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LTE-WiFi Carrier Aggregation for Future 5G Systems: A Feasibility Study and Research Challenges

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Abstract

Multi-Radio Access Technology (multi–RATs) 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 conducted a preliminary 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. For practical deployments, we show that the current advances in cellular technologies form good grounds for actual deployment of integrated LTE-WiFi systems. We also highlight the main research challenges and suggestions for future work.

Keywords: 5G Technologies, LTE-Advanced, Carrier aggregation, WiFi, multi - RATs

1. Introduction

The 3rd Generation Partnership Project (3GPP) has been working on standardizing techniques for LTE-Advanced (LTE-A) systems, which represent the evolution of LTE (Long Term Evolution) wireless communications systems. LTE-A aims at meeting the International Telecommunications Union (ITU) performance requirements, such as higher peak rates. 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), while maintaining backward compatibility with the existing LTE

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standard. Aggregation of up-to five 20-MHz CCs are currently supported in the 3GPP specifications, therefore allowing for a 100 MHz achievable bandwidth for LTE-A users. 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 aggregated 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 CCs from bands belonging to different RATs are aggregated. 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. 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.

This work aims at motivating the research in the area of multi-RAT CA. In particular, we present a feasibility study of the application of CA in an LTE-WiFi multi-RAT system. Our study revealed significant similarity between LTE and WiFi physical layer specifications. This, in addition to the existing advances in multi-RAT network deployments and architectures [13] [14], motivates further research to study the feasibility of specific LTE-WiFi CA scenarios.

2. LTE System Design

Here, we summarize the main components of the LTE network architecture, and then present the physical layer specifications.

2.1. LTE System Architecture

LTE 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 known as eNodeBs. LTE includes the Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and the EPC (Evolved Packet Core), and uses bearers to route IP traffic from the PDN to the UE, where a bearer is an IP packet flow. 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 neighbouring eNodeBs and allows multiple functions, including interference coordination and load balancing [20].

2.2. Physical Layer Design

3GPP defines three Control channels, a shared data channel (PDSCH), a physical broadcast channel (PBCH), a random access channel (DRACH), and reference signals for LTE Downlink. The control channels are transmitted in the control region which is located at the beginning of each subframe; namely, in the 1st 1, 2, or 3 OFDM symbols [3], and the PBCH is 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 colour) 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), which are used for UE cell search and synchronization procedures. Note that in LTE, time is divided into 10-ms frames, each of which is divided into ten subframes, and each subframe is divided into two time slots. Finally, a slot is divided into seven OFDM symbols (or six symbols in case of extended OFDM cyclic prefix). 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 15-kHz subcarriers and therefore occupies 180 kHz. A 180 kHz frequency block for a symbol duration is termed as a resource block (RB). The details on the number of RBs available within each bandwidth are provided in Section 4.3. Finally, within each RB, the reference signals are allocated to resource elements (REs) within a pattern that optimizes channel estimation and equalization, where an RE is a 15-kHz subcarrier x 1 OFDM symbol resource available for transmission. Each RB therefore includes 7x12 = 84 REs, in case of normal cyclic prefix duration.

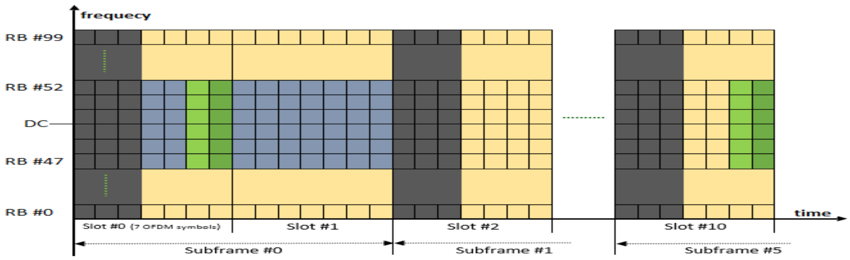


Figure 1. Downlink Logical-to-Physical channels mappings

In the Uplink, 3GPP defines three physical channels and reference signals [12]: the PUSCH (Physical Uplink Shared Channel); the PUCCH (Physical Uplink Control channel) which is located at the edges of the band; and the PURACH (Physical Uplink Random Access Channel) for uplink random access which 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.

In terms of access schemes, LTE adopts the Orthogonal Frequency Division Multiple Access (OFDM) scheme in the downlink. 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. The main advantage of OFDM is its robustness against Inter Symbol Interference (ISI) and low complexity receivers. 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 superimposition of the multicarrier symbols in time domain) and which requires a highly linear RF power amplifier [1]. 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 is difficult to tolerate for the transmitter of the mobile terminal [1]. In order to overcome this limitation, LTE adopts SC-FDMA in the uplink. SC-FDMA is a variation of the OFDM scheme, 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. In effect, the SC-FDMA signal achieves a single-carrier nature and concequently a low PAPR. For further details on OFDM and SC-FDMA designs, the interested reader is referred to [1] and [2] respectively.

3. Carrier Aggregation in LTE-A

LTE Releases 8/9 satisfy to a large extent the ITU-R requirements [11]. LTE-A fully satisfies these requirements and even exceeds them in some aspects [15]. Carrier Aggregation (CA) is one of the main features of LTE-A [10]. This section presents the concept of CA, its modes, and deployment scenarios. For information on other advanced techniques that were introduced in LTE-A, the interested reader is referred to [19], which summarizes these techniques and surveys the research challenges for LTE-A.

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. It is the process of grouping multiple LTE component carriers (CCs) to allow LTE-A devices to use them as one carrier to achieve higher bandwidth. CA can be achieved in a contiguous mode (i.e. the aggregated CCs are adjacent in frequency domain) and in a non-contiguous mode. Additionally, non-contiguous CA can use CCs from the same band or from different bands. CA maintains backward compatibility with LTE Releases 8/9 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 [4]. 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. In particular, the SC-FDMA scheme is not suitable for contiguous CA when the aggregated bandwidth is for bandwidths wider than 20 MHz; as that would break the backward compatibility requirement. The single-carrier properties need to be broken at the Release 8/9 CC edges, because these are reserved for the PUCCH control signalling. For this reason, enhanced access schemes are being considered for LTE-A uplink. Figure 2 presents the transmitter block diagrams for two candidate schemes, namely, clustered SC-FDMA and NxSC-FDMA, also known as multiple SC-FDMA

[10]. Clustered DFT-S-OFDM keeps a single 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.

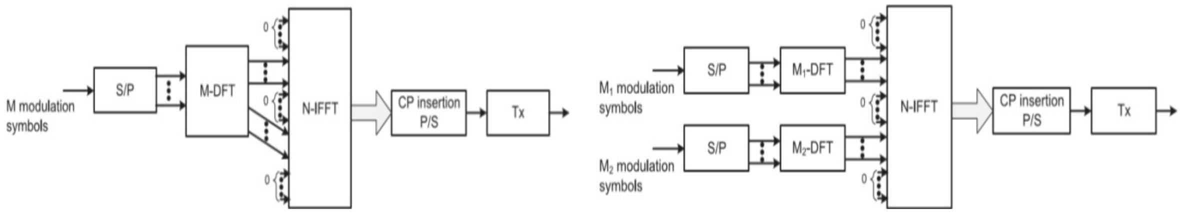


Figure 2. Transmitter diagram of clustered SC – FDMA (left) and NxSC–FDMA (right)

4. 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.

4.1. Non-Technical Consideration

Operators' input is one consideration to account for when selecting CA scenarios. In LTE, 3GPP selected aggregation scenarios for feasibility study based on operators' input, which are naturally affected by their specific needs and band-ownership [6].

4.2. Intra-Band Technical Constraints

For a better understanding of the technical constraints, we first present an example of a candidate deployment scenario. Figure 3 shows a band plan and carrier aggregation scenarios that were under discussion for deployment in Europe [6].

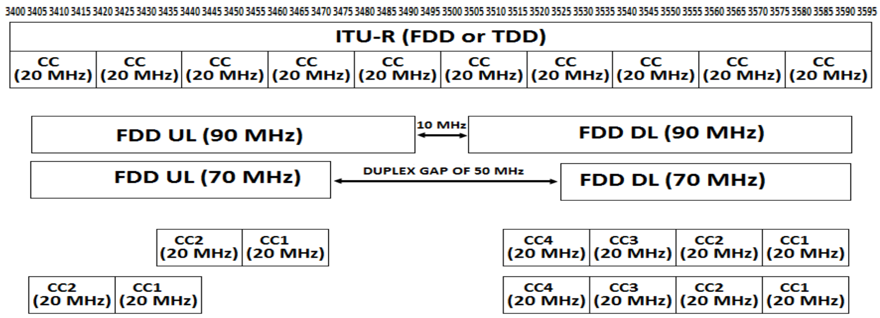
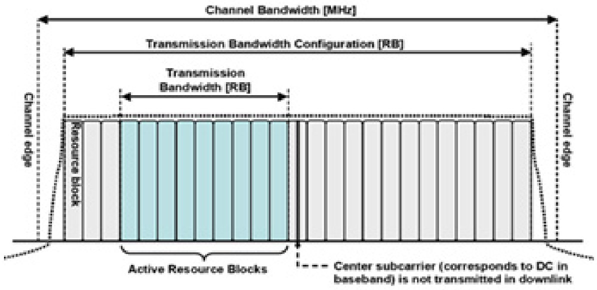


Figure 3. Carrier aggregation scenario deployment

In Figure 3, the 3.5 200-MHz-wide GHz band is shown (can accommodate 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 10 MHz spacing; the second provides smaller UL and DL bands and a wider duplex gap. The figure also presents different choices of CC positions and duplexer gaps that are considered for aggregation. These choices have implications on the performance. In particular, a larger duplex gap implies a more complex duplexer [7], but on the other hand, the duplex gap should be sufficiently large to reduce self-interference. For example, in the figure, there is high potential for self-interference between transmission on CC1 in the UL and reception on CC4 in the DL when the duplex gap is small. Finally, the higher the number of aggregated CCs, the higher the spectral efficiency is because more CCs imply more transmissions and receptions of user data on the specified frequencies. Thus, there is a trade-off between duplexer design and self-interference on one hand and spectral efficiency on the other hand.

4.3. 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 latter signifies the allowed number of resource blocks that can be used for transmission. Figure 4 illustrate this concept.



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

Figure 4. Channel/Transmission Bandwidth specifications

The channel raster in LTE Release 8 is 100 kHz, meaning that the carrier center frequency must be an integer multiple of 100 kHz. This requirement is a consequence of the channel bandwidth specifications discussed above and the need to maintain orthogonality of the aggregated carriers. To efficiently meet this requirement in LTE-A, the difference between the center frequencies of contiguously aggregated CCs shall be a multiple of 300 kHz [6].

5. LTE-WiFi CA: Feasibility Considerations and Research Challenges

Multi-RAT CA is expected to be part of 3GPP Release 12 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 [5]. As presented above, specific scenarios have been defined for LTE-LTE CA, and 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.

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 [16], and the study is only concerned with the OFDM specifications [8]. 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 (BSS) could coordinate with the WiFi access points (APs) in the covered area to request WiFi channels in the contention-free mode, thus appearing as a WiFi user. The borrowed (i.e., granted) channels will be used by the LTE-A BSS as though they are part of the LTE-A spectrum. The coordination between the BSS and an AP may occur over the air interface, by having the BSS 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 BSS-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 [5] 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. In this section, we present the main feasibility considerations and challenges for LTE-WiFi CA deployment.

5.1. Physical Layer Design Compatibility

Our study revealed many similarities between WiFi and LTE in terms of access scheme design and channel raster requirements, which motivates the application of CA on these two standards.

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 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.

For the channel raster, aggregating LTE and WiFi channels should be compatible with the LTE-A 300 kHz channel raster. In our 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 [9] presents the band specifications for the WiFi standard. Channels from this band should be chosen so that their center frequency is a multiple of 100 kHz to satisfy LTE's channel raster requirements. The channel center frequencies in the 802.11 standard are defined as:

$CCF = CSF + 5 \times nCH$, 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; and 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.

5.2. LTE-WIFI Integration through HetNets

A functional LTE-WiFi CA deployment requires proper coordination between the LTE and WiFi systems through integrated network architecture. Generally speaking, the existing advances in the cellular systems technologies allow for such multi-RAT integrated network architectures. These advances include the existing deployments of heterogeneous networks (HetNets) and small cells [13]. 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 1 summarizes the differences between these two kinds. By referring to Table 1, we see that the femtocell deployment can be applied to a WiFi cell. A WiFi access point can be deployed as a HeNB, as it shares the same characteristics presented in Table 1 for HeNBs. Given this, in addition to the 3GPP specifications for small-cell – macrocell coordination, LTE-WiFi coordination can be facilitated using small cell architectures.

	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 a regular eNB	Can be different from regular eNB interfaces
Typical deployment coverage	An enterprise, mall, etc. (hotzones)	A house or apartment

Table 1. Small cells: picocells versus femtocells

5.3. Research Challenges

This section details the main research challenges in terms that need to be considered for deploying the system.

5.3.1. AP Discovery and Connection Configuration

The first needed step in an LTE-WiFi 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. In WiFi infrastructure-based systems, the WiFi stations use Beacon request/report pairs for collecting information about available nearby WiFi APs [17]. 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, 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. 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 was mentioned in Section 2.1, the X2 interface connects eNodeBs together and is used for load-balancing, handover, and interference coordination functions. The X2 setup and application protocols can be replicated or modified for supporting LTE-WiFi coordination.

5.3.2. Interference Coordination

Interference is another critical challenge for the application of the aggregation scheme. 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. In particular, two X2 functions, referred to as elementary procedures, are used for interference coordination; namely, the *Resource Status Reporting* and the *Load Indication* procedures. *Resource Status Reporting* is used by the eNodeB to request the reporting of load measurements from another eNodeB. The corresponding measurement elements include radio-resource status and load information at each cell managed by the concerned eNodeB. The *Load Indication* procedure on the other hand, is used to transfer load and interference co-ordination information between eNodeBs controlling intra-frequency neighbouring cells. The main difference between this procedure and the *Resource Status Reporting* procedure is that the latter is initiated by an eNodeB that needs the measurement information and requires a response from another eNodeB, whereas the *Load Indication* procedure is just a load information message sent by an eNodeB, and requires no response meassages. Both procedures can be re-used or modified for LTE-WiFi interference coordination. Further details on X2 procedures can be found in [20].

5.3.3. MAC Layer Time Synchronization

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. A station 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. The WiFi MAC divides time into constant-length superframes, each containing a 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 [18]. In our proposed CA scheme, the LTE eNodeB can only borrow spectrum during contention-free periods, obviously because contention-based access does not provide guaranteed access to the medium on the borrowed WiFi frequency channels to LTE-A UEs that are employing carrier aggregation, or else it will require making changes to the WiFi standard. Hence, proper LTE-WiFi time synchronization is required so that the beginning of the WiFi CFP coincides with the start time of the LTE subframe, and that its length is a multiple of 1ms so that the contention period (CP) starts with the beginning of another LTE-A subframe during which carrier aggregation is “paused” until the following CFP starts. This requirement is feasible since the WiFi stations synchronize their times with the AP through the beacons that the AP sends at the start of each superframe.

6. CONCLUSION AND FUTURE WORK

We presented a system-level design of carrier aggregation for LTE-A involving borrowing spectrum from WiFi. We conducted a feasibility study and outlined the similarities between the access schemes of WiFi and LTE specifications. 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. Our ongoing research work is focusing on developing architecture for coordination between the LTE-A and WiFi infrastructure to perform the allocation of WiFi bands to LTE-A users. 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.

7. ACKNOWLEDGEMENTS

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