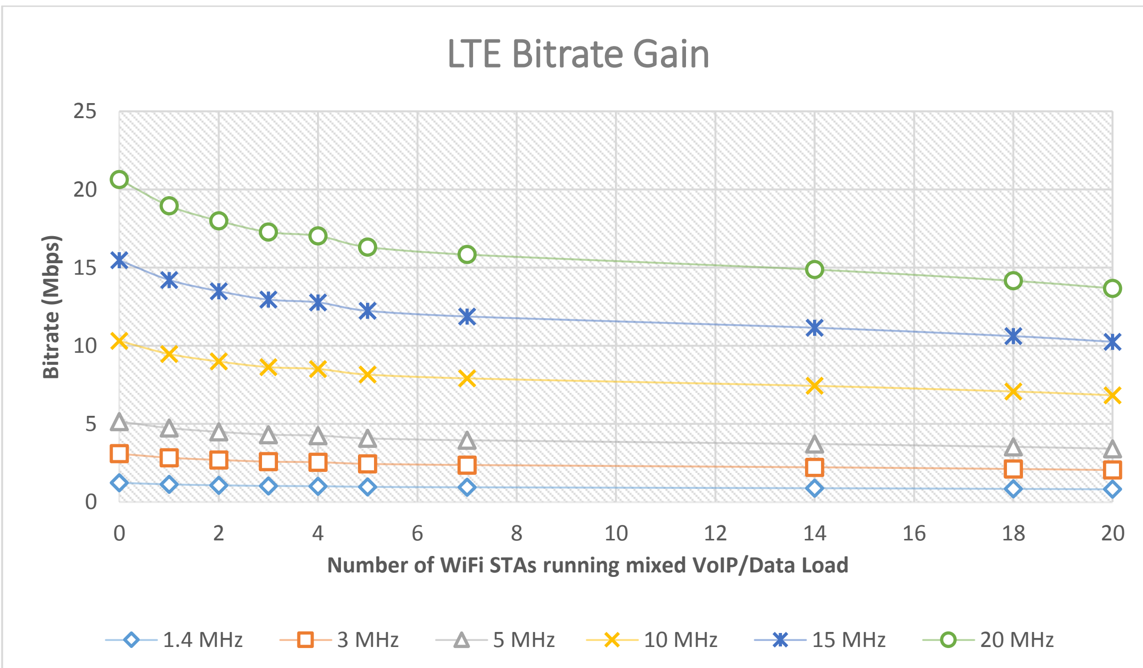

Figure 42. Bitrate Gain

CHAPTER VIII
CONCLUSION

We presented a system-level design of carrier aggregation for LTE- A involving borrowing spectrum from the WiFi spectrum. We conducted a feasibility study and outlined the similarities between the access schemes of WiFi and LTE specifications, and the availability of sufficient spectrum for WiFi in certain scenarios. We proposed a system design for an aggregation mechanism based on the notion of borrowing carrier components from the WiFi spectrum for aggregation with LTE carrier components. In our design, the eNodeB behaves as a WiFi STA and uses HCF access procedures to accessing the WiFi medium. We identified the suitable scenarios for which such an aggregation scheme is useful, and they mainly concern small cells environments where communications between the LTE-A UEs and the eNodeBs are restricted to small geographical areas, thus avoiding interference with distant WiFi users. Our omnet++ simulation results showed significant expected bitrate gains for LTE-A UEs under our scheme and under typical WiFi load scenarios.

Our ongoing research work is targeted toward implementing the scheme physically using Universal Software Radio Peripheral (USRP) software defined radios, and measuring the actual bitrate gains that can be achieved using our scheme.

Finally, further research is needed to tackle the more realistic case of having multiple WiFi BSSs in the LTE cell range, where interference issues may occur.

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APPENDIX A – LTE BANDS

Table 12 presents the E-UTRA operating bands, based on 3GPPspecifications [52] [53].

E-UTRA operating band	Uplink (UL)	Downlink (DL)	Duplex Mode	Channel Bandwidths (MHz)	Frequency Band (MHz)
1	1920 – 1980	2110 – 2170	FDD	5, 10, 15, 20	2100
2	1850 – 1910	1930 – 1990	FDD	1.4, 3, 5, 10, 15, 20	1900
3	1710 – 1785	1805 – 1880	FDD	1.4, 3, 5, 10, 15, 20	1800
4	1710 – 1755	2110 – 2155	FDD	1.4, 3, 5, 10, 15, 20	1700
5	824 – 849	869 – 894	FDD	1.4, 3, 5, 10	850
6 *(replaced by band 19)*	*830 – 840*	*875 – 885*	*FDD*	*5, 10*	*850*
7	2500 – 2570	2620 – 2690	FDD	5, 10, 15, 20	2600
8	880 – 915	925 – 960	FDD	1.4, 3, 5, 10	900
9	1749.9 – 1784.9	1844.9 – 1879.9	FDD	5, 10, 15, 20	1800
10	1710 – 1770	2110 – 2170	FDD	5, 10, 15, 20	1700

11	1427.9 – 1447.9	1475.9 – 1495.9	FDD	5, 10	1500
12	699 – 716	729 – 746	FDD	1.4, 3, 5, 10	700
13	777 – 787	746 – 756	FDD	5, 10	700
14	788 – 798	758 – 768	FDD	5, 10	700
15 *(reserved)*	*1900 – 1920*	*2600 – 2620*	*FDD*	*5, 10*	
16 *(reserved)*	*2010 – 2025*	*2585 – 2600*	*FDD*	*5, 10, 15*	
17	704 – 716	734 – 746	FDD	5, 10	700
18	815 – 830	860 – 875	FDD	5, 10, 15	850
19	830 – 845	875 – 890	FDD	5, 10, 15	850
20	832 – 862	791 – 821	FDD	5, 10, 15, 20	800
21	1447.9 – 1462.9	1495.9 – 1510.9	FDD	5, 10, 15	1500
22	3410 – 3490	3510 – 3590	FDD	5, 10, 15, 20	3500
23	2000 – 2020	2180 – 2200	FDD	1.4, 3, 5, 10, 15, 20	2000
24	1626.5 – 1660.5	1525 – 1559	FDD	5, 10	1600

25	1850 – 1915	1930 – 1995	FDD	1.4, 3, 5, 10, 15, 20	1900
26	814 – 849	859 – 894	FDD	1.4, 3, 5, 10, 15	850
27	807 – 824	852 – 869	FDD	1.4, 3, 5, 10	850
28	703 – 748	758 – 803	FDD	3, 5, 10, 15, 20	700
29	*N/A*	717 – 728	FDD	3, 5, 10	700
30	2305 – 2315	2350 – 2360	FDD	5, 10	2300
31	452.5 – 457.5	462.5 – 467.5	FDD	1.4, 3, 5	450
32	*N/A*	1452 – 1496	FDD	5, 10, 15, 20	1500
not assigned	*1915 – 1920*	*1995 – 2000*	*FDD*		*1900*
not assigned	*1755 – 1780*	*2155 – 2180*	*FDD*		*1700*
study item	*1980 – 2010*	*2170 – 2200*	*FDD*		*2100*
33	1900 – 1920		TDD	5, 10, 15, 20	2100
34	2010 – 2025		TDD	5, 10, 15	2100
35	1850 – 1910		TDD	1.4, 3, 5, 10, 15, 20	1900
36	1930 – 1990		TDD	1.4, 3, 5, 10, 15, 20	1900

37	1910 – 1930	TDD	5, 10, 15, 20	1900
38	2570 – 2620	TDD	5, 10, 15, 20	2600
39	1880 – 1920	TDD	5, 10, 15, 20	1900
40	2300 – 2400	TDD	5, 10, 15, 20	2300
41	2496 – 2690	TDD	5, 10, 15, 20	2500
42	3400 – 3600	TDD	5, 10, 15, 20	3500
43	3600 – 3800	TDD	5, 10, 15, 20	3700
44	703 – 803	TDD	3, 5, 10, 15, 20	700

Table 12. E-UTRA Bands

APPENDIX B - WIFI MIB

The 802.11 Management Information Base (MIB), defined as “ieee802dot11”, includes 4 main objects:

1- dot11smt : = {ieee802do11 1} which is the Station ManagemenT Object.
The SMT object class provides the necessary support at the station to manage the processes in the station such that the station may work cooperatively as a part of an IEEE 802.11 network
2- dot11mac := {ieee802dot11 2}
The MAC object class provides the necessary support for the access control, generation, and verification of frame check sequences (FCSs), and proper delivery of valid data to upper layers.
3- dot11res := {ieee802dot11 3} Resource type ID
4- dot11phy := {ieee802dot11 4}
The PHY object class provides the necessary support for required PHY operational information that may vary from PHY to PHY and from STA to STA to be communicated to upper layers.

The objects’ hierarchy and some of the most relevant attributes of each are presented in the figure below.

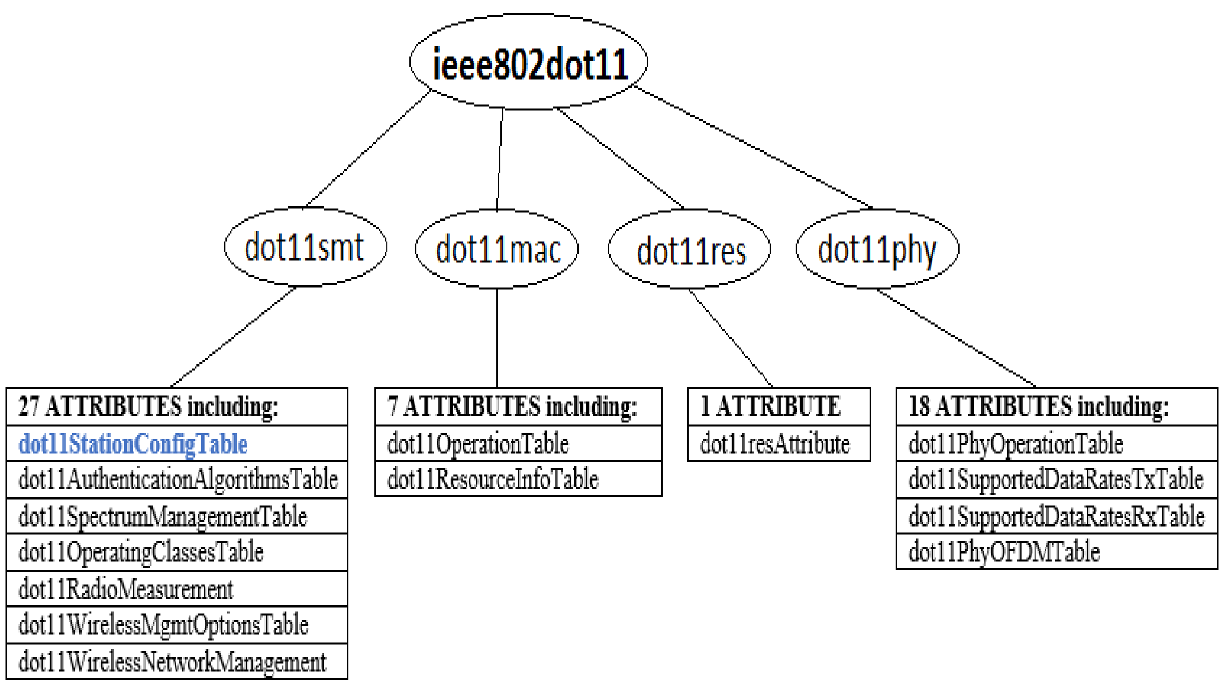

Figure 43. MIB high-level structure

Dot11StationConfigTable

Includes Station Configuration attributes, in tabular form to allow for multiple instances on an agent.

Type: sequence of *dot11StationConfigEntrys.*

The dot11StationConfigEntry:

An entry in the dot11StationConfigTable. It is possible for there to be multiple IEEE 802.11 interfaces on one agent, each with its unique MAC address. The relationship between an IEEE 802.11 interface and an interface in the context of the Internet-standard MIB is one-to-one. As such, the value of an ifIndex object instance can be directly used to identify corresponding instances of the objects defined herein.

ifIndex - Each IEEE 802.11 interface is represented by an ifEntry. Interface tables in this MIB module are indexed by ifIndex.

Each dot11StationConfigEntry in turn is a sequence of attributes including timing and frequency synchronization attributes.

The Tables below present some of the most relevant attributes to our work.

	dot11Medium-OccupancyLimit	**dot11CFPPeriod**	**dot11CFP-MaxDuration**
DESCRIPTION	Indicates the max amount of time that a PC may control the usage of the WM without relinquishing control for long enough to allow at least one instance of DCF access to the medium.	Describes the number of DTIM intervals between the start of CFPs.	Describes the maximum duration of the CFP in TU that may be generated by the PCF.
KIND OF VARIABLE	Control Variable	Status variable	Status variable
TYPE	Unsigned32	Unsigned32	Unsigned32
RANGE (Unit)	(0 .. 1000) TUs	(0 .. 255) DTIM intervals	(0 .. 65535) TUs
DEFAULT VALUE	100 TUs = 102.4 ms	Unspecified	Unspecified
MAX VALUE	1000 TUs = 1024 ms	255 DTIM intervals	65535 TUs = 67107.84 ms (Doesn't make sense! Larger than max dot11OccupancyLimit?)
MAX-ACCESS	read-write	read-only	read-only
SET BY	Written by an external management entity.	In an AP, it is written by the MAC when it receives an MLME-START.request primitive.	In an AP, it is written by the MAC when it receives an MLME-START.request primitive.

		In a non-AP STA, it is written by the MAC when it receives an updated CF Parameter Set in a Beacon frame.	In a non-AP STA, it is written by the MAC when it receives an updated CF Parameter Set in a Beacon frame.
WHEN	Changes take effect as soon as practical in the implementation	Modified by MLME-START.request primitive.	Modified by MLME-START.request primitive.

Table 13. Timing synchronization attributes

	dot11BeaconPeriod	**dot11DTIMPeriod**
DESCRIPTION	Specifies the number of TUs that a station uses for scheduling Beacon transmissions. This value is transmitted in Beacon and Probe Response frames.	Specifies the number of beacon intervals that elapse between transmissions of Beacon frames containing a TIM element whose DTIM Count field is 0. This value is transmitted in the DTIM Period field of Beacon frames.
KIND OF VARIABLE	Control variable	Control Variable
TYPE	Unsigned32	Unsigned32
RANGE	(1 .. 65535) TUs	(1 .. 255)
DEFAULT VALUE	Unspecified	1
MAX VALUE	65535 TUs = 67107.84 ms	255
MAX-ACCESS	read-write	read-write
SET BY	Written by an external management entity. (notice: when the variable is a control variable => it is written by an external management entity)	Written by an external management agent.
WHEN	Changes take effect for the next MLME-START.request primitive.	Changes take effect for the next MLME-START.request primitive.

Table 13 – Cont'd

	dot11Spectrum-Management-Implemented	dot11Spectrum-Management-Required	dot11Operating-Classes-Implemented	dot11Operating-ClassesRequired	dot11CountryString
DESCRIPTION	This attribute, when true, indicates that the station implementation is capable of supporting spectrum management. The capability is disabled otherwise.	A STA uses the defined TPC and DFS procedures if this attribute is true; otherwise it does not use the defined TPC and DFS procedures.	This attribute, when true, indicates that the station implementation is capable of supporting operating classes. The capability is disabled otherwise.	A STA uses the defined operating classes procedures if this attribute is true.	See description below.
KIND OF VARIABLE	Capability Variable	Control Variable	Capability Variable	Control Variable	Control Variable
TYPE	TruthValue	TruthValue	TruthValue	TruthValue	OCTET STRING
RANGE	N/A	N/A	N/A	N/A	Size (3)
DEFAULT VALUE	False	False	False	False	
MAX VALUE	N/A	N/A	N/A	N/A	N/A
MAX-ACCESS	read-only	read-write	read-only	Read-write	read-only
SET BY	Determined by device capabilities.	Written by the SME or external management entity.	Determined by device capabilities.	Written by the SME or external management entity.	Written by the SME.
WHEN	N/A	Changes take effect for the next MLME-START.request primitive.	N/A	Changes take effect for the next MLME-START.request primitive.	

Table 14. Spectrum-related attributes

	dot11OperationalRateSet	dot11RMChannel-LoadMeasurement-Activated	dot11Wireless-Management-Implemented
DESCRIPTION	Specifies the set of non-HT data rates at which the station may transmit data. The attribute that specifies the set of HT data rates is dot11HTOperationalMCSSet.	See later (Note that: Channel Load = Integer((channel busy	See later

	Each octet contains a value representing a rate. Each rate is within the range from 2 to 127, corresponding to data rates in increments of 500 kbit/s from 1 Mb/s to 63.5 Mb/s, and is sup- ported (as indicated in the supported rates table) for receiving data. This value is reported in transmitted Beacon, Probe Request, Probe Response, Association Request, Association Response, Reassociation Request, and Reassociation Response frames, and is used to determine whether a BSS with which the station desires to synchronize is suitable. It is also used when starting a BSS, as specified in 6.3.4.	time/(MeasurementDuration × 1024)) × 255)	
KIND OF **VARIABLE**	Status Variable		
TYPE	OCTET STRING	TruthValue	TruthValue
RANGE/SIZE	SIZE (1 .. 126)		
MAX VALUE	N/A		
DEFAULT **VALUE**	N/A		
MAX-ACCESS	Read-only		
SET BY	The SME.		
WHEN	When joining or establishing a BSS.		

Table 15. Other relevant attributes.

For a complete presentation of all the MIB entries, the interested reader is referred to ANNEX E of the standard [30].