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Spectrum OverLay through aggregation
of heterogeneous DispERsed Bands

FP7 Contract Number: 619687

WP2 – Carrier aggregation over HetNets and h-RATs: Objectives, Scenarios and Requirements

D2.1
Application scenarios and use cases

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Abstract

Application scenarios and use cases: This document will define the scenarios and use cases that will be derived from requirements and that the framework definition in WP3 will consider. It is noted that these scenarios and use cases may be incrementally added to throughout the duration of the project, if it transpires that it is necessary to do so. Moreover, an extensive state of the art related to T2.1 is included at the beginning of this document.

Keywords SOLDER, use cases, scenarios, system requirements.

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Executive Summary

The aim of this document is threefold: a) to present in much detail the current situation of Carrier Aggregation (CA) as a key element technology in 4G wireless systems such as LTE-Advanced (LTE-A) as originally standardized by 3GPP, b) to sketch potential application scenarios and use cases of CA in heterogeneous networks (HetNets) and heterogeneous radio access technology (h-RATs) systems, and c) to give a clear overview of challenges and opportunities which remain open in the next years and how the how the SOLDER project will contribute in addressing some of them both in physical and MAC layer (PHY/MAC).

The current situation of CA technology is described according to the Roadmap set by 3GPP in the Releases of LTE-A, and specifically as originally standardized in Releases 10, 11 and 12. The above state-of-the-art studies the implementation of CA in PHY/MAC layers and also provides the necessary framework for the radio resource management (RRM) between primary and secondary cells (PCell/SCell) serving the user equipment (UE) both in Uplink (UL) and Downlink (DL).

In this deliverable new application scenarios and use cases for possible implementation of CA are defined. In particular cases such as LTE-LTE, LTE-Unlicensed, LTE-TVWS, LTE-WiFi are analysed. These scenarios can be potentially used to increase the capacity area-density, to present practical solutions for HetNets and h-RATs and in general improving the QoS of the UE.

Finally, since the CA is still a very promising technique and unexplored in wireless communications, there is a number of open issues that challenging the SOLDER project. It is apparent that the challenges exist due to aggregation should be achieved among various systems, technologies and spectrum opportunities. For HetNets the transceiver designs to operate in different HetBands and band combinations for small-cell/macrocells, the operation of UE in UL operation in intra- or inter-band CA scenarios, the interference cancelation techniques for mitigation of heavy inter-cell interference, and Link adaptation issues when PCell/SCell serves the UE in a HetNet compose a set of real challenging issues. Other problems which challenge the implementation of CA in HetNets are the channel measurements and feedback reporting capability of the UE for selecting the appropriate CC for aggregation.

Apparently, similar challenges exist for utilization of CA in h-RATs. In h-RATs the problems seem to be very tough since the aggregation should combine different types of spectrum, including licensed spectrum, unlicensed spectrum (e.g, WiFi) and emerging forms of spectrum such as TV white space and spectrum freed by concepts such as authorised/licensed shared access. The SOLDER project focus on specific problem in PHY/MAC layers such as multi-band LTE CA to extend the already standard of five CCs, multi-RAT CA where the CA should not only aggregate various CCs but also should overcome the problem of aggregation of different access technologies. Other challenging issues in h-RATs are the utilization of LTE in unlicensed spectrum (LTE-U), the aggregation of LTE and WiFi bands where critical interference issues exist in UE receiver for adjacent LTE and WiFi frequencies, and RRM in providing dynamic allocation of resources, interference management, and load-balancing of the traffic between the different aggregated h-RATs resources.

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1. Introduction

4G mobile communication systems achieve high data rates, which could be compared with those provided by landline communications. Several key technologies played a significant role towards this end among them Carrier Aggregation (CA). CA has been introduced in long term evolution (LTE) since the Rel-10 (LTE-Advanced) and is also used in recent wireless local area network (WLAN) system sometimes referred as channel or carrier bundling. CA consists in aggregating several carriers. It could then enable very large bandwidth and has the supplementary benefit of facilitating the use of fragmented spectrum for wireless operators. As a result, CA is becoming a hot topic, both from research perspective and soon to come, from commercial deployment standpoint. SOLDER project aims at generalizing CA to consider the possibility of aggregating several bands of same system or several systems. SOLDER is trying to bring a pragmatic step forward towards flexible spectrum usage as promoted since long by software definable radio addicts. Aggregation could be seen at different layers and thereby parts of the network as illustrated by the Figure 1. Radio access network (RAN)-based aggregation is mainly considered through the spectrum aggregation using the CA concept. On the core network side, it could be considered for the upper layers involving mainly the internet protocol (IP) in conjunction with the Internet. Such aggregation of the system is the traffic aggregation and steering from different access points of user terminals. Clearly, the aggregation currently is not a matter of spectrum but also layers that are able to encapsulate multiple data and traffics as we explained in this document below.

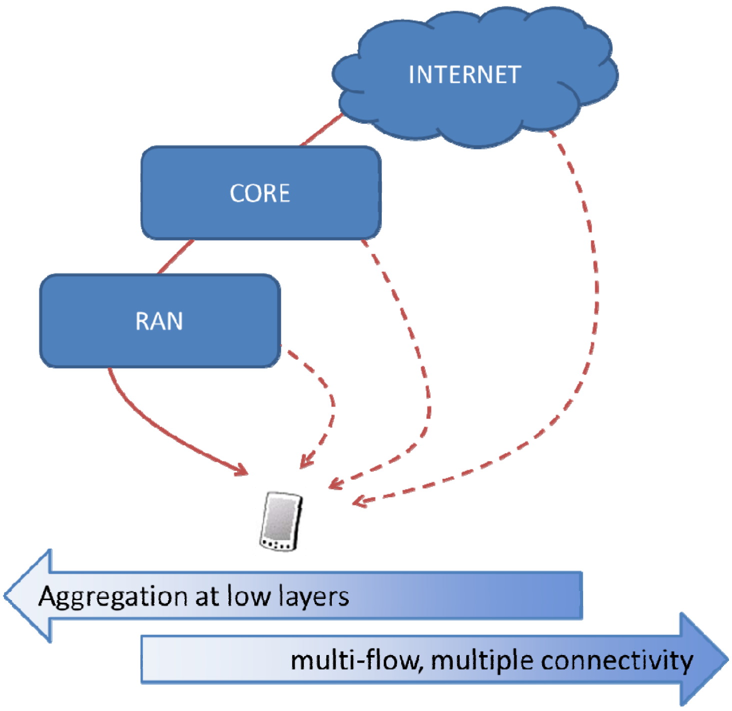

Figure 1: Several options of aggregation.

More specifically, the aggregation could be done at radio access level, using the same radio access, either at the same frequency band or in a different band; one could imagine to aggregate several radio access systems but still at low layer [Physical Layer (PHY)/ Media

Access Control (MAC)]; aggregation could be done at core network level, using one or several technology; or aggregation could be done above the IP layer, as for instance techniques of multi-flow or multiple connectivity involving split and merge of traffic rather at the application layer than at the lower layers. From the state of the art of this document is obvious that this is the main directions in the area of aggregation between heterogeneous networks and access technologies as we explain below. Moreover, particular scenarios are considered based on releases and specification of particular standardization bodies and industrial proposals. Several kinds of spectrum aggregation and system aggregation are made clear by this document. However, since the main focus of SOLDER project is the aggregation at low layers, our work in this document focuses on the physical, medium access control and radio resource management layers.

To this end, Section 2 provides a state of the art based on recent advances in the area of CA in heterogeneous networks (HetNets) and radio access technologies (h-RATs). Details about technical solutions in these areas concentrating on the lower layers are given. In particular, Section 2.1 provides a review of carrier aggregation in LTE-A assuming mainly Rel-10 and beyond. Section 2.3 provides a review of carrier aggregation in heterogeneous networks and what kinds of solutions have been given so far. Both industrial and academic innovations are presented, i.e. patents and scientific publications. In an identical way, Section 2.3 opens the state of the art to multi-radio aggregation looking into the different radio access technologies. Although all layers are considered, eventually Section 2.3 has more relation to the upper layers. In Section 3 potential CA application scenarios and use cases for both HetNets and h-RATs are presented. Finally, Section 4 mentions summarizes all the outcomes of our literature review, and what kind of open issues and challenges are identified in any type of aggregation and related to any layer.

2. State-of-the-art on aggregation of wireless communication technologies

The explosion of mobile data traffic, which is expected to grow by at least three orders of magnitude in the next decade, may be supported neither by current radio technologies nor by their envisioned enhancements. Conventional PHY techniques are not anymore sufficient to increase the spectral efficiency and meet the future requirements of broadband wireless networks [1]. On the other hand, new cross-layer concepts are more promising to meet those requirements and pave the way for the future wireless networks. More specifically, coordinated multipoint (CoMP) transmission and reception [2]-[4] result in important performance gains in terms of capacity and cell edge user throughput by coordinating the transmissions between adjacent cells. Another scheme that plays a vital role in increasing the system's throughput is the Inter-Cell Interference Coordination (ICIC), which in LTE is mostly limited to the frequency domain, through the partial use of frequency resources and the adaptation of power levels [5]. Following the CoMP concept and extending it to the coordination and/or cooperation between macro-cells and smaller cells, the concept of HetNets reflect the current trend for designing the future wireless networks.
3rd Generation Partnership Project (3GPP) has also introduced the enhanced inter-cell interference coordination (eICIC) that provides means for macro and pico access nodes to time-share the radio resources for downlink transmissions [6]. eICIC is realized either by the almost blank subframes (ABS) or by the flexible user association and cell selection bias techniques. Although the concept of cooperation and coordination between cells reduces the interference and hence increases the system's capacity, to provide 1 Gbps in the downlink for 4G LTE; however, even with the improvements in spectral efficiency is not possible to achieve this high rate within the maximum 20 MHz channel. To this end, a novel concept was introduced, i.e., the CA technique, which increases the usable spectrum for the end-user by aggregating multiple frequency carriers in a band (intra-band scenario) or different frequency bands (inter-band scenario) as shown in Figure 2.

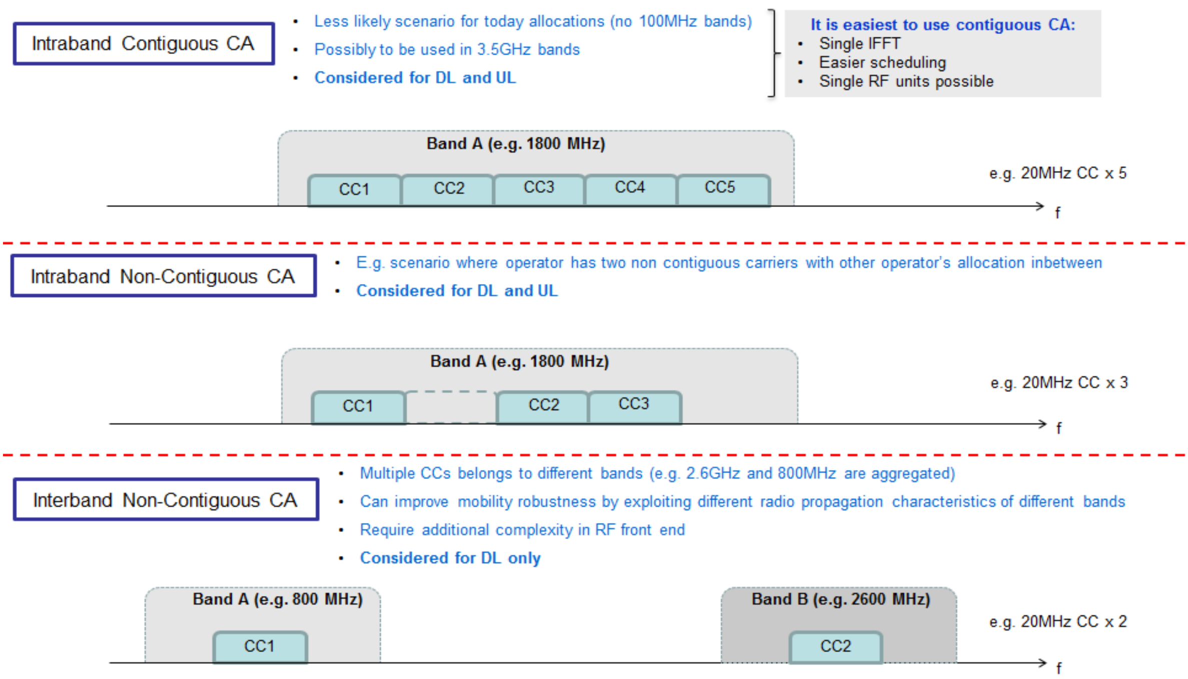

Figure 2: LTE-Advanced CA options.

2.1 Carrier aggregation in 3GPP LTE-A

Two types of CA approaches have been proposed, including contiguous CA and non-contiguous CA. For the contiguous CA approach, the multiple component carriers (CC)s are adjacent to each other; therefore, one fast Fourier transform (FFT) module and one radio frequency (RF) frontend can be used in theory to implement continuous CA. However, due to the fact that the spectrums currently allocated are scattered and a continuous 100 MHz bandwidth (corresponding to 5 CC, the maximum number of aggregated carriers in LTE) is unlikely to be available for LTE-A system, the non-contiguous CA approach seems more practical. As stated earlier Figure 2 depicts the possible carrier aggregation schemes in LTE-A. Among many other good introductions to the LTE-A CA are presented in [7], [8].

2.1.1 3GPP Release 10

The required spectral scaling for the future broadband wireless networks for both downlink (DL) and uplink (UL) (Table 1), can be achieved either by employing multi-antenna capabilities (up to 8x8 in the DL and up to 4x4 in the UL) or by applying spectrum (carrier) aggregation. In LTE Rel-10, the aggregation of up to 2 component carriers (CC)s is allowed. The bandwidth occupied by each CC may be 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz or 20 MHz, which results in an aggregated bandwidth of up to 100MHz.

Table 1: Operating bands for LTE-Advanced (E-UTRA operating bands) [9].

E-UTRA Operating Band	UL operating band base station (BS) receive UE transmit	DL operating band BS transmit UE receive
	FUL_low – FUL_high	FDL_low – FDL_high
1	1920 MHz - 1980 MHz	2110 MHz - 2170 MHz
2	1850 MHz - 1910 MHz	1930 MHz - 1990 MHz
3	1710 MHz - 1785 MHz	1805 MHz - 1880 MHz
4	1710 MHz - 1755 MHz	2110 MHz - 2155 MHz
5	824 MHz - 849 MHz	869 MHz - 894MHz
6[1]	830 MHz - 840 MHz	875 MHz - 885 MHz
7	2500 MHz - 2570 MHz	2620 MHz - 2690 MHz
8	880 MHz - 915 MHz	925 MHz - 960 MHz
9	1749.9 MHz - 1784.9 MHz	1844.9 MHz - 1879.9 MHz
10	1710 MHz - 1770 MHz	2110 MHz - 2170 MHz
11	1427.9 MHz - [1447.9] MHz	1475.9 MHz - [1495.9] MHz
12	698 MHz - 716 MHz	728 MHz - 746 MHz
13	777 MHz - 787 MHz	746 MHz - 756 MHz
14	788 MHz - 798 MHz	758 MHz - 768 MHz
15	Reserved	Reserved
16	Reserved	Reserved
17	704 MHz - 716 MHz	734 MHz - 746 MHz
18	815 MHz - 830 MHz	860 MHz - 875 MHz
19	830 MHz - 845 MHz	875 MHz - 890 MHz
20	832 MHz 862 MHz	791 MHz 821 MHz
21	1447.9 MHz 1462.9 MHz	1495.9 MHz 1510.9 MHz

[1] Band 6 is not applicable

22	[3410] MHz [3500] MHz	[3510] MHz [3600] MHz
…	…	…
33	1900 MHz - 1920 MHz	1900 MHz - 1920 MHz
34	2010 MHz - 2025 MHz	2010 MHz - 2025 MHz
35	1850 MHz - 1910 MHz	1850 MHz - 1910 MHz
36	1930 MHz - 1990 MHz	1930 MHz - 1990 MHz
37	1910 MHz - 1930 MHz	1910 MHz - 1930 MHz
38	2570 MHz - 2620 MHz	2570 MHz - 2620 MHz
39	1880 MHz - 1920 MHz	1880 MHz - 1920 MHz
40	2300 MHz - 2400 MHz	2300 MHz - 2400 MHz
41	[3400] MHz [3600] MHz	[3400] MHz [3600] MHz

For the intra-band and inter-band contiguous CA supported by LTE Rel-10, the combinations are listed in Table 2 and Table 3 below.

Table 2: Intra-band contiguous CA.

Band	**E-UTRA Band**	**UL operating band**			**DL operating band**			**Duplex Mode**
		BS receive / UE transmit			**BS transmit / UE receive**			
		FUL_low – FUL_high			**FDL_low – FDL_high**			
CA_1	1	1920 MHz	-	1980 MHz	2110 MHZ	-	2170 MHz	FDD
CA_40	40	2300 MHZ	-	2400 MHZ	2300 MHz		2400 MHz	TDD

Table 3: Inter-band non-contiguous CA.

Band	**E-UTRA Band**	**UL operating band**			**DL operating band**			**Duplex Mode**
		BS receive / UE transmit			**BS transmit / UE receive**			
		FUL_low – FUL_high			**FDL_low – FDL_high**			
CA_1-5	1	1920 MHz	-	1980 MHz	2110 MHZ	-	2170 MHz	FDD
	5	824 MHZ	-	849 MHZ	869 MHz		894MHz	

LTE Rel-10 in practice is limited to intra-band contiguous CA, i.e. the different carriers are part of the same frequency band and, thus, have similar radio characteristics, which simplifies switching on/off carriers without the use of extensive measurements, but reduces diversity on the other side. Moreover, intra-band non-contiguous CA will not be realized until LTE Rel-11 [10]. For aggregation of non-contiguous CC, each carrier should meet existing LTE spectrum requirements such as emission mask, adjacent channel leakage and spurious emission to provide backward compatibility and ensure minimal interference to adjacent carriers.

In Figure 3, some of the potential deployment scenarios for CA are illustrated. In Rel-10, for the uplink, the focus is laid on the support of intra-band carrier aggregations (e.g. scenarios (a), as well as scenarios (b) and (c) when F1 and F2 are in the same band). For the downlink, all scenarios should be supported in Rel-10.

<u>Scenario (a)</u>: **F1 and F2 cells are co-located and overlaid**, providing nearly the same coverage. Both layers provide sufficient coverage and mobility can be supported on both layers too. A likely scenario is when F1 and F2 are of the same band, e.g., 2 GHz, 800 MHz, etc. It is expected that aggregation is possible between overlaid F1 and F2 cells.

<u>Scenario (b)</u>: **F1 and F2 cells are co-located and overlaid**, but F2 has smaller coverage due to larger path loss. Only F1 provides sufficient coverage and F2 is used to improve throughput. Mobility is performed based on F1 coverage. A likely scenario is when F1 and F2

are of different bands, e.g., F1 = {800 MHz, 2 GHz} and F2 = {3.5 GHz}, etc. It is expected that aggregation is possible between overlaid F1 and F2 cells.

Scenario (c): **F1 and F2 cells are co-located** but F2 antennas are directed to the cell boundaries of F1 so that cell edge throughput is increased. F1 provides sufficient coverage but F2 potentially has holes, e.g., due to larger path loss. Mobility is based on F1 coverage. A likely scenario is when F1 and F2 are of different bands, e.g., F1 = {800 MHz, 2 GHz} and F2 = {3.5 GHz}, etc. It is expected that F1 and F2 cells of the same eNB can be aggregated where coverage overlaps.

Scenario (d): **F1 provides macro coverage and on F2 Remote Radio Heads (RRHs)** are used to improve throughput at hot spots. Mobility is performed based on F1 coverage. A likely scenario is when F1 and F2 are of different bands, e.g., F1 = {800 MHz, 2 GHz} and F2 = {3.5 GHz}, etc. It is expected that F2 RRHs cells can be aggregated with the underlying F1 macro cells.

Scenario (e): Similar to scenario (b), but frequency selective repeaters are deployed so that coverage is extended for one of the carrier frequencies. It is expected that F1 and F2 cells of the same eNB can be aggregated where coverage overlaps.

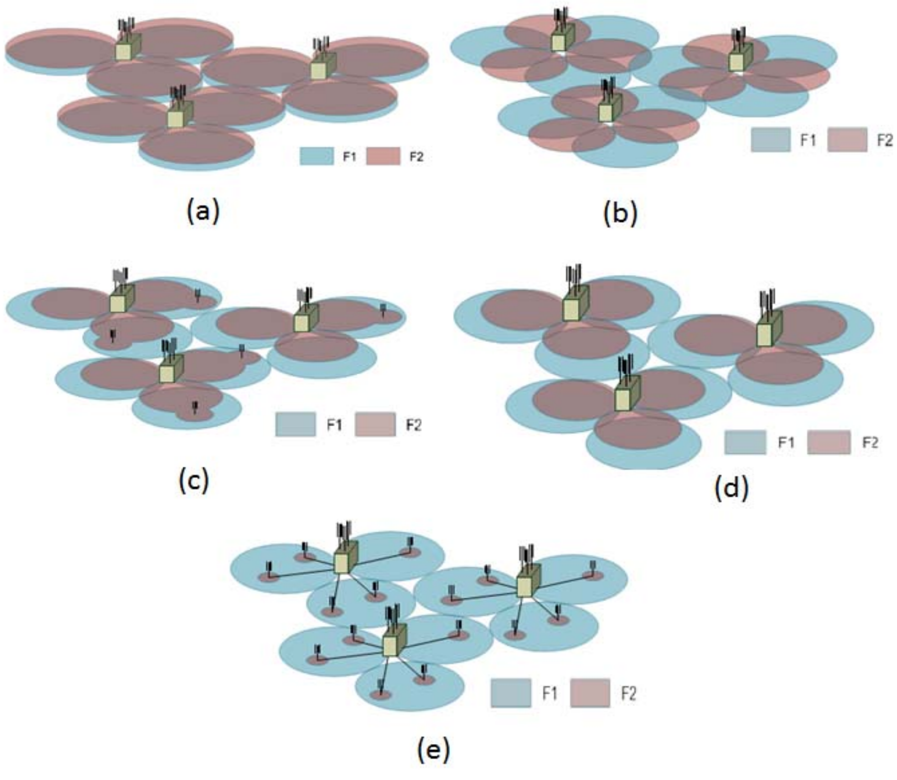

Figure 3: Deployment scenarios in LTE Rel-10.

2.1.2 3GPP Release 11

LTE Rel-11 except for realizing the intra-band non-contiguous CA, will also support inter-band non-contiguous CA [11]. Every new release of LTE is expected to support new combinations of band aggregation. Some CA combinations proposed by vendors and operators are given in Table 4 and Table 5.

Table 4: CA combinations for LTE Rel-11.

Band#	Band (MHz)	Duplex	Band combination	Operator Activities	Band#
2	PCS	FDD	Inter	USA	AT&T, US
17	700(754-716/734-746)	FDD	Inter		
4	AWS	FDD	Inter	USA	AT&T , US
5	850 (24/849-869-894]	FDD	Inter		
4	AWS	FDD	Inter	USA	Rogers, Canada
7	2600	FDD	Inter		
4	AWS	FDD	Inter	USA	Regional Operators
12	700(696-716/728-746)	FDD	Inter		
4	AWS	FDD	Inter	USA	Verizon
13	705(777-737/746-756)	FDD	Inter		
4	AWS	FDD	Inter	USA	AT&t
17	700(704-716/734-736)	FDD	Inter		
5	850 (824/849-869-894)	FDD	Inter	USA	Regional Operators
12	700(698-716/728-746)	FDD	Inter		
5	850(24/849-869-894)	FDD	Inter	USA	AT&T
17	700(754-716/734-746)	FDD	Inter		
41	3600-3800	TDD	Inter	Global	Softbank, Japan (Huawei)
3	1800	FDD	Inter	Europe	Lebanon Touch [Huawei]
20	800	FDD	Inter		
7	2600	FDD	Inter	Europe	SFR, France, Vodafone Germany (Huawei),O2 Germany (Huawei)
20	800	FDD	Inter		
8	900	FDD	Inter	Europe	3GPP Work Item Rapporteur: Vodafone
20	800	FDD	Inter		
7	2600	FDD	Intra	Global	Tele2/Telenor, Sweden (Huawei)
1	2100	FDD	Inter	Japan	3 GPP Work Item Rapporteur; KDDI, Japan
18	800 Lower (815-830/860-875)	FDD	Inter		
1	2100	FDD	Inter	Japan	DoCoMo, Japan
19	300 MHz Upper (830-845/875-890)	FDD	Inter		
1	2100	FDD	Inter	Japan	DoCoMo, Japan
21	1500 Upper (1447.9-1462.9/1495.9-1510.9]	FDD	Inter		
3	1800	FDD	Inter	South Korea	SKT (Ericsson, NSN, Samsung)
5	850 (824/849-869-894)	FDD	Inter		
3	1800	FDD	Inter	Europe, Asia	Telstra, Australia (Ericsson), KT, South Korea
8	900	FDD	Inter		
11	1500 Lower (1427.9-1447.9/1475.9-1495.9)	FDD	Inter	Japan	3GPP Work Item Rapporteur: KDDI, Japan
18	800 Lower (815-830/860-875)	FDD	Inter		
38	2600 (2570-1620-2570-2620)	TDD	Intra	Global	3GPP Work Item Rapporteur: Huawei

Table 5: CA deployment scenarios for LTE Rel-11.

Deployment scenario		Carrier aggregation
FDD	Contiguous single band UL: 40 MHz DL: 80 MHz	UL: 2x20 MHz (3.5 GHz) DL: 4x20 MHz (3.5 GHz)
	Non-contiguous multiple bands UL: 40 MHz DL: 40 MHz	UL: 10 MHz (1.8 GHz)+ 10 MHz (2.1 GHz)+ 20 MHz (2.6 GHz)+ DL: 10 MHz (1.8 GHz)+ 10 MHz (2.1 GHz)+ 20 MHz (2.6 GHz)+
TDD	Contiguous single band 100 MHz	5x20 MHz (2.3 GHz)
	Non-contiguous single band 80 MHz	2x20 MHz (2.6 GHz) + 2x20 MHz (2.6 GHz)

The majority of band combinations have been submitted by US-based network operators. Most of these combinations seek aggregation of currently deployed LTE networks at 700 MHz or in general lower frequencies with frequency blocks around 2 GHz, mainly in what is known as the Advanced Wireless Services (AWS) spectrum and corresponds in the 3GPP terminology to frequency band 4.

2.1.3 PHY layer design

In the following, the various Tx architectures options are provided according to where the component carriers are combined, i.e., at digital baseband, or in analogue waveforms before RF mixer, or after mixer but before the power amplifier (PA), or after the PA [12].

Scenario 1: Intra-band contiguous CA
Single baseband + IFFT + DAC + mixer + PA receiver. In an adjacent contiguous common carrier aggregation scenario, the UE very likely has one PA. Connected to the PA can be a single RF chain, a zero-IF mixer, a wideband DAC, and a wideband IFFT.

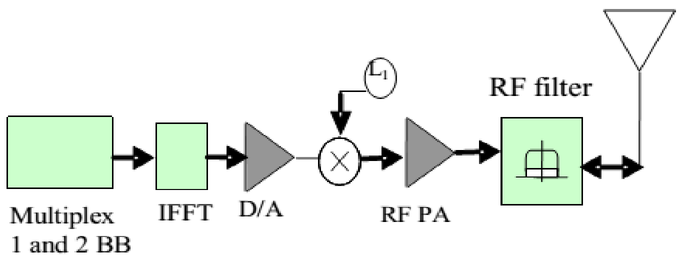

Figure 4: UE Transmitter Architecture for Scenario 1.

Scenario 2: Intra-band contiguous and non-contiguous
Multiple (baseband + IFFT + DAC), single (stage-1 IF mixer + combiner @ IF + stage-2 RF mixer + PA). It combines analogue baseband waveforms from each Component Carrier first (e.g., via a mixer operating at an IF of roughly the bandwidth of the other component carrier in the example of 2-component carrier aggregation). Then the resulting wideband signal is up-converted to RF.

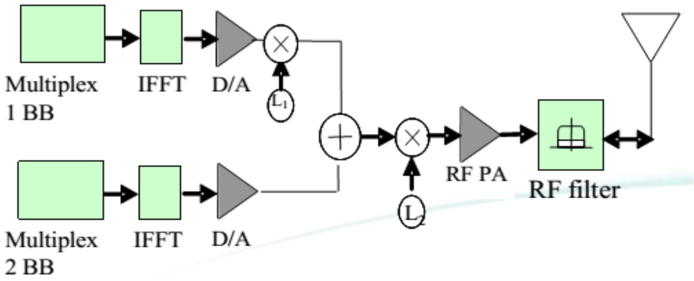

Figure 5: UE Transmitter Architecture for Scenario 2.

Scenario 3: Intra-band contiguous and non-contiguous
Multiple (baseband + IFFT + DAC + mixer), low power combiner at RF, and single PA. It performs ZIF up-conversion of each component carrier before combining and feeding them into a single PA.

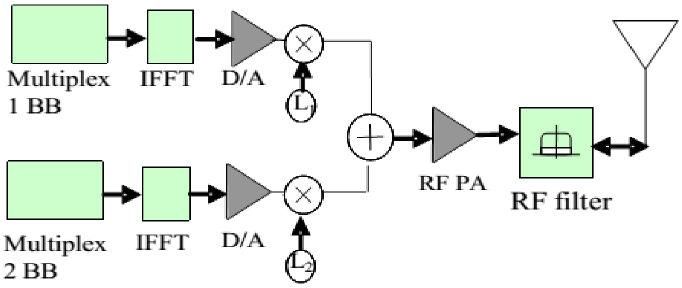

Figure 6: Tx architecture for Scenario 3.

Scenario 4: Inter-Band CA
Multiple (baseband + IFFT + DAC + mixer + PA), high-power combiner to single antenna OR dual antenna (MIMO). It employs multiple RF chains and multiple PAs after which the high-power signals are combined and fed into a single antenna. PA coupling at the UE can be challenging for option-D.

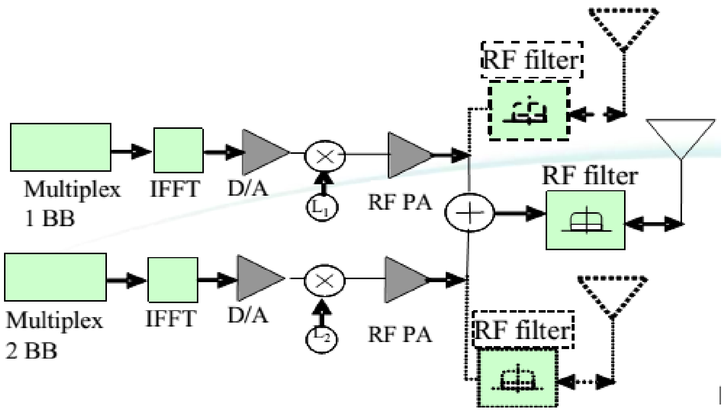

Figure 7: Tx architecture for Scenario 4.

Single-chip receiver for CA: A single-chip signal splitting carrier aggregation receiver architecture as shown in Figure 8 including a primary antenna, a secondary antenna and a transceiver chip where a simultaneous hybrid dual receiver path [13] (Figure 8).

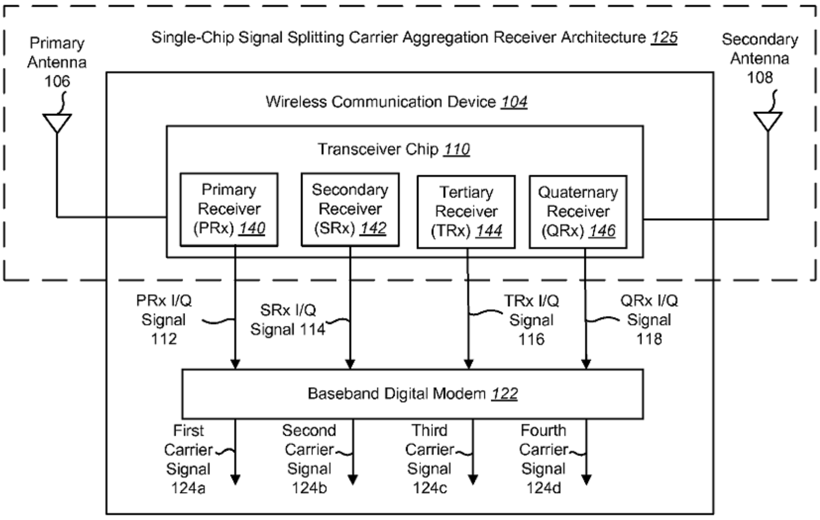

Figure 8: Single-chip receiver for CA [13].

According to [13], a first signal is received using a primary antenna, which is routed through a primary receiver on a transceiver chip in the single chip signal splitting carrier aggregation receiver in order to obtain a primary in-phase/quadrature (I/Q) signal, while a second signal is received using a secondary antenna, which is routed through a secondary receiver on the transceiver chip to obtain a secondary in-phase/quadrature signal. The second signal is routed through a quaternary receiver on the transceiver chip to obtain a Rx I/Q signal.

Downlink Channel Quality: DL channel quality in LTE Rel-8 and 9 is estimated at the UE and reported via the channel state information (CSI) Information Element (IE). In LTE Rel-10, the same procedure is followed but the existence of multiple CCs requires that Channel Quality Indicator (CQI) must be evaluated and reported for each CC individually when CA is active. The CQI, as well as downlink HARQ ACK/NACK indicators and other information, is reported to the base station (BS) via the uplink control information (UCI) IE. There is exactly one physical uplink shared channel (PUCCH) and it is on the PCell regardless of the number of CCs, hence the UCI for each CC should be reported via this PUCCH if the terminal does not have a PUSCH configured. In order to distinguish which UCI belongs to a given CC, the header of the UCI contains a carrier indicator field (CIF) [14].

MIMO CA receiver reuse architecture: In [15] a wireless communication device is presented configured for receiving a wireless multiple-input and multiple-output signal. The wireless communication device includes a first multiple-input and multiple-output (MIMO) carrier aggregation receiver reuse architecture. The first multiple-input and multiple-output carrier aggregation receiver reuse architecture includes a first antenna, a second antenna and a transceiver chip. The first multiple-input and multiple-output carrier aggregation receiver reuse architecture reuses a first carrier aggregation receiver path. The wireless communication device also includes a second MIMO carrier aggregation receiver reuse architecture. The second multiple-input and multiple-output carrier aggregation receiver reuse architecture includes a third antenna, a fourth antenna and a receiver chip. The second multiple-input and multiple-output carrier aggregation receiver reuse architecture reuses a second carrier aggregation receiver path. This operation is described in the flowchart in Figure 9. The first multiple-input and MIMO carrier aggregation receiver reuse architecture includes a first antenna, a low-pass high-pass diplexer, a switch, four duplexers, a second antenna, a second low-pass high-pass diplexer, a second switch, four surface acoustic wave (SAW) filters and a transceiver chip. The second antenna may be a WLAN antenna.

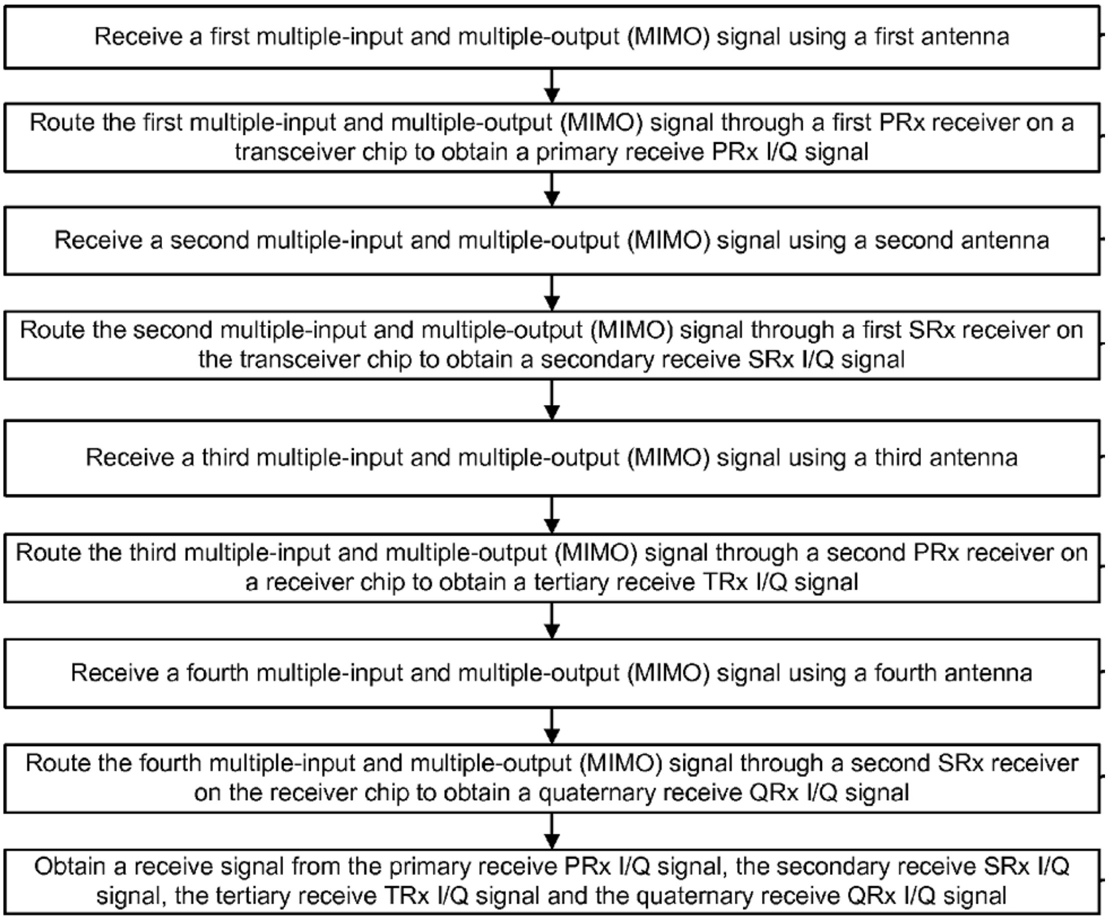

Figure 9: MIMO carrier aggregation receiver reuse architecture.

2.1.4 MAC layer design

Regarding the MAC layer, it plays the role of the multiplexing entity for the aggregated component carriers. Each MAC entity will provide to its corresponding CC its own PHY entity, providing resource mapping, data modulation, HARQ, and channel coding (Figure 10). More specifically:

- Data aggregation happens in MAC layer, the multi-carrier nature of carrier aggregation is not visible to the core network
- The MAC layer divides the data between different CCs and separates the HARQ processes for each CC.
- There is one transport block, up to two in case of spatial multiplexing, and one HARQ entity per scheduled component carrier.
- A UE can be scheduled over multiple component carriers simultaneously, but one random access procedure at any time.

The BS's MAC layer scheduler must have knowledge of all active CCs. This differs from pre-Rel-10 LTE schedulers, which need consider only one cell carrier at a time. Furthermore, it must consider the DL and UL channel conditions across the entire aggregated bandwidth. This increases the complexity of the BS scheduler. For example, the scheduler could decide to send all of a given UE's downlink transport blocks on CC1, but to receive all of that UE's uplink transport blocks on CC2.

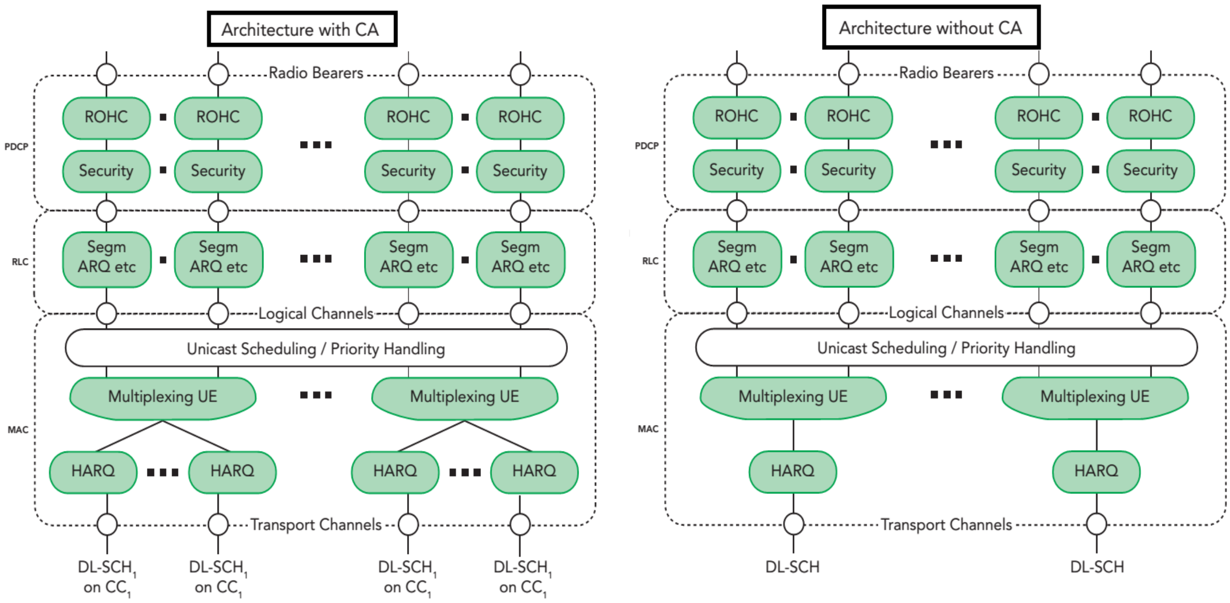

Figure 10 : Evolution of MAC for LTE-A CA [14].

Rele-11 also supports CA with multiple uplink Timing Advances (TAs) and other enhancements to support non-collocated cells, e.g. multiple uplink power control instances or improved sounding reference symbols. One of the key scenarios is the extensive use of RRHs connected via fibre to a central baseband unit (see [16] for further information). An indicative heterogeneous networks (HetNet) scenario is shown in Figure 11, where macro-cells which overlay small cells both simultaneously use the same component carriers, requiring inter-cell interference coordination .

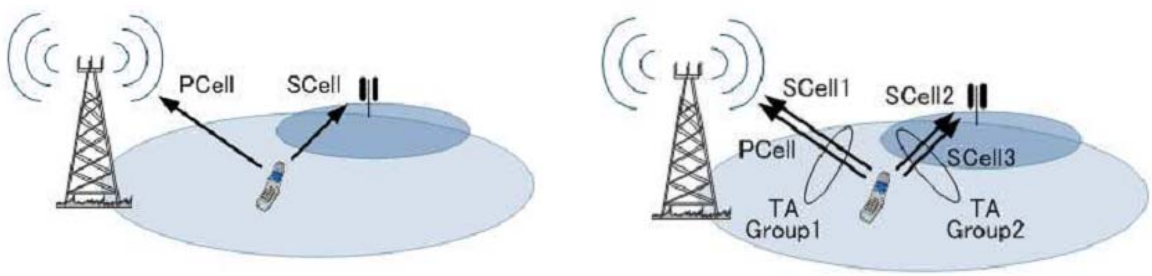

Figure 11: Single and multiple timing advance concepts [16].

The multi-site CA, released in LTE-A Rel-11, supports multiple uplink TA enhanced uplink power control for HetNet (Figure 12). For such a scenario, the macro BS could serve as PCell providing system information, radio resource control (RRC) signalling and bandwidth limited data transmission, while the small BS would serve local high data rate requirements.

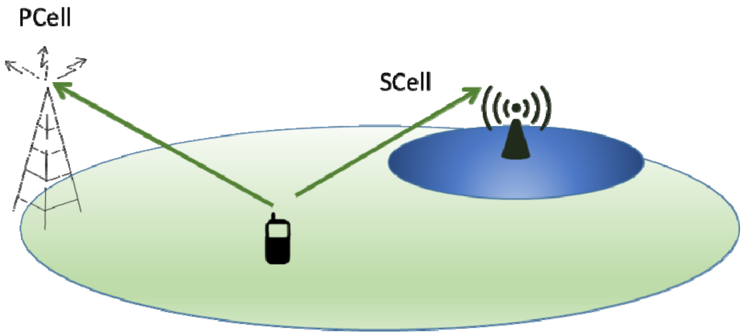

Figure 12: Multi-site CA with multiple TA in Rel-11.

2.1.5 Radio resource management

2.1.5.1 Cell configuration for CA

Cell configuration is also a useful technique in multi-layers (i.e. cells) CA. CA requires the introduction of the Primary and Secondary serving cells. The PCell handles the RRC connection establishment/re-establishment, with the Primary Component Carriers (PCCs) corresponding to the PCell for both UL and DL. The secondary serving cell (SCell) is configured after the connection establishment to provide additional radio resources, i.e. Secondary Component Carriers (SCCs) for UL and DL. Some details about the functionality of PCell and SCell are given below:

- **PCell:**
  - Measurement and mobility procedure are based on PCell,
  - Random access procedure is performed over PCell.
- **SCell:**
  - MAC layer based dynamic activation/deactivation procedure is supported for SCell with battery saving,
  - Information can be cross-scheduled.

If CA is configured for a particular UE, the operation is based on the following assumptions:

- There is always one Component Carrier, that the UE is camped at and that is used for signalling (RRC and NAS) – this is called PCC,
- if there is more than one CC configured, it is used as an extra resource for data transmission – this is called SCC,
- there is a linking between PCC in DL and UL,
- number of CCs in the DL shall be larger or equal to number of UL CCs,
- each CC can have different BW size,
- each UE can have different CC configuration and different configured PCC,
- switching between CCs - for PCC change - is based on HO procedure,
- UE measures all the CCs in the DL, and sends PUCCH only in UL PCC, and
- the grants and assignments may be done with the use of cross-carrier scheduling (i.e. for example DCI in DL CC1 can allocate resources in DL CC2).

It is evident that RRC and MAC are important layers for the cell configuration in CA over HetNets. A configuration example is depicted in Figure 13 below, which shows the CA procedure for CA Configuration, i.e. activation/deactivation. The procedure explains the usage of the new procedures within RRC and MAC layer which is CA addition/release at RRC layer and CA activation/deactivation at MAC layer which adds more complexity to the scheduler.

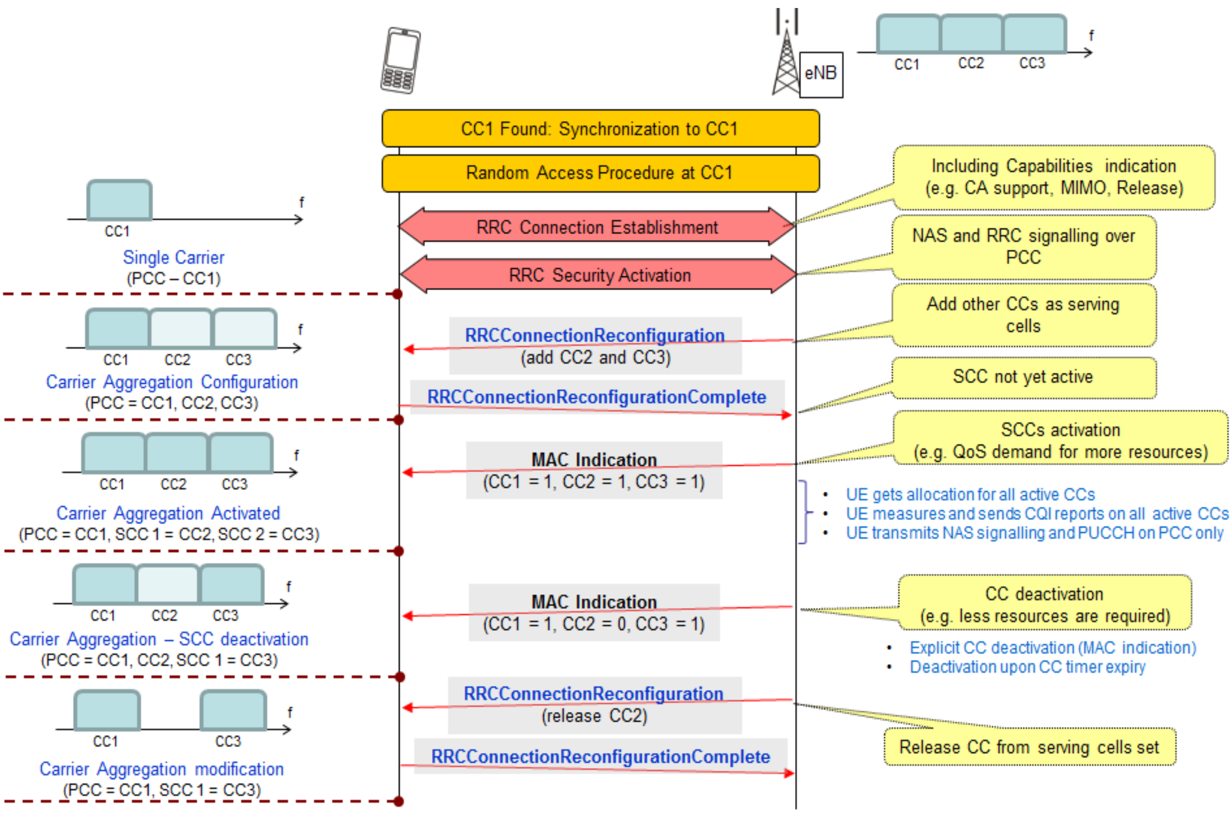

Figure 13: CA procedures: RRC control with CC activation and deactivation.

One important consideration in radio resource management for aggregation in LTE-A is the choice of CC that are aggregated, based on considerations such as the resulting utility that is achieved through CA, and the interactions with traffic loads/requirements and better sharing among users. In this context, reference [17] has taken into account the diversity of performance among CC and attempted to aggregate CCs more appropriately given that. The proposed scheme is assessed with regard to increased throughput, spectrum utilisation, fairness and other aspects. Results show an improvement in utility of CA as well as enhanced fairness compared with assessed alternative approaches.

2.1.5.2 Cross carrier scheduling

Cross carrier scheduling consists in using the control channel from the primary cell to indicate the allocation on the secondary channel. It has been set as an optional feature for the UE, when introduced in Rel. 10. Figure 14 illustrates the use of cross carrier scheduling. On the left part of the Figure, regular scheduling is used. The UE has to demodulate control channels from both primary and secondary cells to know where are scheduled its data channels. On the right side of the Figure, Cross carrier scheduling is used: the control channel of the Primary channel allocates data resource on both Primary and Secondary cells.

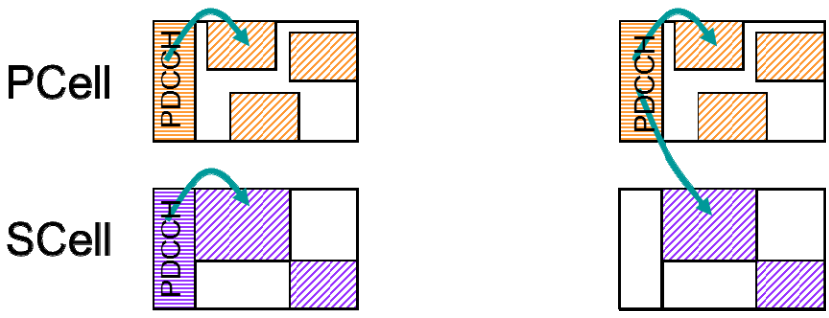

Figure 14: Illustration of cross carrier scheduling.

In addition of saving resource on the secondary cell, Cross-carrier scheduling provides interference management for control channels known. The goal is to reduce interference in HetNet scenarios with CA where a combination of macros, smalls-cells and relays is used. Cross-carrier scheduling is only used to schedule resources on a SCell without PDCCH. CC1 of Macro Cell would cause high interference to CC1 of the pico-cell, therefore the pico-cell uses CC2 for physical downlink shared channel (PDCCH) messages to schedule PDSCH transmission on CC1.

2.2 Carrier aggregation in HetNets

A HetNet consists of a mix of macro-cells and low-power nodes such as pico-cells, femto-cells, remote radio heads (RRHs), or relays, which are overlaid within macro-cells (Figure 15). Under the cooperative framework, the concept of HetNets, relies on the deployment of heterogeneous low power nodes (LPN)s within the macrocell [18], [19]. The HetNet deployments provide a wide area coverage through the macro cell and a more targeted coverage of special zones (e.g., areas with increased traffic or areas with weak signal reception) through the LPNs. The HetNet concept is also part of the 3GPPLTE network architecture, where the LPNs include the pico-cells, femtocells, home eNodeBs (eNB)s and relay nodes [20]-[24]. The small cells may operate at different bands or reuse the same bands as the macro cell. In the latter case, interference management between the macro- and the small cells is required [25]. According to [26] the possible deployments of HetNets, frequency partitioning can be combined with power control to achieve better performance. Different from the partial co-channel configuration for Home NB, frequency partitioning can be performed at the granularities of RBs within a carrier, which enables more flexible coordination not only between Macro and Home eNodeB, but also between the Home eNodeBs. If adaptive frequency partitioning is used, possible information exchanges between Home eNodeBs may need to be supported. The resources used in Macro and Home eNodeBs can also be partitioned and coordinated in the time dimension. Different time zone or UL-DL configurations between HeNBs and macro eNBs or among HeNBs under specific conditions may provide some flexibility for interference coordination. However, it may also bring new interference risks. Further interference mitigation method based on the time partitioning is FFS.

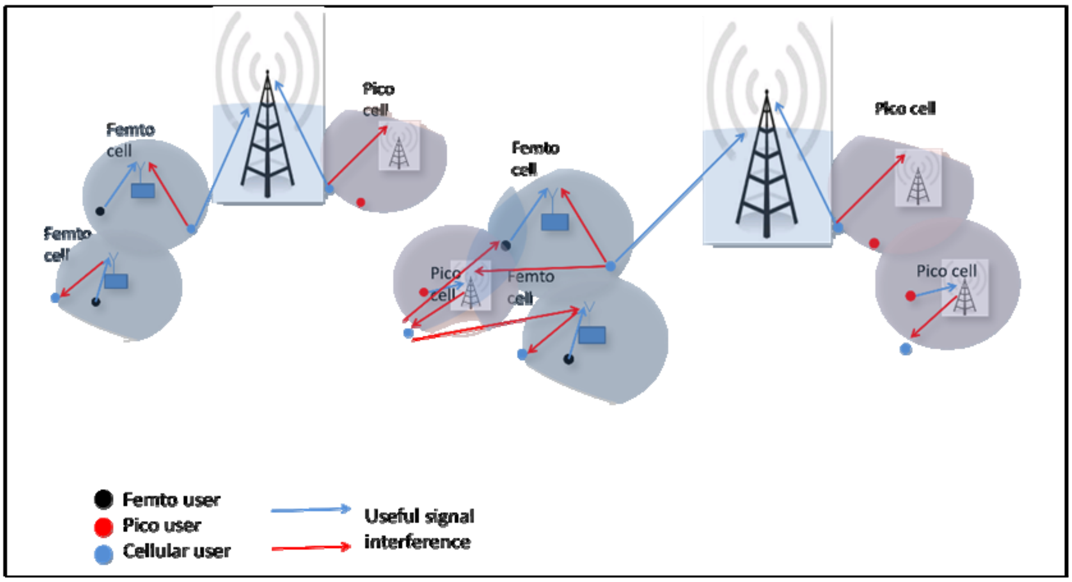

Figure 15: A two-tier HetNet.

2.2.1 3GPP Release 12

In LTE Rel-12 and beyond the following items are discussed with respect to CA in HetNets. First, new band combinations will be introduced, which will mainly address significant omissions from Rel-10 and Rel-11, such as the non-inclusion of the Asia Pacific (APT700) MHz band plan, which is now widely adopted across the Asia Pacific region and by a growing pool of service providers in Latin America (see Table 6). 3GPP Rel-12 will also include work items for CA 3-band implementations across the North American bands – 2, 4, 5, 13, 17 and 30. Moreover, Rel-12 is expected to allow for the aggregation of carriers belonging to radio transmitters from different sites, including the aggregation of macro cell layer carriers with carriers from the small cell layer (inter-site CA). Rel-12 will be the standard reference for the 3800-4200 MHz band.

Table 6: Expected CA combinations in LTE Rel-12

Band#	Band (MHz)	Duplex	Band combination	Operator Activities (Launch, Trial, Planned)
1 7	2100 2500	FDD FDD	Inter Inter	China Telecom
1	2100	FDD	Inter	3GPP Work Item Rapporteur: Softbank, Japan
8	900	FDD	Inter	
1 11	2100 1500 Lower (1427 9-1447 9/1475 9-1495 9)	FDD FDD	Inter Inter	3GPP Work Item Rapporteur: Softbank –Japan
1 26	2100 850+ (814-849 /859-894)	FDD FDD	Inter Inter	3GPP Work Item Rapporteur: KDDI, Japan
2 4	PCS AWS	FDD FDD	Inter Inter	3GPP Work Item Rapporteur : T- Mobile, US
2 5	PCS 850(824/849-869-894)	FDD FDD	Inter Inter	3GPP Work I tem Rapporteur : AT&T, US
2 1 2	PCS 700 (698-716/728-746)	FDD FDD	Inter Inter	3G PP Work Item Rapporteur : US Ce 11 u la r, US
2 1 3	PCS 700 (777-737/746-756)	FDD FDD	Inter Inter	3GPP Work Item Rapporteur : Ericsson
3 19	1800 800 Upper (830-845/875-890)	FDD FDD	Inter Inter	3GPP Work Item Rapporteur: DoCoMo, Japan
3 26	1800 850+ (814-849/859-894)	FDD FDD	Inter Inter	3GPP Work Item Rapporteur: KT, South Korea
3 28	1800 700APT (703-748 /758-803)	FDD FDD	Inter Inter	Vodafone New Zealand (NSN)
5 7	850(824/849-869-894) 2 600	FDD FDD	Inter Inter	3G PP Work Item Rapporteur: LG U+, South Korea
5 25	850(824/849-869-894) 1900+ (1850-1915 /1930-1995)	FDD FDD	Inter Inter	3G PP Work Item Rapporteur: US Ce1ular, US
8 11	EGSM (880-915/925-960 1500 Lower (1427 9-1447 9/1475 9-1495 9)	FDD FDD	Inter Inter	3GPP Work Item Rapporteur: Softbank, Japan
8	EGSM (880-915/925-960)	FDD	Inter	3GPP Work Item Rapporteur: KT, South Korea

26	850+(814-849/859-894)	FDD	Inter	
12 25	700 (698-716/723-746) 1900+ (1850-1915/l930-1995)	FDD FDD	Inter Inter	3G PP work Item Rapporteur: US Ce1lular, US
19 21	800 Upper (830-845/875-890) 1500 Upper (1447 9-14 62 9/1495 9-1510 9)	FDD FDD	Inter Inter	3GPP Work Item Rapporteur: DoCoMo, Japan
23 29	2000 S Band [2000-2020/2180-2200] 700 DL (717-728)	FDD FDD	Inter Inter	3 GPP Work Item Rapporteur: DISH, US
39 41	1900 (18800-1920/1880-1920] 2600(249 6-2690/249 6- 2690)	TDD TDD	Inter Inter	3GPP Work Item Rapporteur: China Mobile, China
3	1800	FDD	Intra-Contiguous	3GPP Work Item Rapporteur: China Unicom, China
23	2000 S	FDD	Intra-Contiguous	3GPP Work Item Rapporteur DISH, US
27	800 SMR	FDD	Intra-Contiguous	3GPP Work Item Rapporteur: NII Holdings, US
39	1900	TDD	Intra-Contiguous	3GPP Work Item Rapporteur China Mobile, China
41	2600	TDD	Intra-Contiguous	Clearwire (Sprint), USA, China Mobile, China (ZTE, Ericsson)
2	PCS	FDD	Intra-Non Contiguous	3GPP Work 1 te m Rapporteur : Eric s so n
3	1800	FDD	Intra-Non Contiguous	33 PP Work: Item Rapporteur : s K Te lee om, SO uth Korea
4	AWS	FDD	Intra-Non Contiguous	3GPP Work Item Rapporteur: T-Mobile, US
7	2600	FDD	Intra-Non Contiguous	3GPP Work Item Rapporteur: Ericsson
23	2000 S	FDD	Intra-Non Contiguous	3GPP Work Item Rapporteur DISH, US
25	1900+	FDD	Intra-Non contiguous	3G PP Work Item Rapporteur: sprint, us
41	2Done00	TDD	Intra-Non Contiguous	3G PP Work Item Rapporteur: sprint. us

2.2.2 PHY layer

In [28] a RF design is presented for supporting MIMO and CA in devices using a single inverse FFT (IFFT) block so as to reduce FFT complexity caused by multiple IFFT blocks and be able to support not only the intra-band CA but also the inter-band CA by such single architecture (Figure 16). In this way, the Rx can support HetNets CA but in a strict way without supporting femtocell or picocell transmission for the inter-band scenario.

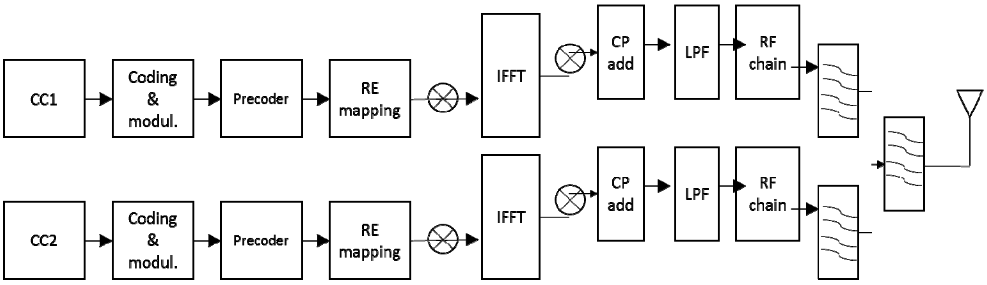

Figure 16: The RF design proposed in [28].

A downlink orthogonal frequency division multiplexing access (OFDMA) scheme that can receive multi-band and multi-mode signals using sub-sampling method with time division multiplexing (TDM) in the same time combined with beam-forming technology was proposed in [29]. That receiver is also able to receive over two bands, signals with one sample & holder and ADC. The authors in [30] presented a single-chip receiver supporting both NC intra-band and inter-band CA with the capability to receive up to three carriers simultaneously (Figure 17). The latter one is considered as CA in HetNets RF design. Going into more details, in [30] the authors proposed two-component inter-band aggregation schemes where one band from one group is aggregated with one band from another group. By considering CA in terms of groups (Table 7) rather than bands, this concept reduces the possible permutations of the aggregation schemes. As RF blocks such as RF amplifiers can be adaptable across the frequencies of the selected groups, it also reduces the number of different RF amplifiers which need to be provided; e.g. to just 5 different ones, it also allows for a reduction in their overall number by appropriate arrangement.

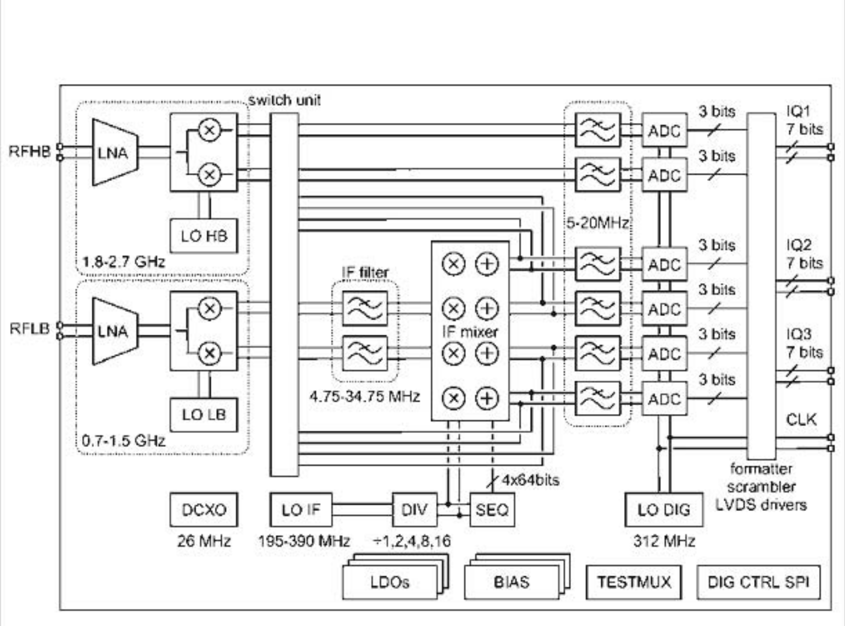

Figure 17: The receiver proposed in [30].

Further to the above, aggregation may be performed between the macro cell and small cells in different bands even using different types of spectrum. Reference [31], for example, proposes a means to optimise the aggregation of channel opportunities in television white space (TVWS) for femtocells, taking into account the inter-femtocell interference characteristics, as managed by a centralised database. This is one interesting example of how the introduction of a geolocation database may be used not just for secondary-primary coexistence management, but also for coexistence among secondaries. Moreover, it is noted that small-cells may themselves aggregate spectrum opportunities and access rights over different types of spectrum [32]. As an additional observation, both when it comes to aggregating and sharing of spectrum and using/optimising aspects such as transmission power in cases of small cells sharing with one or more macro cells, CR technologies may assist parameterisation and decisions for such purposes [33]. Here it is noted that CRs might have access or be able to infer localised knowledge such as on shadowing characteristics over local links, to an extent which the higher-level network management entities could not achieve. Further, CRs are also important considering that, as cells become smaller and smaller and networks more difficult to manage, there are more associated statistical uncertainties in the signal-to-interference-plus-noise ratio (SINR) that will be achieved and other factors. Localised, autonomous and intelligent management is a key to addressing this issue. As a further supporting observation, it is noted that significant industrial interests are promoting aggregation particularly with a view to services and bands being used by small cells that are aggregated with resources of larger cells [41].

Table 7: The frequency groups proposed in [30].

Frequency group	E-UTRA bands	DL frequency range (MHz)	DL frequency range (MHz)
A	5, 6, 8, 12-14, 17-20, 26	728 - 960	698 - 915
B	11, 21, 24	1476 - 1559	1428 - 1660

C	1-4, 9, 10, 23, 25, 33-37, 39	1805 - 2200	1710 - 2020
D	7, 38, 40, 41	2300 - 2690	2300 - 2690
E	42, 43	3400 - 3800	3400 - 3800

Besides the aggregation of either frequency division duplex (FDD) or time division duplex (TDD) carriers, the aggregation between FDD and TDD carriers has also attracted the research interest [35]. In [35], the authors compared the differences of LTE FDD and TDD specifications in control signalling format and subframe timing and three problems are identified, two of which are related to the primary serving cell configuration and the rest one is concerned with cross-carrier scheduling. With respect to the three problems the corresponding solutions were proposed and their pros and cons were analysed, respectively. CA in higher bands (3.5/3.6 GHz) was indicated in [36], where a prototype five-CA technique for TD-LTE is referred.

In HetNets, the interference mitigation plays an important role, where multiple resources of signals co-exist. The LTE Rel-10 enhanced ICIC techniques enable interfering cells to configure subframes with almost no transmissions, referred to as almost blank subframes (ABS). With the configuration of ABS, UE processing needs to be extended compared to the UE served in traditional cellular networks in order to fully achieve the capacity increase enabled by the heterogeneous networks [37]. Another important role of the UE in LTE heterogeneous networks is to cope with interference, which is not completely avoided by the configuration of ABS. The design of UE poses several challenges related to the modem design, the RF filters and chains, etc. [38]. Additionally, the cross-tier interference in HetNets can be managed through CA techniques. As an indicative example, control signaling of a macrocell is assigned at one carrier, while control signaling of a pico and/or femtocell is assigned at the other carrier. It is obvious that the allocation of control channels degrades significantly the cross-tier interference.

2.2.2.1 OFDM schemes supporting CA

The modulation scheme to be employed for CA plays a critical role, especially when aggregation of non-contiguous bands is necessary where many challenges occur [39]. In CA systems, the significant increase in peak-to-average power ratio (PAPR) of the time domain signal. Therefore, the PA has to operate with sufficient power back-off to accommodate large peaks. In [40] the authors proposed two stages of Noise Shaping process for reducing the PAPR of the carrier aggregated composite signal which is a transmitter-side processing technique and does not require any information at the receiver (Figure 18).

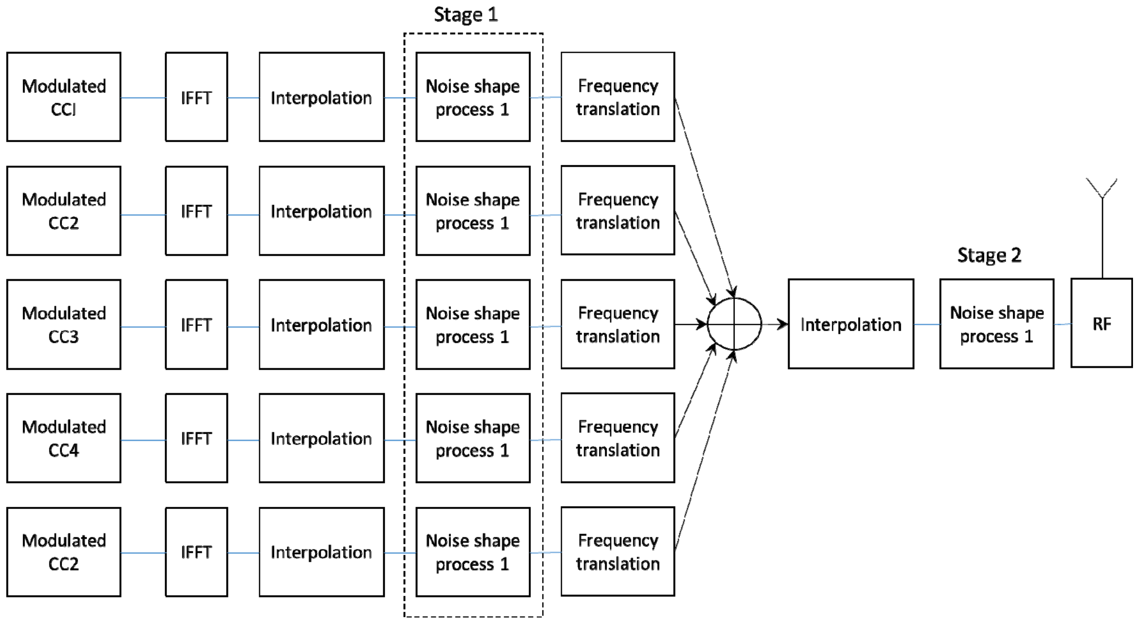

Figure 18: Transmitter architecture for N-x-OFDMA system with two stage noise shaping process [40].

A CA scheme is introduced in [34] for the case where two or more transmitters are involved in transmitting aggregated OFDM carriers, with possible applications for handover situations and multipoint transmission, such as transmission diversity, network MIMO and spatial multiplexing, where a receiver receives signals from more than one transmitter. In [41] a technique is provided to reduce the power amplifier metric in a LTE-A system with CA from non-contiguous frequency resources. The method of transmitting modulation symbols on multiple component carriers is illustrated in Figure 19. Furthermore, the Non Contiguous Orthogonal Frequency division multiplexing (NC-OFDM) scheme has attracted considerable attention for cognitive radio systems and carrier aggregation [42], [43].

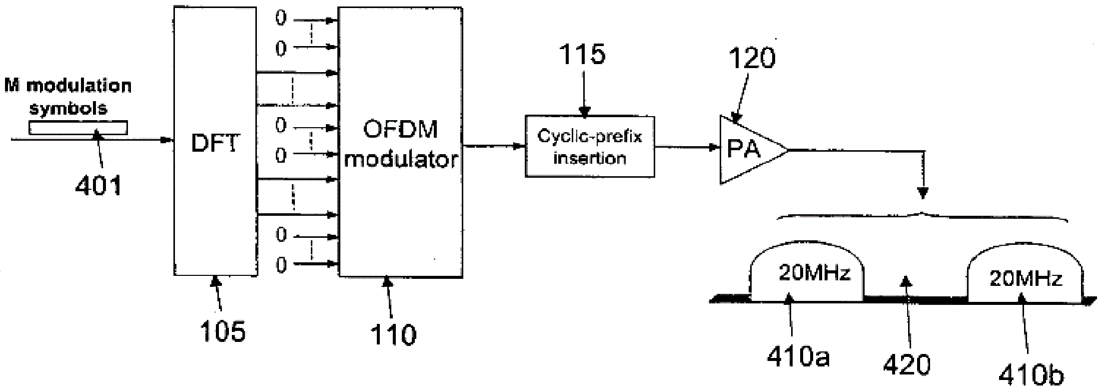

Figure 19: A modified OFDM scheme for CA in LTE-A systems [41].

In [44] a method is presented for reducing the amount of network resources that are used for signalling, which may be particularly high when MIMO is employed. This method utilizes heterogeneous pilots, i.e., signals that have different signal structures and/or characteristics from that of the primary information-bearing signal, so that no resources of the primary information-bearing signal are used (e.g., a wireless network with OFDM-based random access technology (RAT) uses spread-spectrum signals for heterogeneous pilots). Furthermore, these heterogeneous pilots can be made to be transmit-device specific or receive-device specific, in multi-transmit-device, multi-receive-device communications, such as distributed MIMO and CoMP.

2.2.2.2 Filter Bank as a Carrier Aggregation in PHY layer

OFDM, or OFDMA, DFT-precoded OFDM and NC-OFDM schemes have been proposed for many carrier aggregation scenarios. However, for some carrier aggregation scenarios, OFDM based PHY layer could be an undesirable solution. Indeed, OFDM is a poor fit because the filters associated with its synthesized subcarrier signals have relatively large side lobes and such lobes will result in

1) Transmitter side: leakage of signal power among the bands of different users and/or services
2) Receiver side: potentially high inter-carrier interference if an undesired signal has been captured inside the analysis bandwidth.

Although suggestions have been made to improve the side lobes of OFDM through the use of filtered OFDM [45], these solutions are generally very limited in performance. The leakage and interference problems can be elegantly alleviated by the use of Filter Bank MultiCarrier (FBMC) [46] since such filter banks can be designed with arbitrarily small side lobes. In FBMC, a set of parallel data symbols $s_k(t)$ are transmitted through a bank of modulated filters, as in Figure 20. The difference between OFDM and FBMC lies in the choice of the prototype filters $p_T(t)$ and $p_R(t)$. Note that for OFDM, the filters have rectangular pulses. The selection of $p_T(t)$ and $p_R(t)$ varies depending on the adopted FBMC modulation technique.

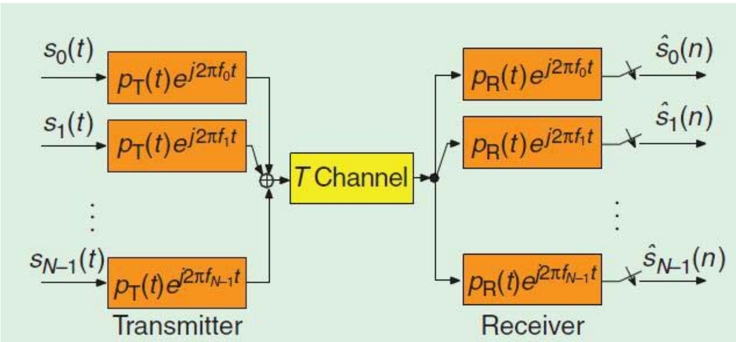

Figure 20: Block diagram of an FBMC transceiver. This structure is also applicable to OFDM [46].

Finally, another appealing aspect of FBMC is its better spectral efficiency with regards to OFDM technique. There is theoretically no need of cyclic prefix due to the fact that the time/frequency subcarrier localization is very limited.

2.2.2.3 Diversity schemes for CA

Besides CA, MIMO is an essential element for achieving the demanding data rate requirements of future wireless networks. Massive MIMO for two-tier HetNets was introduced in [47] where the base station is equipped with a large number of antennas which estimate the interfering subspace from the received uplink signals. This information is used for designing DL precoders which reduce the interference to the small cells tier. In [48] a frequency domain packet scheduling scheme was proposed for the selection and pairing of the MU-MIMO UEs, as well as a framework for joint CA and MU-MIMO scheduling (Figure 21).

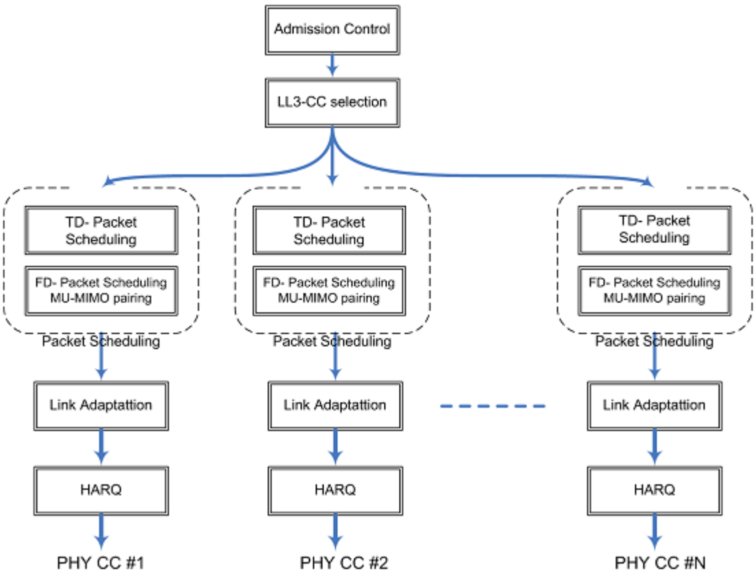

Figure 21: A framework for combined MU-MIMO and CA transmission and scheduling [48].

2.2.2.4 Interference management in aggregated HetNets

Interference coordination: In [49] a practical CA-based scheme with two steps is proposed to deal with the interference between femtocells. To ensure the fairness between femtocells, only one carrier is assigned to each femtocell based on the measurement of the inter-cell interference in the first step. Then, after calculating either of two proposed utility functions, more carriers are attempted to be used by a femtocell in order to improve the system spectrum efficiency in the second step. A Cooperative Power Setting Scheme to mitigate the intra-tier interference among CA-based femtocells was introduced in [50]. The femtocells cooperatively adjust their transmission power aiming at optimizing the total throughput on each CC. The transmission power of each femtocell will be adjusted repeatedly and autonomously to approach the maximum available throughput.
Considering HetNets there are several scenarios which cause interference between different cells, e.g., when the downlink transmission is from a macro-eNB (MeNB) to a UE that is close to it (i.e., within signal range of) then a Home eNode B (HeNB) interferes with DL transmissions to UEs connected to the HeNB, or when the UL transmission from a UE connected to a macro-eNB that is close to a HeNB severely interferes with the UL of a UE connected to the HeNB. A method is proposed for mitigating the interference, by using a mapping between the cells and the resources that are allowed to be used for all of the dynamic data scheduling. The mapping function maps at least one of an identity such as the Product Configuration Identification (PCID), a parameter related to the cell load, etc. to the resources [51].

Interference cancellation: An important aspect of the interference management is also the interference cancellation. Especially the UE in HetNets must be able to cope with the interference from several heterogeneous resources. An Almost Blank Subframes (ABS) technique cannot solve this problem definitely. Reference signals for channel quality measurement and demodulation, and cell acquisition signals must be transmitted on a predetermined schedule from all base stations causing a high level of interference to UE. Interference cancellation at the UE side without special action of the network can be provided when actively exchanging data between the UE and the network [52]. To this end, the UE needs to perform measurements and reporting procedures in order to ensure that proper connection with the network is maintained and the network can adequately schedule data to and from the UE. One possible approach for interference mitigation is to decode and suppress the interference from the useful signal. Such approach is non-linear. The rationale behind this interference cancellation technique is that if the interference is strong, it can be decoded and cancelled one by one from the strongest interference; this is known as successive interference cancellation (SIC) [53]. Some of the most important SIC techniques are presented in [54]:

- *Complexity Reduction Strategies based* on SIC methodology: These techniques provide low implementation complexity in comparison to the *compensate-based strategies*, and also because the utilization of a signalling procedure of pilot tones between the transmitter and the receiver is not required. The novelty of this approach is based on the adoption of the IC method on a reliability classification basis in order to compensate carrier frequency offset (CFO) and, thus, to reduce multiple access interference (MAI), resulting to a total ICI relaxation.
- *Sliced-Processing Window Techniques:* This technique uses the fundamental observation where largest ICI contribution in a reference subcarrier is mainly caused by its neighbouring ones. It has got less computational complexity in the reception process compared to the above. It is used in high mobility users in doubly selective channel fading environments caused by Doppler frequency spread.
- *Zero forcing (ZF)*-SIC receivers in MIMO systems: Aiming to significantly reduce the system latency and at the same time to preserve the bit error rate (BER) in acceptable levels.
- *Complexity Reduced MIMO-SIC detectors:* Minimum mean square error (MMSE) equalization for MIMO-SIC detectors has received most of the research attention in the last years, due to the error resilience and the high efficiency that preserves. However, the research community still strives to reduce the computational complexity of such schemes in order to improve the overall system latency combined with high BER performance, especially for the demanding future implementations. The complexity reduction in such schemes is obtained by exploiting the sparseness of the modified channel matrix.
- *MIMO-SIC Detectors based on* cyclic redundancy check *(*CRC*) codes*: Since these codes are responsible for the validity of the received data block they can also be used for the SIC process in order to enhance the system reliability.
- *Parallel SIC Implementation on MIMO-OFDM Systems:* The classical ML-SIC receiver is prohibitive for practical implementations due to the increased overall system latency, especially when MIMO infrastructures are supported. In parallel SIC implementation approach, several partial SIC receivers are applied to different OFDM sub-bands separately while they are executed in parallel simultaneously.
- *CCI Mitigation with MIMO-OFDM SIC Receivers*: Schemes that adopt a SIC reception method, where the CCI components are detected and then cancelled through an iterative process, are found to be beneficial, as they outperforms the conventional non-SIC reception scheme in terms of BER performance at the expense of a slightly increased computational complexity.

Other interference mitigation approaches can be found in the literature, especially linear approaches such as the MMSE-IRC (Minimum Mean Square Error Interference Rejection and Cancellation) already considered as baseline receiver since Rel-11 by the 3GPP.

2.2.3 MAC layer design

2.2.3.1 Link adaptation

As it has been shown, link adaptation (e.g., AMC) can increase the throughput of a wireless communication system. The correct operation of link adaptation depends in the efficient estimation of the packet error rate (PER), which determines the selection of the appropriate modulation and coding scheme. This task becomes more challenging in systems employing MIMO, because of the different link quality of the different spatial streams and subcarriers. In [55] several link quality metrics are investigated and evaluated for fast link adaptation with MIMO and OFDM aiming at improving the PER estimation accuracy. Another issue in link adaptation in MIMO-OFDM systems is related to practical impairments, such as like non-Gaussian noise, different frame lengths, or channel nonlinearities. Taking into account these facts as well as the problem of matching frame error rates (FER) to channel state information, new FER predictors are designed, which are able to capture the effect of these practical impairments. In [56] a multi-RAT CA for WWANs assisted by WLANs is proposed, where the services are mapped dynamically between the WWAN radio and the WLAN radio, according to the service requirements and the network conditions. According to the proposed scheme, WiFi radios in the WLAN spectrum are treated as a “virtual” or “extension” carrier for seamless inclusion in the 3GPP operator’s access network by extending the CA concept (Figure 22).

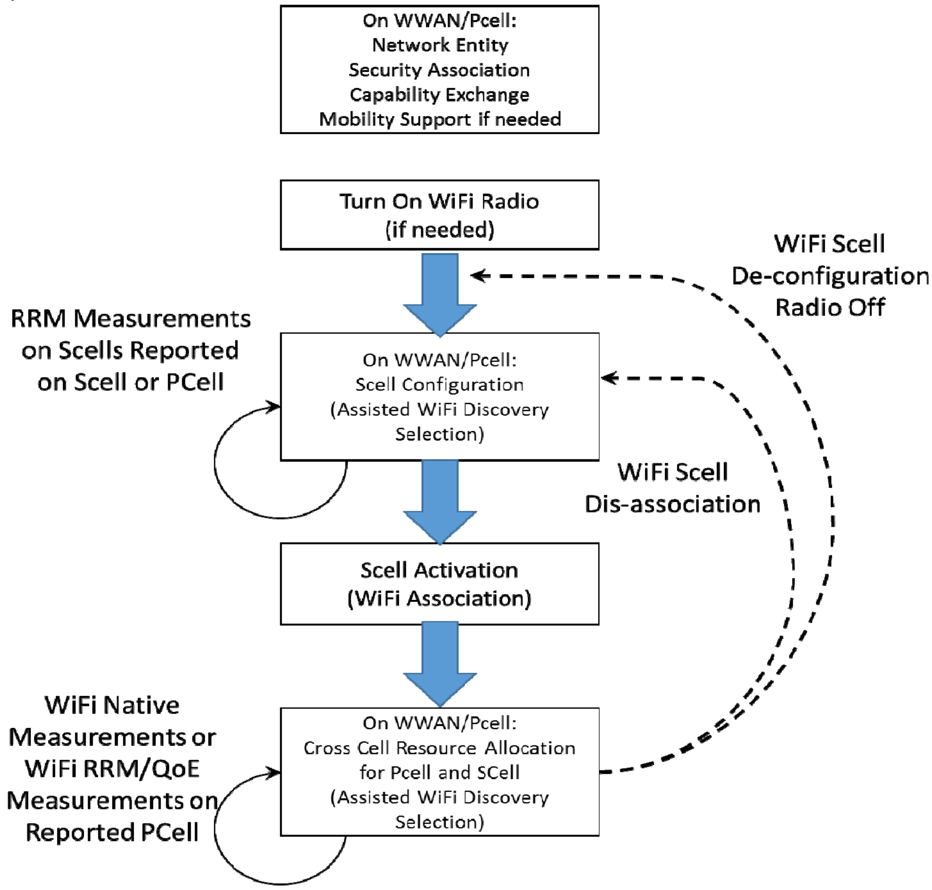

Figure 22: Link adaptation between WWAN and WLAN.

In [57] a method is presented for providing uplink power control signalling of a UE for semi-persistent scheduling with carrier aggregation. The method comprises the operation of receiving a transmitter power control (TPC) CA physical downlink control channel (PDCCH) configuration information element (IE) identifying a location of information to adjust an uplink power control of a selected component carrier of the UE using semi-persistent scheduling. This method provides a flexible means to explicitly adjust the power control of each component carrier for each individual UE. The authors in [58] investigate experimentally the achievable downlink throughput performance when uplink control information (UCI) feedback mechanism using the PUSCH, which enables minimization of the UCI overhead while maintaining the required reception quality, is applied in asymmetric CA (Figure 23).

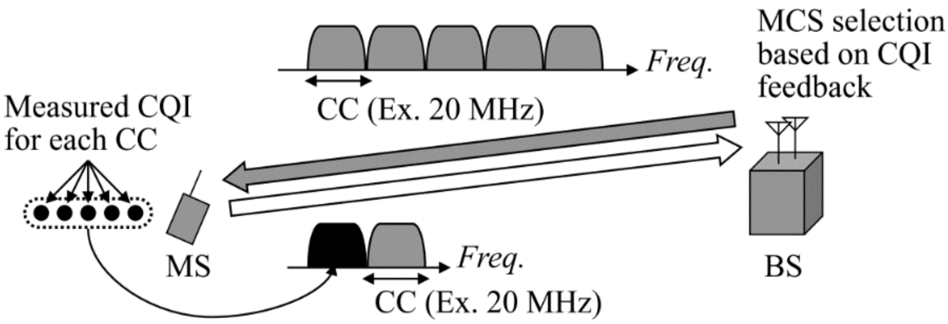

Figure 23: Link adaptation techniques in DL for asymmetric CA [58].

Channel measurement reporting and CSI feedback: To select a suitable data rate, in practice a suitable modulation scheme and channel-coding rate, the transmitter needs information (e.g., ACK, NACK, CSI) about the radio-link channel conditions [59]. In the case of a system based on FDD, only the receiver can accurately estimate the radio-link channel conditions. For the downlink, the BS transmits a pilot signal which is used by the terminal to estimate the channel conditions and then reported back to the BS. The transmitter needs to have knowledge of channel conditions at the time of transmission. In most practical systems the terminal predicts the conditions in the near future which are similar to the current conditions and report the measured channel conditions to the BS. However, the more rapid the time-domain channel variations, the less efficient the link adaptation. Also, it is true that there will be a delay between the time when the terminal measured the channel and the time this information is fed back to BS So, if the terminal starts moving at high speed, the measurement reports will be outdated once arriving at the base station. In such cases, it is often preferable to perform link adaptation on the long-term average channel quality and rely on hybrid ARQ with soft combining for the rapid adaptation. For the uplink, estimation of the uplink channel conditions is not as straightforward at least in FDD, as there is typically no reference signal transmitted with constant power from each terminal [60]. The standard has however defined the SRS (sounding reference signal) which could be used to sound the UL channels at the cost of overhead. For TDD systems, the instantaneous uplink signal conditions could be estimated from downlink measurements of the terminal, due to the reciprocity of the multi-path fading. However, it should then be noted that this may not provide full knowledge of the downlink channel conditions [60]. A UE may be configured to generate CSI that is provided back to the BS. The BS may use CSI to adjust its communication with the respective UE, or possibly other UEs. For example, the BS may receive and utilize CSI from multiple UEs to adjust its communication scheduling among the various UEs within its coverage area (or cell).

2.2.4 Radio resource management (RRM)

RRM is a system level control in the eNodeB of radio resources such as user scheduling, link adaptation, handover, and transmit-power (see Figure 24) [61]. For MIMO in LTE uplink, both user data and the Demodulation Reference Signals (DRS) are precoded by a precoder as selected by the eNodeB. Thus, these reference signals cannot be used for selection of precoders for future transmissions. Instead the Sounding Reference Signals (SRS) are used for channel quality measurements. The SRS transmissions typically span a larger frequency interval than the user data and are not pre-coded. Radio resource management measurements and reporting, and CSI feedback procedures enable the network to obtain information about the current radio conditions at the UE. For example, the reference signal received power (RSRP) measurement is a type of RRM measurement that provides information on the signal strength of the serving and neighboring cells, and is utilized to facilitate handover. CSI feedback provides serving cell channel quality and potentially spatial channel indication that can be utilized at the eNB scheduler to select a proper modulation and coding and precoding scheme.

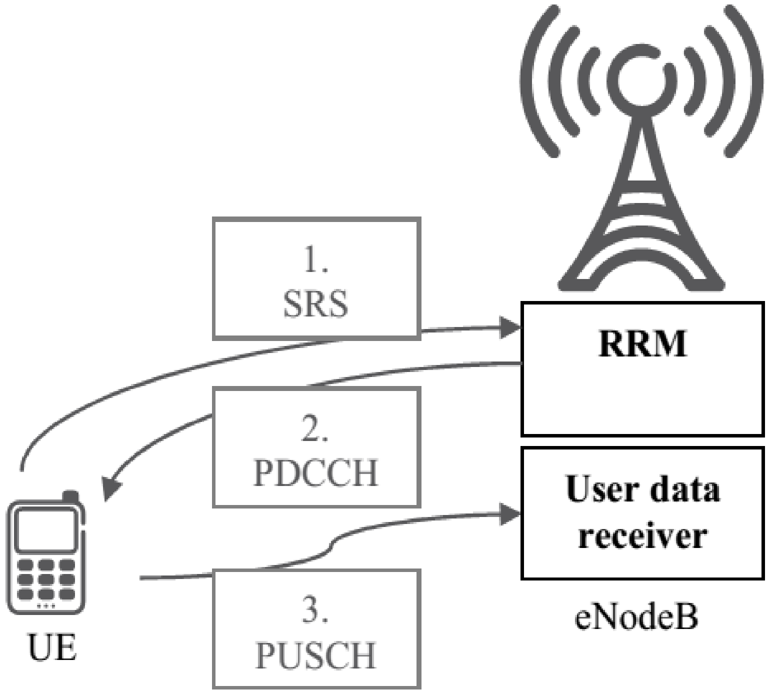

Figure 24: RRM and user data receiver in eNodeB [61].

The enhanced intercell interference coordination (eICIC) feature was added in LTE Rel-10 to ensure reliable LTE operation in HetNets network deployments. The LTE Rel-10 eICIC techniques enable interfering cells to configure subframes with almost no transmissions, referred to as almost blank subframes (ABS). Thus, UE under strong interference conditions can be served in the ABS by their respective serving cells. Therefore, resource-specific channel measurements and feedback should be configured for UE under potentially severe interference since ABS can cause interference to significantly vary from one subframe to another. The above RRM channel measurements and channel state (CSI) information to the protected subframes the LTE Rel-10 networks and UE support enabling biased handover decisions without risking radio link failure at UE [52].

- ***RRM Measurement Procedure:*** The measurements enabled via the *RRCConnectionReconfiguration* message are used to configure radio resources after RRC connection is set up when UE transitions from *RRC_IDLE to RRC_CONNECTED* states, or to reconfigure radio resources at any point afterward. UE evaluates the quality of the radio link, SINR measured on CRS, and every radio frame to meet the quality thresholds [52].
- ***CSI Feedback Procedure:*** The CSI measurements consist of channel and interference measurements. In order to ensure proper UE feedback, it is necessary to ensure restricted measurements, at least for the interference part. Accurate measurements of the channel and interference are critical for scheduling efficiency. CSI feedback is configured through an *RRCConnectionReconfiguration* message. If restricted CSI feedback is configured, there are two sets of subframe patterns signaled to the UE. These two sets are disjoint, and the union of the two sets does not need to add up to all subframes [52].

2.3 Carrier aggregation in h-RATs

Besides the HetNet concept, the cooperation of different radio access technologies has attracted particular interest as an efficient method to increase the capacity of the network. Among them the capacity offloading to non-cellular radio technologies, especially to 802.11-based WLANs (i.e., WiFi) is considered as a cost-efficient, easy to deploy solution [62]-[66]. It is also noted that, in line with offloading and also supporting aggregation of links between WiFi and LTE, and potentially other services, numerous efforts have been undertaken to combine WiFi and LTE and other capabilities, particularly through integrated WiFi Access Points with Femto-cells [67]-[70]. Building more WiFi hot spots is significantly more cost efficient than network upgrades or small cells deployments. Furthermore, taking into account the huge number of WiFi access points (APs) already installed at home or at work, it becomes evident that a very dense network is already deployed. It is interesting to note that the IEEE 802.11 standard includes a convergence with 3GPP standards through the Extensible Authentication Protocol Subscriber Identity Module (EAP-SIM) protocol for authentication and key agreement protocol enabler for utilizing the WLAN APs for offloading cellular data in practice [71]-[73].

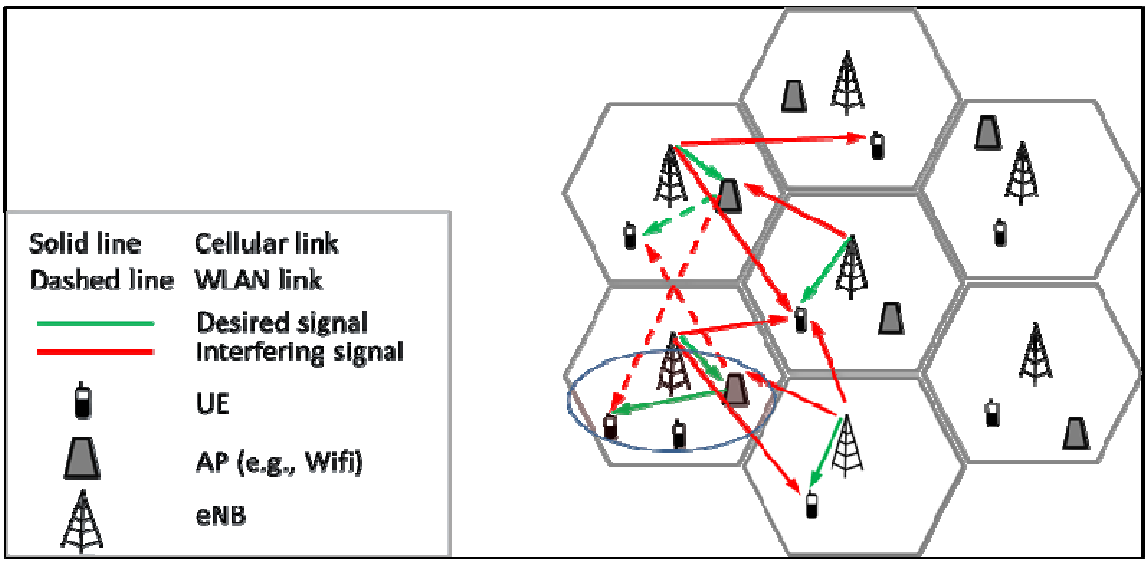

Figure 25: A multi-cell h-RAT network.

Moreover, the IEEE P1900.4 working group addresses the heterogeneity of wireless access technologies by introducing a management system which decides upon a set of actions required to optimize radio resource usage and quality of services [10]. In general the cooperation of different radio technologies in terms of spectrum sharing is expected to play critical role in future broadband wireless networks. Spectrum sharing between RATs operating in licensed bands or between RATs operating in licensed and non-licensed bands is under investigation. For example, regarding LTE, the candidate frequency bands for spectrum sharing are the following:

- 470-694 MHz and 694-790 MHz (TV broadcasting bands)
- L-Band (1452–1492 MHz) for terrestrial mobile/fixed communications networks supplemental downlink (MFCN SDL)
- 2GHz Mobile Satellite Service (MSS) band (1980-2010 // 2170-2200 MHz)
- 3400-3600 and 3600-3800 MHz bands (WiMAX band)
- 3800-4200 MHz (C-band)

Advanced in this area can be also found in the industry. For example, in [74] methods and apparatus that can be used for the aggregation of heterogeneous wireless communication techniques, namely radio component carriers provided by eNBs, light/optical component carries provided by optical devices (LEDs, televisions, projectors) and sound/acoustic component carriers (sonars), are presented. The proposed communication method is adapted to a wireless communication station and includes aggregating physical channel resources respectively corresponding to heterogeneous access technologies in a Layer 2 or below the Layer 2 in a protocol stack. The physical channel resources may be heterogeneous component carriers, such as radio component carrier(s), optical component carrier(s) and/or acoustic component carrier(s). The communication method for aggregation of heterogeneous component carriers is adapted for a communication device, and includes following steps: aggregating physical channel resources respectively corresponding to heterogeneous access technologies in a Layer 2 or below the Layer 2 in a protocol stack and communicating with at least one wireless communication station through the physical channel resources respectively corresponding to the heterogeneous access technologies.

2.3.1 LTE and HSPA

LTE networks are increasingly expanded; while at the same time the existing high speed packet access (HSPA) networks are expanded and upgraded with the more advanced HSPA+ features in order meet the demands for high-speed wireless data access. Due to the major investments in the HSPA+ infrastructure and the vast and rapidly increasing HSPA+ based mobile broadband device penetration the two networks can be foreseen to coexist in parallel for years to come. The evolution of both HSPA+ and LTE standards has introduced aggregation of carriers for higher data rates, better load balancing and increased spectrum utilization between the two RATs [75]. Further, solutions exist for aggregation among links in HSPA [76], and such aggregation might itself also be aggregated with LTE carriers. HSPA+LTE aggregation capable UEs can enjoy improved data rates by utilizing efficiently both LTE and HSPA spectrum without reducing the data rates of the HSPA UEs.

2.3.2 Multi-RAT CA

A timing adjustment mechanism is introduced in [77], where a common uplink timing adjustment parameter value is estimated for UE transmissions in the multi-RAT communications network and provided for transmission to one or more UEs. That signalling parameter value is common to both the first and second RATs and useable by the one or more UEs to adjust transmit timing of uplink carriers belonging to the different RATs. The common timing adjustment parameter value may be provided, for example, in order to coordinate UE transmit timing of a first uplink carrier associated with the first RAT and of a second uplink carrier associated with the second RAT. A multi-RAT UE concurrently receives a first downlink carrier associated with the first RAT and a second different downlink carrier associated with the second RAT. The UE receives the common timing adjustment parameter value on one of those downlink carriers and adjusts a transmit timing of a first uplink carrier associated with the first RAT and of a second uplink carrier associated with the second RAT (Figure 26).

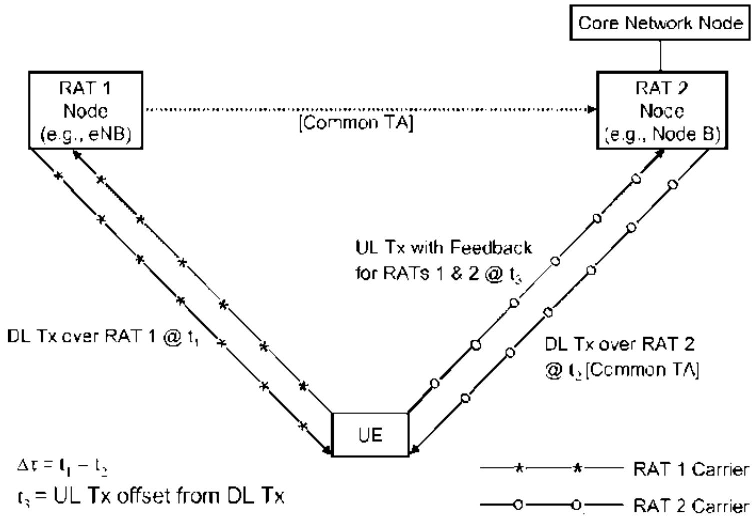

Figure 26: Time synchronization for multi-RAT CA systems.

2.3.3 LTE and TVWS

TVWS is an excellent opportunity for many types of systems to obtain extra spectrum/capacity on an opportunistic basis. It is logical to also consider LTE networks being employed in TVWS. However, there are a number of differences for such systems in TVWS compared with other forms of “license-exempt” spectrum usage, driven largely by the regulations are in place or being developed in order to ensure appropriate protection and performance of incumbents in terrestrial TV bands. The associated regulations, or development work towards regulations and associated tentative rules, can be accessed at references [78]-[86].

From the CA principle (see Figure 27), TVWS can be used for improving user peak-rate, network traffic offload and/or, in specific geographical areas, a coverage extension. Carrier Aggregation, as a network controlled function, can be considered in the downlink only to fit asymmetric services or in both downlink and uplink, CA in TVWS may improve e.g. FDD radio technologies for asymmetric services by allocating extra DL resources. When performing carrier aggregation of TVWS bands with LTE bands, the system may potentially employ either TDD or FDD on TVWS bands. Since operators are adopting either TDD or FDD (depending on their licensed spectrum) and chip vendors are supporting both TDD and FDD versions of LTE, both techniques are important to consider.

The TVWS bands can be used for downlink only, uplink only, or both uplink and downlink transmission. In downlink only or uplink only, the TVWS bands will inherently use FDD. If the carrier(s) in TVWS are used for both uplink and downlink, then FDD and TDD modes are both possible for TVWS:

- In FDD mode, the TVWS band can be split into non-overlapping channels, each one assigned to either uplink or downlink.
- In TDD mode, a single channel in TVWS would have to be shared by time division between the downlink and uplink.

It is noted, in the case of CA involving LTE in TVWS, performance at the PHY layer may be affected by a larger amount of interference, or a greater interference uncertainty than would be the case in licensed spectrum. This is because of the large number of types systems that might share TVWS with LTE, generally on an uncontrolled basis. Methods to cope with this interference for an LTE PHY operating in TVWS would be desirable, including enhanced link adaptation mechanisms or triggers thereof, and enhancements to other mitigation mechanisms such as coding.

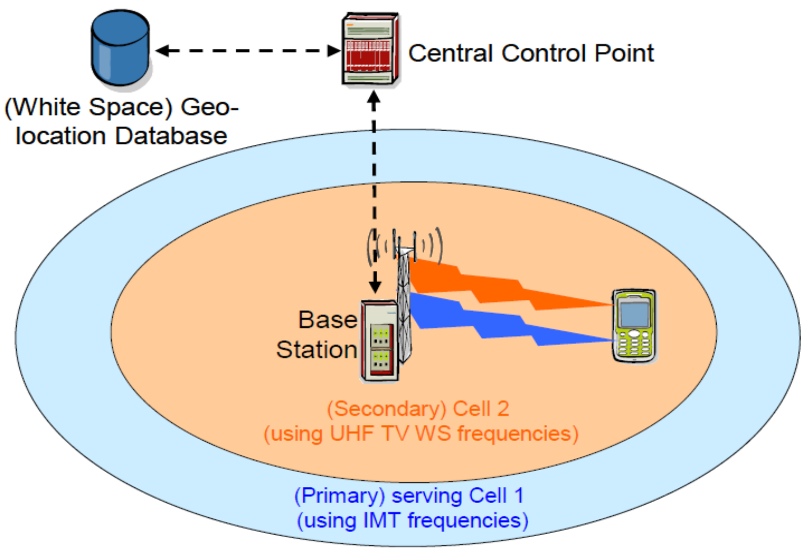

Figure 27: Carrier Aggregation of LTE band and UHF TV band.

The work in [87] explores the capacity of white space networks by developing a detailed model that includes all the major variables, and is cognizant of Federal Communications Commission (FCC) regulations that provide constraints on incumbent protection (Figure 28). It is noted that at the MAC layer there may not be so many differences for operation in TVWS as compared with unlicensed spectrum or indeed licensed spectrum. However, should spectrum sensing be used to ascertain spectrum opportunities (it is noted that spectrum sensing is still allowed to determine access opportunities in TVWS, at very low transmission powers, under the FCC's rules [78], [79]), the silence periods at the MAC would be necessary to perform sensing. Further, given aspects such as interference in TVWS, the LTE MAC might be adjusted or enhanced in order to select and use those channels/resources that are not be used by other secondary systems.
Some other fundamental differences of the MAC in TVWS are of course that the MAC must only use the TV channels and associated powers as authorized by the geolocation database, and that user LTE carriers have to fit within the 8MHz or 6MHz TV channels as used by TV systems. Carriers up to 5MHz may therefore be used, or greater-bandwidth carriers may be used if adjacent free TV channels are aggregated. Various combinations of carriers might

potentially also be aggregated in this case to fill a TV channel, such as 5+3MHz to fill an 8MHz TV channel.

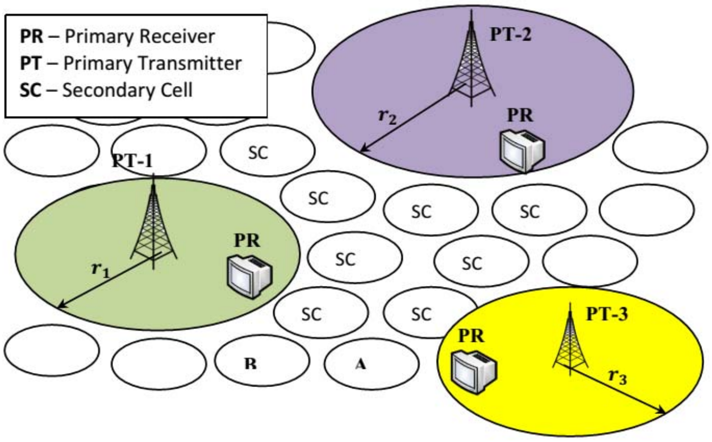

Figure 28: Coexistence of primary and secondary cellular networks [87]

2.3.4 LTE and WiFi

2.3.4.1 PHY and MAC Layers

In [88] specific adaptations to LTE Rel. 12 and beyond systems are proposed in order to perform dynamic resource identification, allocation and termination functions among different RATs for example between LTE and 802.11 networks (Figure 29). Nevertheless, this patent is not limited to these two RATs. The method in [88] requires new protocols and entities, such as the intra-networking spectrum management entity (SME). Furthermore the method relies on Dynamic Spectrum Sharing (DSS) measurement control and signalling between the different APs in order to make decisions on the available spectrum. Details about these operations at the PHY and MAC layers are not given in [88] (Figure 30).

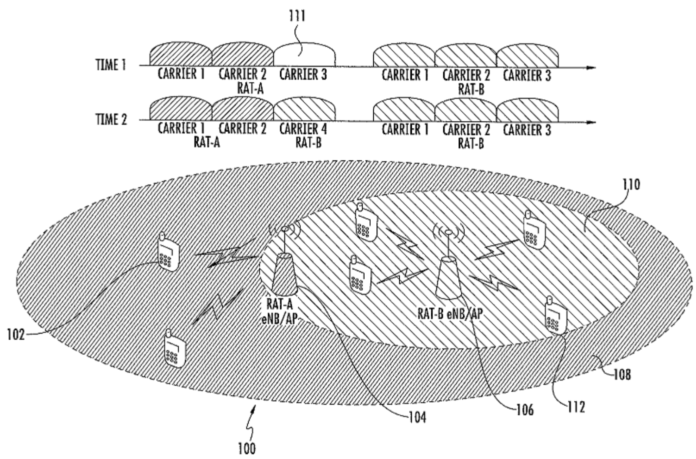

Figure 29*: CA* between heterogeneous RATs [88].

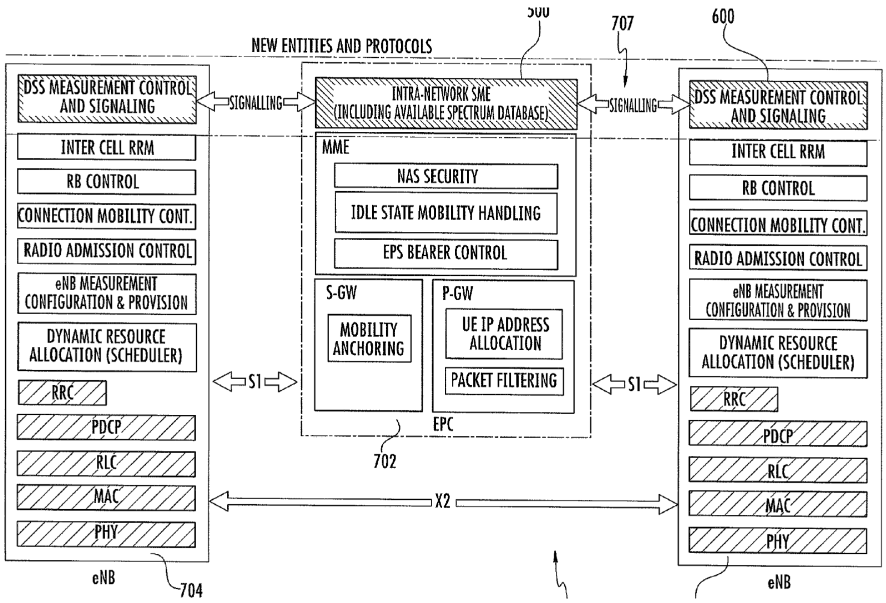

Figure 30: New protocols and entities for CA between h-RATs [88].

2.3.5 Radio Resource Management

RRM encompasses a wide range of techniques and procedures, including power control, scheduling, cell search, cell reselection, handover, radio link or connection monitoring, and connection establishment and re-establishment [89]. 3GPP provides several mechanisms to support RRM, even for heterogeneous networks using different radio access technologies (RATs) such as GSM, UMTS, and LTE. RRM for heterogeneous networks combining 3GPP with non-3GPP RATs is less developed, but some solutions exist.

The IEEE 802.21 standard [90] has been developed to allow a mobile terminal (MT) to seamlessly roam across different types of network access technologies, such as 802.11 (WLAN), 802.16 (WiMAX) or cellular systems (3GPP and 3GPP2). This standard addresses mobility at higher layer level (layer2 or even above IP). An overview of the basic services provided by the standard is given in Section A1.

The standard has been designed to facilitate handover, providing services to report measurements and actions to change certain radio parameters. However, these services can also be used for radio resource management of heterogeneous RATs. In the project MEDIEVAL for example, it has been used to report measurements to a flow manager that would route data flows over different air interfaces to a user [91]. In the project SPECTRA on the other hand, it is used to report measurements to a cognitive radio resource manager that manages a radio environment map and enforces policies for the use of spectral white spaces [92]. Some more examples on the use of 802.21 are given in [93]- [96].

3. Application scenarios and use cases

This section discusses SOLDER application scenarios and use cases for CA. It is noted that many of the scenarios/use cases at this stage are presented in a broad sense, clearly showing the usefulness of the SOLDER project: The specific detail that the project works on in its aggregation work may be slightly narrower than the content presented here depending on how key research topics develop with the duration of the project, both within the project and based on external stimuli/developments from outside of SOLDER.

3.1 CA Application Scenarios in HetNets: LTE-A and beyond

First covered are aggregation scenarios and use cases in HetNets, assuming the scope of LTE-A and beyond.

3.1.1 LTE Release 12 and beyond

A recent introduced in Rel-12 HetNet application scenario is the new carrier type (NCT), which aims to improving the system performance by allowing non-backward compatible carrier utilization [27] This will results in enhance the spectrum efficiency through the overhead signalling reduction and the improved support for HetNet through the interference avoidance from cell-specific reference signal. An example of NCT is illustrated in Figure 31. SOLDER will consider this application scenario for development as long as the challenges are more significant than the TDD/FDD CA scenario described below. This will be derived by our details requirement analysis within the next deliverables of WP2

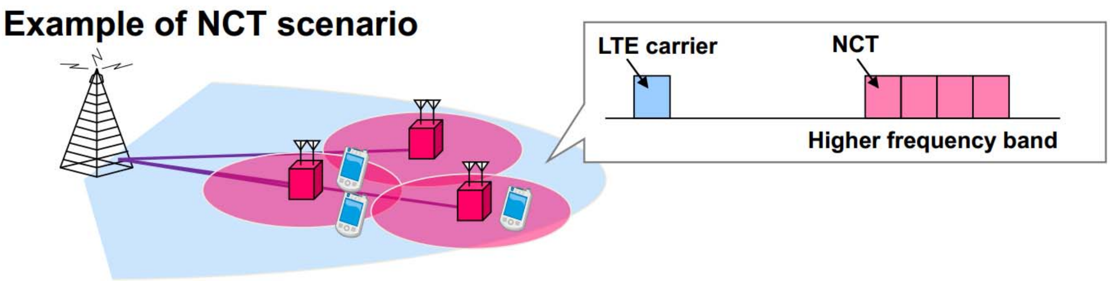

Figure 31: NCT in LTE Rel-12 and beyond [27].

Furthermore, Rel-12 introduces a new CA in HetNets application scenario that will allow the TDD/FDD joint operation with LTE TDD/FDD carrier aggregation feature (3GPP RAN60 and RAN 62). The goal is to identify deployment scenarios of joint operation on FDD and TDD spectrum, and network/UE requirement to support joint FDD/TDD operation. Possible deployment scenarios may be the following:

- FDD+TDD co-located, and FDD+TDD non-co-located with ideal backhaul.
- FDD+TDD non-co-located (small cell scenarios, and macro-macro scenario), with non-ideal backhaul, subject to the outcome of the non-ideal backhaul related study items where relevant.

In order to achieve these kinds of operations, the UEs should be able to:

- access both legacy FDD and legacy TDD single mode carriers,
- receive simultaneously FDD and TDD carriers (i.e. DL aggregation),

- transmit simultaneously on FDD and TDD (i.e. UL aggregation)
- transmit and receive simultaneously on FDD and TDD (i.e. full duplex)

All the above required functionalities are expected to increase the complexity and the energy consumption of the UE.

The multi-band CA can also be effectively mixed low-frequency FDD bands with high-frequency TDD bands and offer high speed mobile broadband across wide areas. The above FDD+TDD scenarios will be one of potential application scenarios in future years. For example big companies such as NSN, Huawei and Vodafone have already demonstrated FDD+TDD scenarios in LTE-A CA technology. For example Huawei's demo with Vodafone will be involving 3 FDD carriers and 1 TDD carrier.
Aggregating data in a UE which served by both FDD serving cell and TDD serving cell seems to offer high benefits to the operation and data rate of the UE since it exploits the benefits of dual mode (FDD+TDD). However, this requires more RF and baseband capabilities at the UE and also high-layer specification changes in order to fully support the FDD+TDD joint operation. Briefly, some performance results might focus on:

- Throughput analysis for possible scenarios
- The study of the sensitivity of the LTE FDD receiver by the presence of LTE TDD transmitters and new advanced interference mitigation techniques
- The effect of strong fading/and or shadowing conditions in FDD/TDD joint operation

So, SOLDER application scenarios could expand the use of more FDD+TDD carriers and find the optimum combination that improves dramatically the data rate speed.

3.1.2 Carrier aggregation bands for future releases

The Digital Agenda for Europe's RSPP has identified ambitious short-term targets for the European spectrum. Table 8 presents the frequency bands that would best accomplish this objective. These bands are used from different cellular layers in HetNets and thereby they can be used as application scenarios of CA in HetNets in the course of SOLDER development.

Table 8: Additional mobile broadband (MBB) spectrum to become widely commercially available before 2015 [111].

Band Name	3GPP #	UL (MHz)	DL (MHz)	Dpx mode	Av. BW (MHz)	
L-Band (EU)	TBD	NA-NA	1452-1492	SDL	1x	40
2GHz MSS band (EU)	TBD	1980-2170	2170-2200	FDD	2x	30
2300-TDD	40	2300-2400	2300-2400	TDD	1x	100
3500-TDD	42	3400-3600	3400-3600	TDD	1x	200
3700-TDD	43	3600-3800	3600-3800	TDD	1x	200
Total additional MBB spectrum by Dec. 2015					**600**	

Regarding the spectrum use for the longer term is shown in Table 9. It is obvious that lower bands in 700-800 MHz and higher in 3800-4200 MHz are considered for the long-term that can be taken into account as application scenarios of SOLDER CA in HetNets or h-RATs. This is not clear yet, i.e. whether a scenario of future bands for CA, and depends on regulatory decisions on the way that will be used. SOLDER could potentially shows the performance impact for such a scenario making assumptions about the exploitation.

Table 9: Additional mobile broadband (MBB) spectrum to become available after 2016 as a result of WRC-15 [111].

Band Name[2]	3GPP #	UL (MHz)	DL (MHz)	Dpx mode	Av. BW (MHz)	
470-694(*)(**)	TBD	TBD- TBD	TBD-TBD	TBD	-	224
700 (Region 1) (***)	TBD	703-733	758-788	FDD	2x	30
L-band ext. 1 (EU) (*)(**)	TBD	1375-1400	1427-1452	TBD	-	50
L-band ext. 2 (EU) (*)(**)	TBD	1350-1375	1492-1517	TBD	-	50
2700-2900 (*)(**)	TBD	TBD-TBD	TBD-TBD	TBD	-	200
3900 (*)(**)	TBD	3800-4200	3800-4200	TDD	-	400
Total additional MBB spectrum from 2016					**984**	

In what follows, we present additional use cases for the spectrum aggregation proposed for the short-term and long-term with some details on their exploitation. As also mentioned above, SOLDER can assume several CA in HetNets and h-RATs future implementations based on the information above in the Tables and the details below in the bullet list.

Spectrum for the shorter term

- 2300MHz band (2300-2400 MHz): In the short term, the 2300MHz band represents the most promising opportunity for freeing up new spectrum for Long-Term Evolution (LTE) across Europe. As market trends reveal the increasing take-up of Time Division Duplexing (TDD), the application of LTE-TDD in this band is a significant opportunity for EU member states to improve overall spectrum utilization and to meet the RSPP's 1200MHz objective. Early adopters in Europe will be able to exploit the economies of scale that are now consolidating in other regions. Ongoing European harmonization of the 2300MHz band will be completed by June 2014, including the option to apply the LSA scheme for those administrations that consider the re-farming of incumbent services impractical or too expensive.
- 3400-3600 and 3600-3800 MHz bands: The 3400-3800 MHz range is ideal for such focused coverage. This is due to its large span of contiguous spectrum and its reduced coverage capability, which improves the interference management associated with denser cellular topologies. The 3400-3800 MHz range will also be exploited for macro cell coverage also addressing the backhaul application. Although many EU member states have auctioned the 3400-3600 MHz spectrum for WiMAX technologies, operators are now preparing for a future transition to LTE. Fewer auctions have taken place so far in the 3600-3800 MHz range.

Spectrum for the longer term

- 470-694 MHz: This range of the spectrum possesses excellent propagation properties which are suitable for a wide variety of rollouts, from wide-area rural coverage to deep indoor penetration in the urban environment. However, this band is currently used by

[2] (*) Band plan not discuss yet.
(**) Subhect to WRC-15 decisions.
(***) 2x33 MHz band plan is also being considered.

television, which has prompted a debate on the future of Digital Terrestrial Video Broadcasting (DVB-T). From a technology standpoint, mobile technologies already have the capabilities to become the converged network supporting both broadcasting and MBB services.

- 694-790 MHz: In Europe, the 700MHz band will become the most important band for LTE, given its high propagation characteristics and its potential for global harmonization. The 2012 World Radio Communication Conference (WRC-12) decided to add the new mobile service co-primary allocation (and IMT identification) for this band in International Telecommunication Union Radiocommunication Sector (ITU-R) Region 1 (Europe, the Middle East and Africa), to be effective immediately after WRC-15. The ITU and CEPT have consequently started their studies addressing the future band plan, the coexistence issues as well as the impact of this new allocation in terms of cross-border coordination. To benefit the future economies of scale and international roaming, The adoption of the lower duplexer (2x30MHz) in the APT 700 FDD band plan is the most appropriate choice
- 2700-2900 MHz: The 2700-2900 MHz band is an interesting candidate for future IMT identification at the WRC-15 due to its adjacency to the 2500-2690 MHz range. This would allow for wider assignments across the overall 2500-2900 MHz range. The supply of lower cost RF components would be facilitated by the commercial availability of 2600MHz, while the rollouts in the 2700-2900 MHz range would leverage on the existing 2600MHz rollouts grid and installation infrastructure.

Utilization of the 3800-4200 MHz frequency range

The 3800-4200 MHz range will exploit the LTE-Advanced capability for up to 100MHz channels. While LTE is developed to support the scalable bandwidth up to 20MHz, LTE-Advanced Rel-10 offers support for wider bandwidths up to 100 MHz thanks to the CA of up to 5 carriers belonging to the same band, or to different bands, within the same base station site (intra-site CA). LTE-Advanced Rel-12 will allow for the aggregation of carriers belonging to radio transmitters from different sites including the aggregation of Macro Cell layer carriers with carriers from the Small Cell layer (inter-site CA).
An update of the WRC-07 coexistence studies on the 3800-4200 MHz frequency range will be considered, based on updated parameters and assumptions, considering the Macro Cell rollout scenario as well as new rollout scenarios such as outdoor and indoor Small Cell scenarios that is interested within the framework of SOLDER. In the context of the extensive discussions taking place across the globe on the future utilization of portions of spectrum within the whole 3400-4200 MHz range, this proposal would place Europe in a leading role with a forward-looking strategy for the expansion of mobile broadband services.

EUs demand for ubiquitous connectivity with consistent Quality of Experience throughout the entire coverage area (“cell-edge-free”) requires adequate LTE evolution in terms of features and topology. Some of the target usage scenarios within the Macro Cell and Small Cell layers are described in details below:

- LTE-Advanced rollouts both in terms of Macro Cell layer and Small Cell layer coverage in both indoor and outdoor scenarios.
    - The Small Cell nodes provide very high traffic capacity and very high user throughput locally.

  - o Macro Cell layer ensures service availability and QoE over the entire coverage area.

- High density hotspots (e.g. few 100s meters separation distances), special events, and indoor areas.

- The 3800-4200 MHz range will exploit the LTE-A capability for up to 100MHz channels. The 3800-4200MHz range will provide a unique contribution to address the growing geographically uneven traffic distribution in hotspot areas thanks to the higher operating frequencies allowing for high capacity dense networks.

3.2 Aggregation in h-RATs

Next covered are the use-cases for aggregation involving h-RATs. Concerning aggregation in h-RATs the following two generic types of aggregation can be described:

Aggregation at the IP layer and above (service aggregation)[3]: The client devices will have separate IP address for each of their network connections. Each of the wireless connections could happen over contiguous or non-contiguous frequency bands. It would be desirable to combine IP streams associated with each of the networks and corresponding IP addresses to aggregate performance across the networks for the same client. The connections could utilize different technologies such as LTE+WLAN or HSPA+WLAN or WLAN + CDMA20001x-EVDO or LTE + WiMAX. Each of the network connections can have its own IP address, and the associated IP streams could be aggregated [98].

Aggregation below the IP layer (carrier aggregation): For aggregation across carriers of the same WWAN technology, or across cells on the same carrier, aggregation could also be considered below the IP layer in the RAN, with a split and merge of traffic managed at an ENodeB (LTE) or an RNC (WCDMA, HSPA) or a BSC (CDMA2000) or an ASN-GW (WiMAX) or a Node B (HSPA) with the possibility of tunnelling data between such nodes, if a multipath communication needs to be established using different technologies (see Figure 32).

Employing concurrently heterogeneous radio access technologies (h-RATs) is an emerging research area with several applications. The concept is simple and relies on utilizing the spectrum (bandwidth) that is unoccupied; either from the same or different systems. Different technologies can be used simultaneously using multiple wireless modems in a single device [98]. We can distinguish the following h-RATs application scenarios:

- An application or data stream may just use only one network at a time and in this way different data streams use different networks, resulting in higher overall throughput.
- A single application or data stream is not able to utilize the multiple wireless network connections simultaneously.

As more and more wireless wide area network (WWAN) data technologies become available and deployed around the world, on different frequency bands, it would be desirable to consider aggregation of services across multiple WWANs to improve the peak rate, throughput and latency performance for data applications delivered to a mobile device. Likewise, aggregation is also helpful across multiple carriers of the same WWAN technology, or across multiple cells on the same carrier. Aggregation across multiple WWANs typically necessitates aggregation above the IP layer. Three indicative examples where carrier

[3] Beyond the scope of the SOLDER project.

aggregation scenarios are deployed in various RATs is illustrated in Figure 32. The scenarios show aggregation in mixed licensed (LTE, HSPA, GSM) and unlicensed (WiFi) bands.

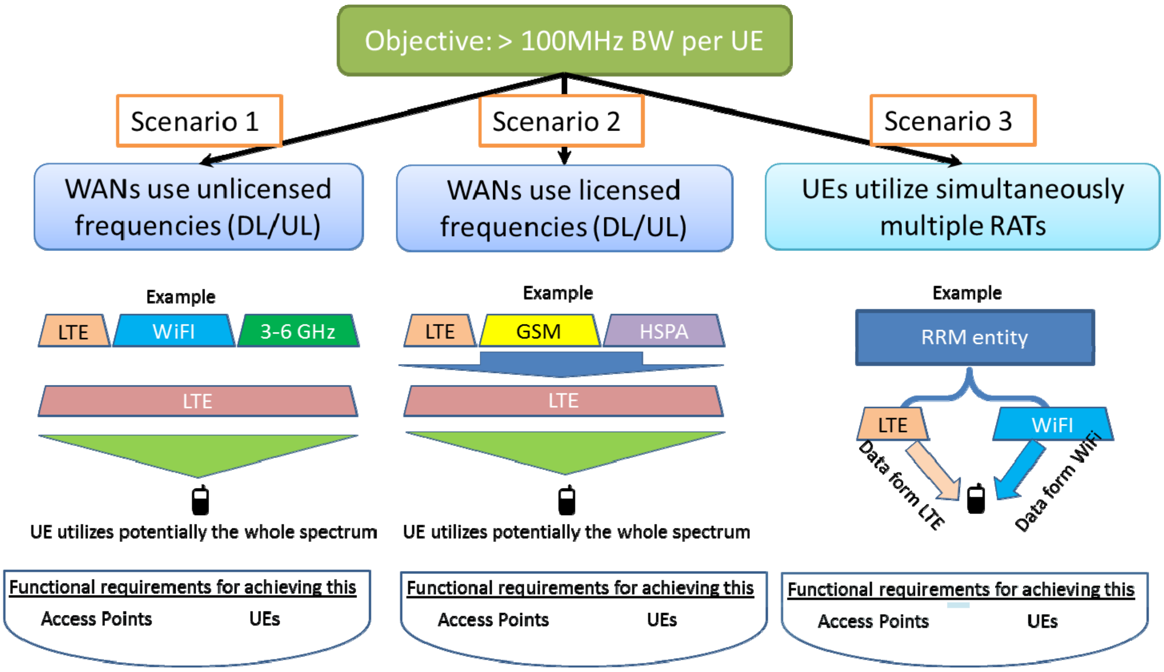

Figure 32: Basic aggregation scenarios in various RATs.

3.2.1 Licensed – Licensed

Aggregation of licensed spectrum opportunities and links/carriers with other licensed spectrum opportunities and links/carriers leads to a clear view of the resulting aggregate capacity and QoS that will be obtained by the aggregation process, hence is preferable for aggregation use-cases that require a high certainty in the resulting performance. Within this scope, SOLDER considers LTE as a baseline for much of its aggregation work and bases the licensed-licensed aggregation strongly around that.

3.2.1.1 LTE – LTE

LTE-LTE aggregation has already been covered for the case of HetNets, however, here it is covered in more detail in order to reflect more general situations than HetNets. This includes aspects such as the types of carriers that are aggregated and the associated mappings in LTE systems.

LTE-LTE aggregation can be considered as the default scenario that has originally motivated the 3GPP. It is the case of aggregation of two LTE carriers, in LTE bands, using same duplex mode (e.g. aggregating one FDD band with another FDD band).

The aggregation could be inter-band or intra-band. For intra-band case, it could be contiguous or non-contiguous. To give illustrative examples of such scenario, the following deployment cases could be mentioned:

- Inter-band:
    - US operator#1: Band 13 + Band 4

  - US operator#2: Band 2 + Band 17
  - Korean operator#1: Band 1 + Band 3
  - Japanese operator#1: Band 1 + Band 19
  - European operator#1: Band 3 + Band 20
  - European operator#2: Band 7 + Band 20

- Intra-band:
  - Chinese operator: Band 39+Band 39
  - US operator: Band 41 + Band 41

Definitely, the list could be extended to additional operators or additional configurations (with 3 DL CC). The UL CA has not yet gained interest from a deployment perspective, especially due to the higher cost impact into the terminal.

The motivation for such aggregation is twofold. First, it allows the operator to get higher (aggregated) bandwidth and therefore is a mean to reach higher peak data throughputs. From a marketing perspective it is a mean to claim to have “the fastest network in the world). Definitely, some operators were not awarded necessarily 20MHz bandwidth (or more) and could not benefit from the full LTE speed. They need to aggregate several pieces of spectrum to reach and go beyond this 20 MHz bandwidth. With two carriers of 20MHz wide each, the operator could serve category 6 terminals with a maximum throughput of 300Mbits/s. Adding up additional carriers could bring additional throughput, say typically 150Mbit/s per 20MHz carrier, assuming “usual” MIMO scheme (up to 2x2 streams per carrier).

This race towards high peak throughput is particularly sensitive for TDD operators which inherently suffer from the naïve – but quite widespread – comparison with FDD operators. In TDD an operator have only 20MHz shared for DL and UL, while in FDD, the operator has actually a pair of bands, 20MHz for DL and 20MHz for UL. As a result, TDD operators were the first to push for intra-band CA in order to beat peak throughput.

The second motivation for an operator to deploy CA, lies in the fact that with a single wireless system, namely LTE, it could harmonize its spectrum which is often fragmented. This is typically the case in the US. Indeed, because of historical reasons, the spectrum is heavily fragmented (with also the burden of having local and national licensed).
CA is a convenient way to operate its complete spectrum with a single technology, facilitating load balancing or QoS management, managing legacy terminals (without CA capability) and advanced terminals (CA-able).

CA provides also an easy mean for inter-cell interference management in context of HetNet (when cells are overlaid: a macro cells being an umbrella to multiple small cells).

SOLDER strives, for performance and efficiency reasons, to perform spectrum aggregation at the lowest layer possible for each considered use case. It is noted again that in the case of aggregation of two or possibly more LTE carriers, operating intra-band, contiguously or non-contiguously using the same duplex method, CA could be achieved at the PHY layer by introducing enhanced PHY capabilities. The use of an enhanced FBMC waveform, could allow for such PHY-layer aggregation.

Many motivations for such aggregation based on FBMC exist. We expect that FBMC helps, when compared with regards to other types of multicarrier communications such as OFDM schemes, in the following ways:

- Increasing the spectral efficiency since FBMC does not require any cyclic prefix

- Reducing interference to other communications since FBMC
  - is capable to handle unsynchronized users
  - has an inherent better protection of other users (coexistence), i.e. lower spectral leakage
  - naturally efficiently exploits fragmented spectrum

We expect that appropriate radiofrequency-baseband co-design helps in:
- Reducing the spectral leakage due to analog non-linearities
- Increasing the energy efficiency of the device

In addition to more conventional infrastructure-based scenarios, SOLDER is aspiring towards aggregation of capacity in more challenges cases such as ad-hoc and device-to-device (D2D) communications. Further, it is noted that aggregation of licensed LTE systems need not necessarily be done involving spectrum that is owned by the same entity. Such aggregation could be between different licensed spectrum chunks that are shared between different owners, greatly enhancing efficiency under limited spectrum availability and satisfying the large bandwidth demand of services to achieve better performance for given users.

Depending on implementation, the same primary user (PU) may be the “owner” of both licensed bands, or alternatively the spectrum may be aggregated with the licensed spectrum of another owner. This will effectively mean that the PU is aggregating his/her resources in one band with the resources of another owner operating as Secondary User (SU) in the other licensed band. In licensed spectrum, the PU has high priority to use their spectrum, meanwhile, SUs might only allowed to opportunistically access that spectrum to enable communication or improve service quality when the spectrum is idle. It is noted that models are actively worked with by operators and associated consortia to allow such sharing between primary spectrum owners, particularly strongly directed to spectrum sharing between mobile communications network operators [113].

Under most current models, it is assumed that under such sharing between licensed spectrum “owners”, whether for the purpose of aggregation to enhance capacity or for coverage provision per se, there is an agreement and signalling method between the operators to share the spectrum (along with some means of associated financial compensation for using the spectrum). However, equally under concepts such as ASA, sharing might also be achieved through DSA and CR mechanisms, such as sensing to find available spectrum providing that appropriate protection to the primary (the spectrum “lender”) is maintained, the primary agrees with that mechanism, and a means to compensate the primary for access to the spectrum is still incorporate.

Such aggregation might be achieved in infrastructure-based models, e.g., under cellular provision, or might be achieved under the assumption of device-to-device (D2D) communications and resources being aggregated for D2D links. This latter case can further be extended to wireless cognitive radio ad-hoc networks (CRAHNs), whereby SUs, partially or wholly without infrastructure (e.g., perhaps even aggregating infrastructure based resources with D2D-accessed resources) might use both spectrum aggregation and dynamic spectrum access to enhance performance. It is aimed for aggregation in such scenarios to be ultimately performed at the MAC layer, through combining the MAC resources of the different networks.

This scenario, both for the infrastructure-based aggregation and non-infrastructure based (e.g., the use of CRAHNs), or indeed even under a combination of the two, will aim to achieve several purposes as follows:

1. Increase the achieved area capacity

2. Achieve higher spectrum efficiency

3. Lower energy consumption, and increase overall energy efficiency (e.g., area-capacity to power consumption ratio for the operator's services)

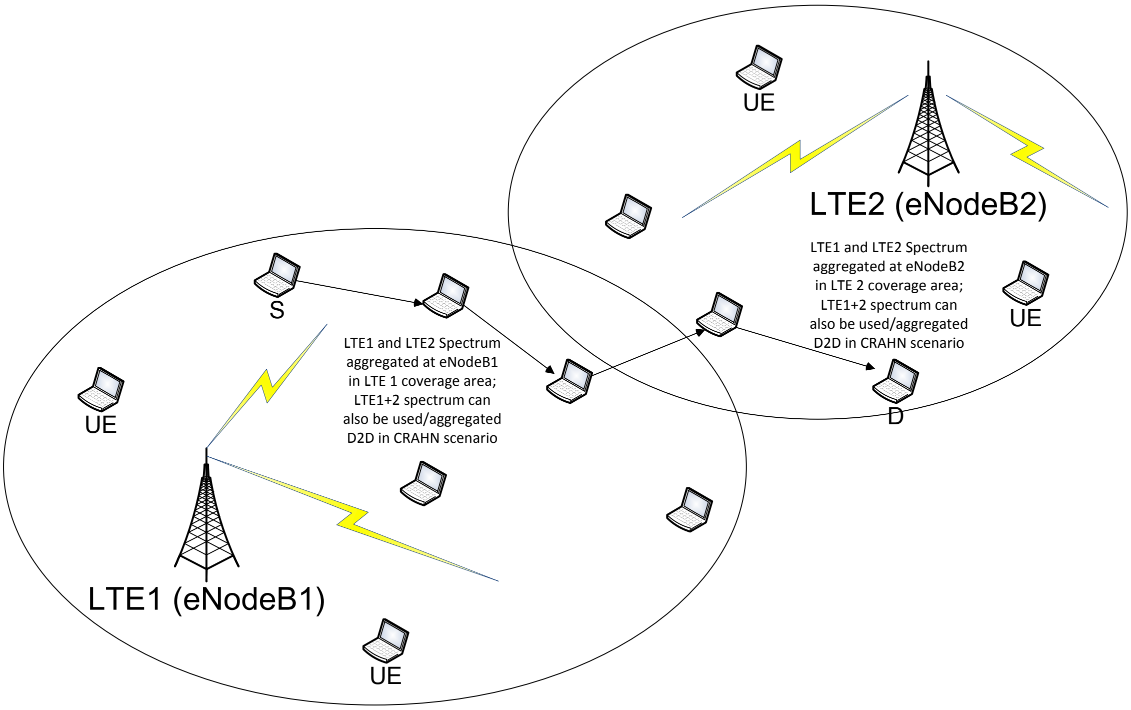

Figure 33: The multi-hop wireless cognitive radio ad-hoc network deployment scenario involving spectrum aggregation between a licensed LTE and licensed LTE system.

Figure 33 depicts the network deployment scenario in multi-hop wireless cognitive radio ad-hoc networks through spectrum aggregation. To provide a simple scenario with realistic results, the scenario only considers two licensed LTE networks, LTE1 and LTE2. Under this scenario, D2D communication is depicted forming a CRAHN, applying to the case where the devices from LTE network 1 are operating in a secondary fashion under the spectrum of LTE network 2. It is noted that these devices (e.g., the destination D) might aggregate not only opportunistic resources for the formulation of the CRAHN, but might also jointly aggregate with the infrastructure-based LTE 1 transmissions.

Regarding the traffic types applicable to this aggregation scenario, it is noted that delay tolerant and non-QoS sensitive traffic is most applicable, especially for the CRAHNs scenario. However, other traffic types might also be easily addressed particularly for the cases where the aggregation is of infrastructure-based provisioned resources.

It is noted that given that LTE is designed to operate in numerous possible frequency ranges with different channel bandwidths, the technology is ripe for aggregation to be considered across multiple bands. For example, SK Telecom has already announced that by the end of 2014 will build out the tri-band LTE Advanced carrier aggregation to combine 10 MHz in 800 MHz band, 20 MHz in 1800 MHz band and 10 MHz in the 2.1 GHz band, to support data rate speeds of up to 450 Mbps. Two S Korean companies plan to roll out tri-band LTE-A CA. LG Uplus by combining of a 40MHz block of spectrum in the 2.6GHz band, a 20MHz block in the 800MHz band and a 20MHz block of 2100MHz frequencies and Samsung by combining triple carriers with 20MHz bandwidth each. It's true that the above tri-band scenarios will effectively trigger the LTE-A technology and thus research can be done in aggregating more frequencies in different LTE-A bands and possible future beyond scenarios could be 4-band or 5-band LTE-A CA schemes. Note, that 3GPP has already standardized in LTE-A the theoretical (up-to-now) aggregation of 5 component carriers can be implemented. Therefore, in this project the aggregation of more than two LTE-A CC is one of possible scenarios that will be studied.

Therefore, performance analysis metrics on the above mutli-band CA scenarios could investigate the following:

- Average DL throughput.
- Spectral efficiency
- Effective capacity per UE
- Signalling overhead

3.2.1.2 Multi-RAT scenarios in LTE-A Rel. 13

The coexistence of multiple RATs introduces many operational coordination problems for network operators (see Figure 34). The co-existence of various RATs (i.e. LTE/UMTS/GSM/CDMA/WLAN) is an obvious reality and it will remain relevant in the future. This raises important issues for operators in terms of coordination across the RATs to achieve better user experience (QoE), efficient resource usage, higher network capacity and easier maintenance, especially in a multi-vendor environment [106].

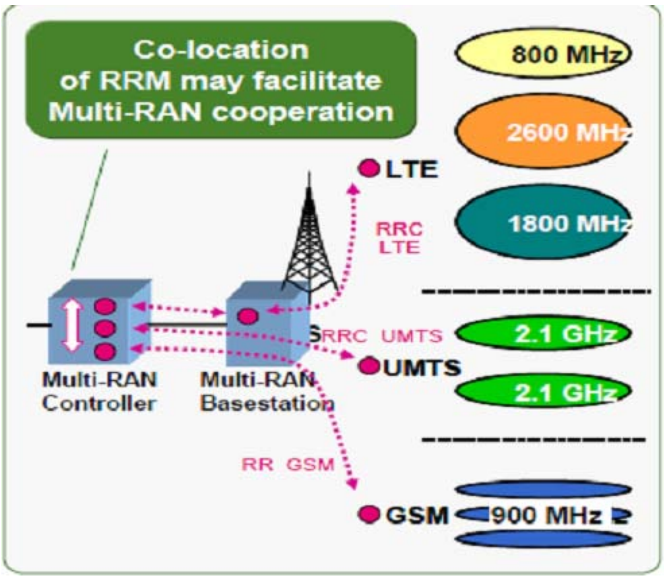

Figure 34: Multi-RAT joint radio operation [106].

For an operator with multi-RAT networks, frequent updated information from all RATs (radio resource management, mobility and traffic load) is required in order to enable efficient coordination by the network. It will be beneficial to consider a general Multi-RATs coordination from RAN perspective to meet the following requirements as specified in LTE-A Rel. 13:

- Steering of UEs among different RATs

- Efficient multi RAT joint radio resource coordination to improve load balancing and for an operator to enable, e.g. spectrum re-farming.
- Enhancement of RAN interfaces and procedures to support the joint operation among different RATs as described above, taking into account the followings:
  - Reuse existing RAN interfaces and procedures as much as possible;
  - No impact on UE operation and air interfaces.
  - Possibility to support different architectures/implementations.

The deployment of concurrent multiband and multi-RATs to cover a specific area creates the necessity for optimal utilization of the data traffic among various access technologies. This technology is called Traffic steering and denotes the functionality to optimally distribute the load among the available cells subject to mobility and interference limitations. CA UEs can concurrently connect to more than one CC and, therefore, fast inter-layer load balancing can be achieved.

The above considerations of the specifics of multi-RAT joint radio operation also touch the SON framework (but also can be seen as a RRM features if developed natively in the MAC layer / RRM). An example configuration is presented in Figure 35 below.

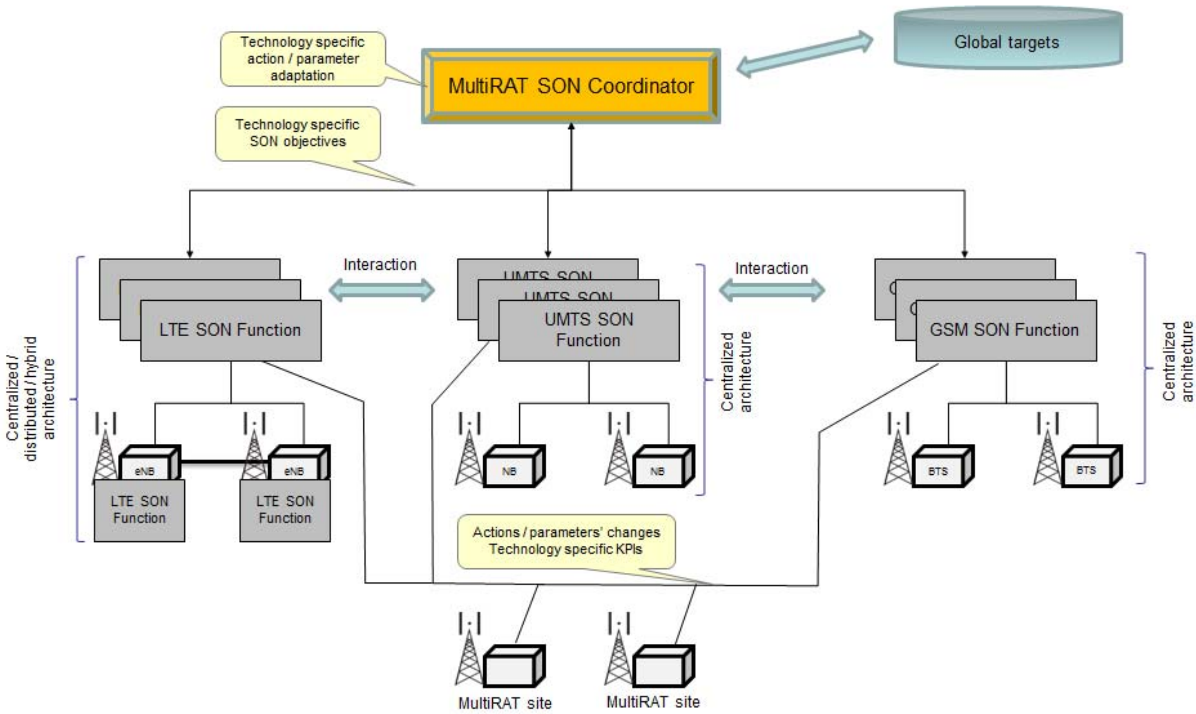

Figure 35: Example high level architecture for Cross-Technology SON.

One of the idea of multi-RAT SON/RRM is to treat all operating networks as global resources (all frequencies and RAT layers), whereas the algorithms shall prioritize and utilize different RATs according to UEs performance capabilities (i.e. treat them in a different manner).

An example strategy is presented in Figure 36 below.

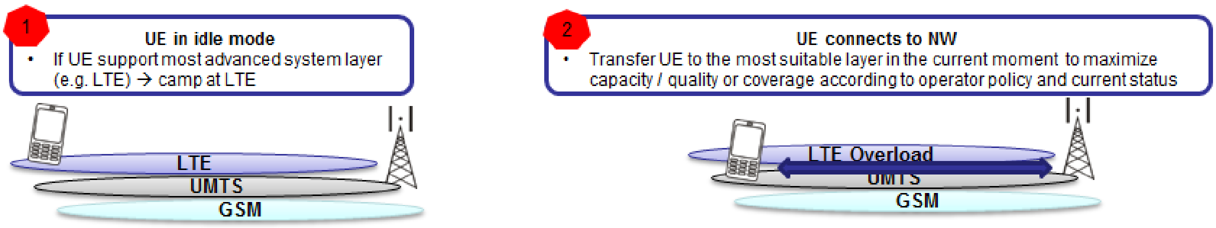

Figure 36: Load balancing for multi-RAT CA.

Treating all the networks as global resources and using all networks while deploying a single set of RRM mechanisms can help to utilize resources more efficiently by e.g. LB/traffic steering via cell reshaping as shown in Figure 37 below.

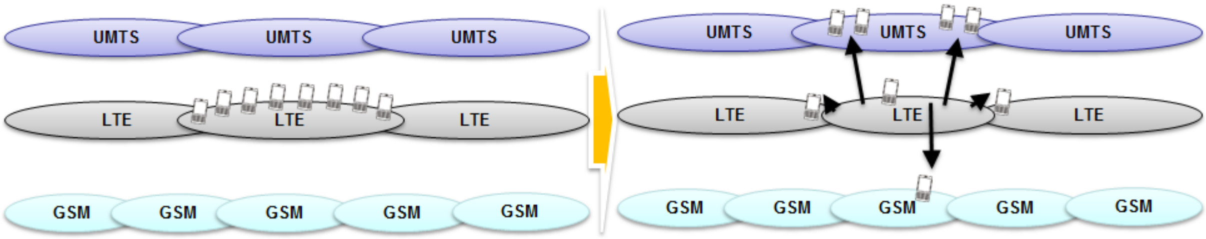

Figure 37: Example load balancing via cell reshaping.

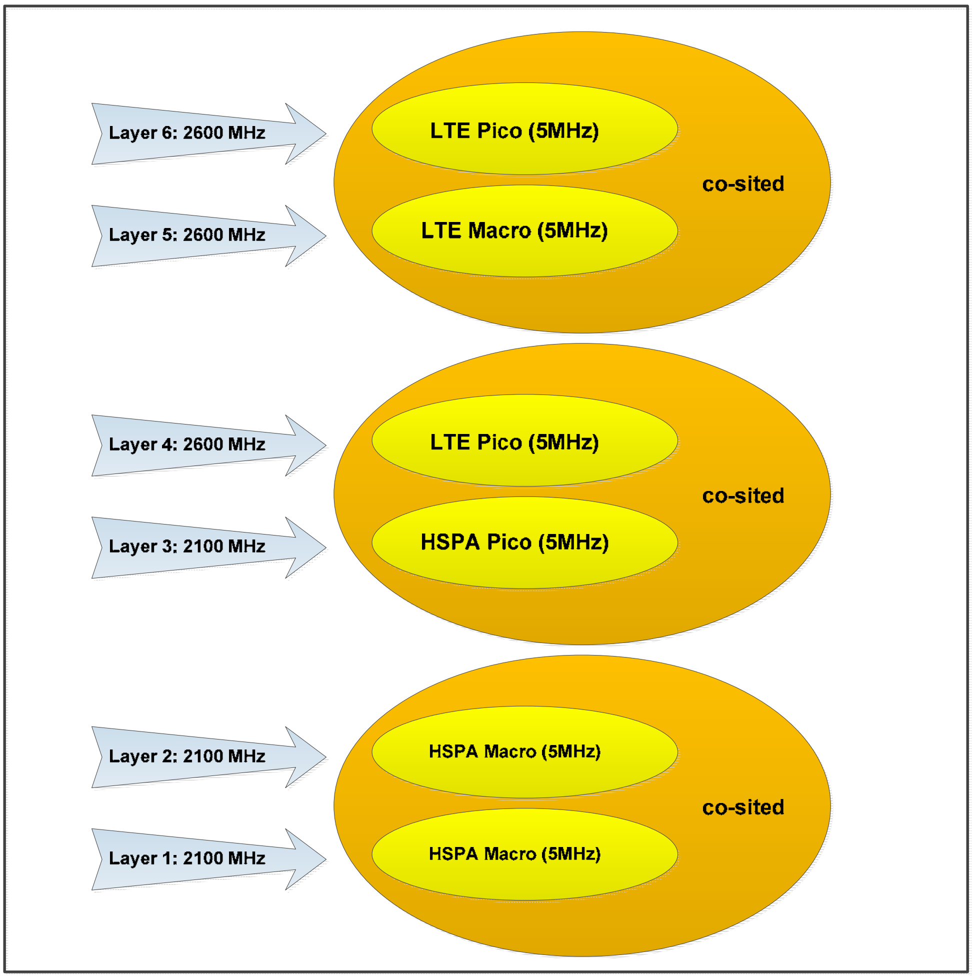

Figure 38: Multi-RAT macro-macro & macro-pico scenario deployment.

In Figure 38, a multi-RAT macro-pico scenario is described where two traffic steering mechanisms are evaluated in HSPA/LTE scenario, where the objective is to offload traffic from the macro-layer to macro/pico-cells. In idle mode, i.e., the state in which no dedicated resources have been established for the user, a static adjustment of the layer priorities in the cell reselection algorithm is performed. A similar deployment model is presented in [149] where in connected mode the parameters of the inter-RAT handover triggering condition are statically adjusted to offload the macro-layer [108].

The analysis of multi-RAT macro-pico scenarios in PHY/MAC layers could be an alternative option for study in SOLDER project. The increase of the effective capacity per UE in co-sited locations could be a feasible goal; however, the effective capacity per user should be studied considering the UE distribution and also how the co-channel interference affects each layer in Figure 38. The study of general RRM mechanisms (that can be seen also as SON features) for multi-RAT spectrum management is an interesting scenario – once we assume that the network, that consists of multiple co-siting technologies is a global resource.

3.2.2 Licensed – Unlicensed Aggregation

The aggregation of licensed spectrum/link/carrier opportunities with unlicensed opportunities can be seen as a useful way to supplement the capacity that operators will achieve, as long as the particular characteristics of unlicensed spectrum and its unreliability are taken into account. Such characteristics might be mapped, for example, to best-effort traffic.

3.2.2.1 LTE – LTE (General Unlicensed)

The utilization of LTE in unlicensed spectrum is described in [100], [101], [109], [110]. Given WiFi has been widely deployed as the most popular access technology for unlicensed spectrum, co-existence of LTE unlicensed and WiFi systems is an important scenario. Due to the fundamental differences in the PHY/MAC design between LTE and WiFi, a direct implementation of LTE may impact the opportunistic channel occupancy of co-channel WiFi especially in some high-load cases.

Qualcomm proposes to create a hybrid system using LTE-Advanced operating in both licensed and unlicensed spectrum at the same time. Specifically, it is proposed that the system shall use the CA feature of LTE-A to aggregate licensed LTE spectrum with unlicensed spectrum in the 5GHz band. The unlicensed spectrum, which would be aggregated with licensed spectrum on the downlink direction only, would be used for data services only. The licensed spectrum would be used for uplink and downlink and would support network control as well as voice and data services. Given the power limits placed on devices using the unlicensed 5GHz band, unlicensed LTE-A would be used mainly in small cells, similar to Wi-Fi [101].

In Figure 39 the Primary carrier uses licensed spectrum (FDD or TDD) while Secondary carrier(s) use unlicensed spectrum. The main drawback is the LTE could occupy the channel after the listen before talk period. Therefore a smart selection of unlicensed bands for improved performance and the coexistence with unlicensed bands (e.g. WiFi) should be carefully treated to protect unlicensed neighbours.

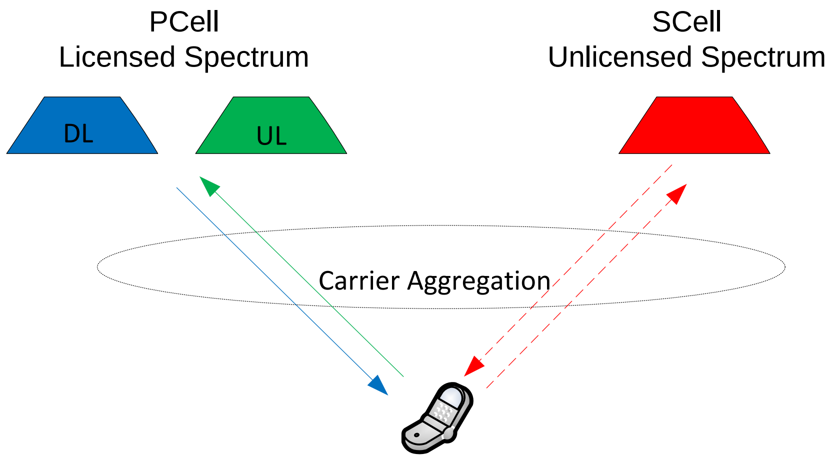

Figure 39: Licensed-Assisted Spectrum.

The desired functional requirements are as follows:

- Cross carrier scheduling for FDD-TDD CA
- Dynamic DTX (on subframe basis)
- Dynamic duplex

From Figure 39 it is true that a combination of both licensed and unlicensed bands and thus CA of different frequency bands can be achieved. The overall aggregation could include unlicensed frequency bands and LTE-A contiguous or non-contiguous CC; A similar application has been already patented in [104]. The scenarios that could be investigated are presented as follows:

- Aggregation of LTE licensed and LTE unlicensed CCs.
- Aggregation of HSPA and LTE respectively or vice versa.
- LTE and WLAN CCs on licensed and unlicensed spectrum respectively. A possible scenario of LTE and WLAN CA comprises of LTE operating in licensed CCs, LTE operating in one set of unlicensed component carriers and the WLAN operating in the second set of unlicensed CCs.
- LTE, HSPA and WLAN CA where LTE and HSPA operating in licensed or in one set of unlicensed CCs or vice-versa and WLAN operating in the second set of unlicensed CCs.
- A mixture of licensed LTE CCs, TVWS operating in one set of unlicensed CCs and unlicensed spectrum through WLAN CCs.
- Licensed TVWS CC in primary cell, LTE in secondary cell and unlicensed spectrum through WLAN CCs.

The current CA solutions provide PHY layer mechanisms to aggregate dispersed component carriers, under the assumption that all component carriers situated in the licensed spectrum bands. However, if some of the components are unlicensed carriers, the PHY and MAC layer carrier aggregation mechanisms need to be revised, and the heterogeneity of using mixed aggregated licensed and unlicensed bands for the UEs need to be revisited. To this end, some involved mechanisms and layers in the licensed and unlicensed are listed as follows [102]-[105]:

- The eNB can detect notable interference increase on carriers on the unlicensed spectrum either from the UE or other transmitting node, which is about to start data transmission. To this end, interference management is important for this application.

- In unlicensed band it could be proposed a kind of "listen-before-talk" procedure that requires from the device to defer its transmission on unlicensed spectrum.
- The MAC level signaling for their served unlicensed spectrum CC, where the eNB is enabled to more dynamically change the multiplexing status per each radio bearer based on more instantaneous characteristics of the unlicensed bands.
- Unlicensed carriers are usually shares and thus the power allocation constraints for those carriers and the coverage area of the component carriers are necessarily different and this should be appropriately addressed.
- Multiplexing the various LTE-A channels onto different CCs in both the licensed and unlicensed bands could result in the calculated transmit power exceeding the UE's maximum allowable transmit power. Unequal maximum power allocation (limits) in the licensed and unlicensed spectrum bands, in the downlink from the base station need also to be addressed.

Several performance metrics can be investigated for the above application scenarios such as:

- The total received capacity of aggregated CCs.
- The formulation of the optimization problem was based on the maximization of the sum of the total throughput in both licensed and unlicensed bands while satisfying QoS requirements of the UEs
- The spectral efficiency of each of the above application scenario.
- Qualitative and quantitative evaluation of the effects of interference between different RATs.
- Error and outage performance analysis.
- Average detection delays on ARQ or HARQ protocols
- Overall network performance with UEs randomly distributed in a square area.

LTE over unlicensed spectrum were presented to introduce new study items related to the use of LTE in the WiFi bands as discussed in the RAN#62 plenary held in December 2013. There is no clear view so far in this application scenario and the topic will be discussed during the next RAN meeting (to be held in March 2014). In the Table below, we make an attempt on clarifying some details about the unlicensed spectrum use in the LTE. There are actually 2 options of using the unlicensed in the LTE as explained.

Table 10: Unlicensed spectrum utilization of LTE.

Option 1: LTE-only proponents, advocating that LTE as-is could be used in WiFi bands.	**Option 2 :** LTE coexisting with other technologies in the WiFi bands.
This scenario is supported by some operators and main LTE vendors. Relevant request for proposals are listed below: • RP-131635 Introducing LTE in unlicensed spectrum. • RP-131680 New WID: New Band for LTE deployment as Supplemental	This scenario is supported by historical WiFi vendors and operators with strong WiFi presence. Relevant request for proposals are listed below: • RP-131701 Drivers, Benefits and Challenges for LTE in Unlicensed Spectrum.

Downlink in unlicensed 5.8 GHz in USA. • RP-131788 New Study Item proposal: Study on LTE Evolution for Unlicensed Spectrum Deployments. • RP-131723 Discussion paper on Unlicensed Spectrum Integration to IMT systems. • RP-132085 New SI: Study on Unlicensed Spectrum Integration to LTE.	• RP-132008 On LTE in Unlicensed Spectrum. • RP-131749 On LTE in Unlicensed Spectrum.

3.2.2.2 LTE – LTE (TVWS)

LTE aggregation with LTE in TVWS can be considered as variation of the LTE-LTE (unlicensed) case argued in Section 3.2.2.1. However, there are several major differences. First, in the TVWS case the bandwidths available to LTE systems will likely be far more constrained, fitting within (in the European case) 8MHz, likely being 5MHz or 3MHz in order to avoid adjacent channel interference effects. Second, the powers available to the LTE systems in TVWS will vary greatly depending on the information returned from the geolocation database, and might vary throughout time. Further, the slave mode operation of user devices is more constrained.

A further difference in this scenario is that likely each other CRAHN connected node will be required to have “master device” access to the geolocation database, thereby making aggregation involving D2D and CRAHNs not applicable in some scenarios where devices in the CRAHN are not already connected to the Internet using some other means. In any case, the implicit assumption is that the devices will also be using LTE in order to aggregate with that, hence will likely also have that internet connectivity through LTE.

3.2.2.3 General Cellular Networks – General Cellular Networks (TVWS)

The spectrum aggregation of licensed cellular networks with license-exempt TV White Space (TVWS) access has good prospects, especially for spectrum efficiency and energy savings. Further, it is noted that recent developments and initiatives by industry regarding use of unlicensed spectrum for LTE and aggregation of that unlicensed spectrum with licensed and other spectrum opportunities for LTE [41], [97]. This section first covers a more general case of such aggregation within SOLDER, which is in-specific to the characteristics of particular cellular networks.

TV spectrum (hence aggregation opportunities therein) in Europe is located in the 470-790 MHz range, having characteristics that are highly desirable for wireless communications. In order to address inefficiency given limited spectrum availability, the FCC in the US has approved solutions such as opportunistic usage of TV white space, whereby Cognitive Radio (CR) technologies might eventually assist the realization of such concepts. In Europe, Ofcom in the UK has developed rules for TV white spaces access, which are currently being tested, and these have been brought to the European level in the form of an ETSI Harmonised European Standard, ETSI 301 598 [86]. Devices that meet the requirements for access to such white space through conformance with the harmonised standard in terms of contacting the geolocation database to ask for availability and allowed power levels (as well as adhering to the numerous other constraints, such as on the transmission mask), can use the spectrum on a license-exempt basis at up to the given power that the database allows for the given class of device, location, antenna characteristic, channel and other aspects. Through this, it will avoid causing interference to primary services such as DTT and PMSE.

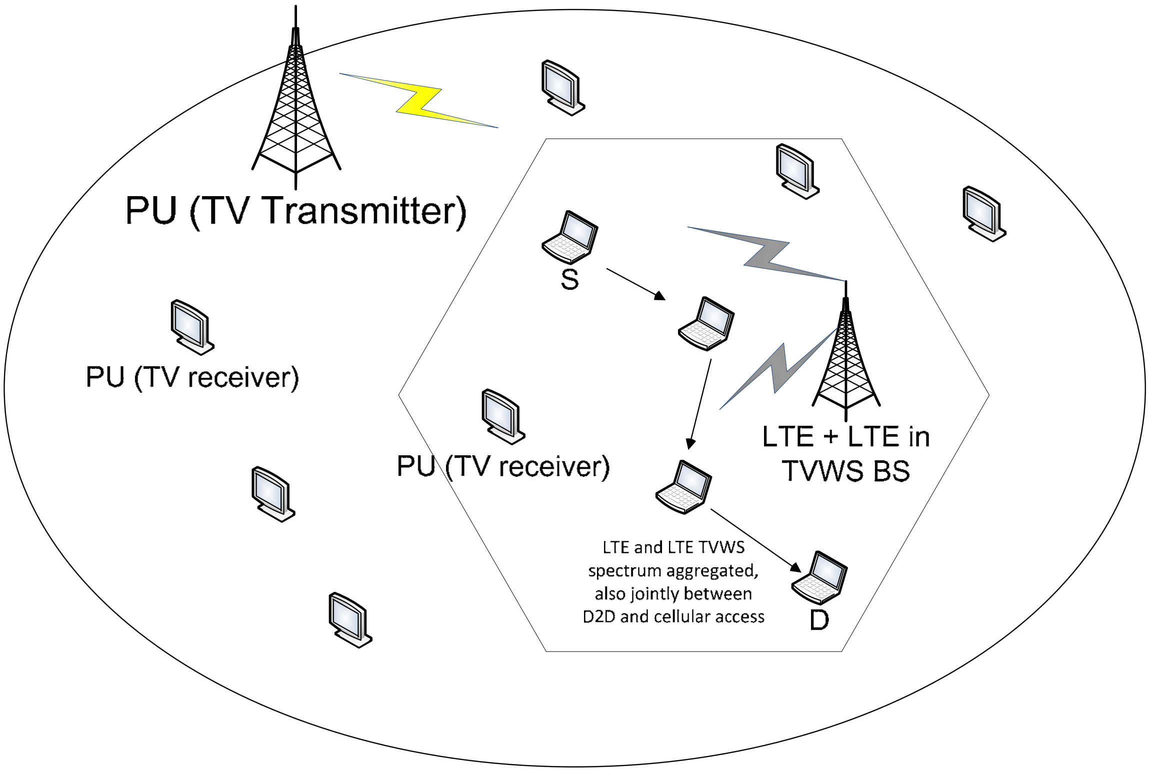

Figure 40: The multi-hop wireless cognitive radio ad-hoc networks deployment scenario: involving spectrum aggregation between cellular networks with licensed TV white space

Considering spectrum aggregation of licensed cellular networks and licensed TVWS in multi-hop CRAHNs or conventional deployment scenarios, the cellular network users are the SUs in TVWS spectrum that must follow SU rules. Figure 40 represents the deployment scenario for spectrum aggregation. It is assumes that the cellular system is located within the coverage area of the TV system, although it is noted that under a more conventional/conservative deployment the TV white space and cellular system will be at different locations. The secondary cellular devices here will attempt to aggregate resources (both from their licensed network, and the unlicensed TV white spaces resources) both for D2D CRAHN infrastructureless connectivity and for infrastructure-based conventional cellular connectivity, noting that the cellular base stations (as well as, clearly, the terminals) might have combined licensed and TV white space access capability. Aggregation in this scenario is aimed to be done ultimately at the at the MAC layer, although noting that the licensed and unlicensed resources will be operating in different bands this may simply take the form of MAC scheduling decisions among the different bands and the aggregation of capacity among those.

This scenario, both for the infrastructure-based aggregation and non-infrastructure based (e.g., the use of CRAHNs), or indeed even under a combination of the two, will aim to achieve several purposes as follows:

1. Increase the achieved area capacity.

2. Achieve higher spectrum efficiency.

3. Lower energy consumption, and increase overall energy efficiency (e.g., area-capacity to power consumption ratio for the operator's services).

Regarding the types of traffic that this scenario could address, clearly the use of unlicensed spectrum or license-exempt access implies that non QoS sensitive traffic may be best served. Further, this is particularly the case for the multi-hop CRAHNs scenario, whereby the capacity among different links and aspects such as reliability will vary greatly.

3.2.2.4 LTE – WiFi (General Unlicensed)

3GPP LTE technology and WiFi protocol based on IEEE 802.11 standard can co-exist to facilitate wireless communication of UE and thus form a smart LTE+WiFi carrier aggregation aiming to increase significantly the overall data throughput and efficiently exploit the radio resources. WiFi transmissions based on MAC procedures (eg RTS, CTS) because there is no centralized control whereas LTE transmissions are managed by a centralized scheduler Apparently, except the above major differences in the technologies of LTE and WiFi, WiFi is susceptible to interference since the band is shared with other WiFi users.

SOLDER projects could investigate scenarios where WiFi access point (AP) working over a specific carrier frequency within unlicensed band is aggregating with a carrier band from LTE. This scenario could be studied both in PHY/MAC layers by considering the limitations imposed by the concurrently use of LTE and WiFi in a UE. The above aggregation is feasible under the condition that the LTE eNodeB demands an extra carrier frequency from a WiFi hotspot to offload some of the DL traffic and/or the UL case. However, this scenario assumes that the UE is capable of operating simultaneously over both the licensed and unlicensed bands ie a mutli-radio device. A major concern with simultaneous operation of LTE and WiFi bands is interference due to UE coexistence of multi-radios operating in adjacent or overlapping radio spectrum bands. The latter must be considered for the proposed data aggregation scenarios concern LTE and WiFi co-existence [112]. Note also that the current LTE+WiFi application scenario differs from the one discussed above in Section 3.2.2.1 from a technical point of view. This is because the former is a pure aggregation of LTE+WiFi carriers with problems related to interference and other channel related issues and the latter describes the implementation of LTE in WiFi spectrum.

LTE and WiFi are very different systems, not only from the physical layer and method of spectrum access but also from a network point of view. While WiFi provides wireless connectivity to the last hop of a traditional 802 local area network, LTE is a fully fledged cellular system with user and mobility management, roaming, etc integrated into the standard. On a physical layer LTE uses a licensed band and the access is centrally coordinated by the eNBs. WiFi on the other hand operates in the unlicensed ISM band and thus needs to both accept interference and not cause harmful interference to other systems operating in the same band. The main differences between WiFi and LTE are listed in Table 11.

Table 11: Comparison of WiFi and LTE

	LTE	**WiFi**
Frequency band	Licensed	Unlicensed
Spectrum access	Centrally coordinated	Distributed (CSMA)
PHY	OFDMA/SC-FDMA	OFDM-CSMA

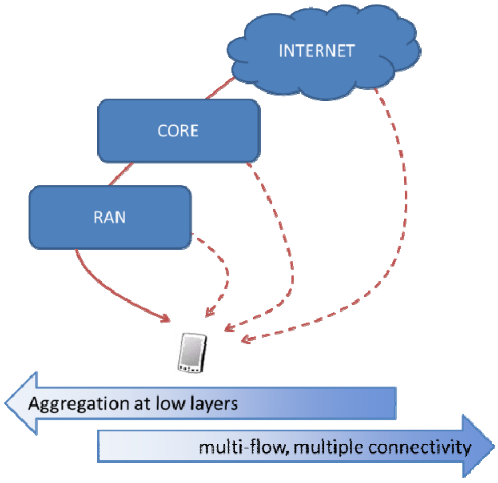

Figure 41: Several options of aggregation.

Aggregation of WiFi and LTE could be seen at different level as illustrated in Figure 41. The aggregation could be done at radio access level, using the same radio access, either at the same frequency band or in a different band; one could imagine to aggregate several radio access systems but still at low layer (PHY/MAC); aggregation could be done at core network level, using one or several technology; or aggregation could be done above the IP layer, as for instance techniques of multi-flow or multiple connectivity involving split and merge of traffic rather at the application layer than at the lower layers. In SOLDER, we focus on the CA at RAN level and we do not plan to address the topic of aggregating flows at a level above IP.

The application scenario for the aggregation of WiFi and LTE are small cells with a high number of users and limited spectrum availability in the licensed band. If the small cell supports aggregation of LTE and WiFi it can use WiFi as an additional carrier. This method would bring improvement for over the scenario where LTE and WiFi are used separately since the base station could balance the traffic according to the needs of the users and the capabilities of both technologies.

The scenario requires a tight integration of LTE and WiFi at the lowest possible layer. The SOLDER vision is that the aggregation will happen at the MAC layer like aggregation of LTE carriers in LTE-Advanced.

3.2.2.5 LTE – WiFi (TVWS)

Spectrum aggregation of licensed LTE with WiFi systems operating on a license-exempt basis in TVWS could achieve significant spectrum efficiency and energy savings.

In spectrum aggregation of licensed LTE with WiFi in TVWS, the same technique of DSA for the system in TVWS might be used, with that access at least for the meantime being based on allowance by a geolocation database [79], [86]. However, the option of performing sensing for TVWS access is not ruled out, noting that the FCC, for example, still allow spectrum sensing-only based access with a very low transmission power for white space devices. Like the spectrum aggregation in licensed LTE + licensed LTE systems, the primary user (PU) in one licensed band will be the SU of the other band, the other band in this case being TVWS. The TV and other primary transmissions in the TVWS must not be interfered with by the WiFi system operation in TVWS.

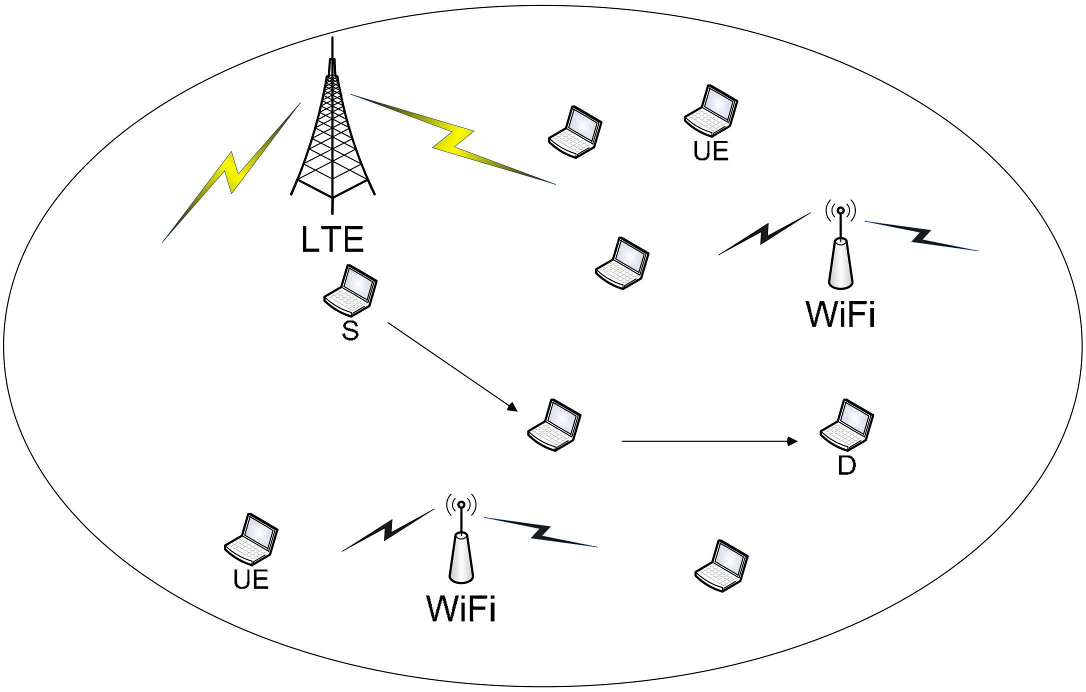

Figure 42: The multi-hop wireless cognitive radio ad-hoc network deployment scenario: involving spectrum aggregation between licensed LTE with licensed WiFi system.

This scenario might, again, apply to either CRAHNs being the target application for aggregation, or through infrastructure-based capacity being aggregated, of both of these in combination. In multi-hop wireless CRAHNs, the networks deployments are shown as Figure 15. One licensed LTE system and several licensed WiFi systems are deployed within a given area. Due to the nature of the systems (being based on different interfaces), the aggregation seems likely to be performed only at the link level.

This scenario, both for the infrastructure-based aggregation and non-infrastructure based (e.g., the use of CRAHNs), or indeed even under a combination of the two, will aim to achieve a number of purposes as follows:

1. Increase the achieved area capacity.

2. Achieve higher spectrum efficiency.

3. Lower energy consumption, and increase overall energy efficiency (e.g., area-capacity to power consumption ratio for the operator's services)

Moreover, the scenario will be particularly applicable to the case where best-effort or non-QoS sensitive traffic is being aggregated, or perhaps scenarios where reliable LTE traffic is augmented by unreliable or best-effort traffic, such as a multimedia broadcast being augmented with non time-sensitive data for the end-user's purview. This is due to the spatial/temporal variation in the availability of WiFi in TVWS as well as some interference from the primary transmissions to the secondary reception, as well as the fact that there will be other competing secondary systems and services in TVWS thereby degrading the quality of the utilised WiFi.

3.2.3 Licensed – Light licensed Aggregation

Light licensing, along with concepts such as LSA, is an interesting avenue that is being currently explored in the research community. For example, one possible model for the future co-primary usage of the 694-790 MHz spectrum by mobile broadband with broadcasting (see, e.g., [114], page 9) is through some form of light license to be issued to the mobile systems (e.g., base stations) operating in such spectrum. Hence, aggregation of these opportunities with licensed spectrum (e.g., the LTE spectrum being used directly above 790MHz) might be an interesting future opportunity.

The scenario for aggregation in such cases is very similar to the LTE-LTE aggregation discussed in Section 3.2.1.1, with the exception that the coverage through such a light-licensing concept might be somewhat patchier depending on the characteristics of the co-primary usage.

4. Open challenges and opportunities for CA in HetNets and h-RATs

Several challenges persist in all of the above forms of CA, and there are various opportunities to enhance the range of CA options that are available to implementers, including the facilitation of aggregation among different types of systems, and among various different types of spectrum opportunities. This section gives an overall clear view about the open issues and challenges in the area of carrier aggregation in heterogeneous networks and radio access technologies based on the thorough literature review and the application scenarios presented in the previous sections.

4.1 Challenges to be addressed in CA over HetNets

There is an opportunity to enhance CA in HetNets as discussed in details above in sections 2 and 3. Here, we provide details on particular technical challenges at system level looking into specific layers and components. This will be useful for the requirements specifications that follow in WP2.

RF design for HetNets (Tx/Rx): a low complexity design of a UE which is suited to carrier aggregation, with the ability to easily cope with various heterogeneous bands and bandwidth combinations. Indicatively, bands of 2 GHz and 3 GHz must be able to incorporate to the new prototype RF architecture. Moreover, the FDD+TDD must be also provided with separate designs for co-located or non-co-located small-cells/macrocells. The last scenario is much more challenging by the typical HetNet with micro/pico CA since the Rx/Tx has to work with both legacy FDD and legacy TDD single mode carriers, to receive and transmit simultaneously over FDD and TDD carriers. The above challenges on RF & UE design could be quantified by studying performance metrics such as: throughput analysis, how the LTE FDD receiver is affected by LTE TDD transmissions, new interference mitigation techniques, performance in fading/shadowing environment etc.

UE in Intra-band CA scenarios: From RF perspective, intra-band contiguous aggregated carriers have similar properties as a corresponding wider carrier being transmitted and received. Rel-10 requires more stringent linearity requirements on the power amplifier than Release 8/9. UE will need to use less transmitter power for the amplifier to remain in the linear region Use of multiple CC on UL should be optional and only used for cases where

UEs are not at the cell edge. For the base station, it has less impact - it corresponds in practice to multi-carrier configuration already supported in earlier releases.

UE in Inter-Band CA Scenarios: the inter-band CA requires multiple simultaneous receive chains and multiple simultaneous transmit chains in case of UL CA. Challenging radio environment in terms of intermodulation and cross-modulation within the UE device. Need to design front-end components that help reduce harmonics, and other inter-modulation products, which meet 3GPP requirements. Simultaneous transmit or receive with mandatory MIMO support add significantly to the challenge of antenna design. For the base station it has less impact – similar to current base stations supporting multiple bands.

Interference cancellation (UE assisted*):* SOLDER will investigate interference mitigation techniques in the UE. Even if Carrier Aggregation in Hetnet could be used to limit the inter-cell interference, the UE will anyway face residual interference. As a result, Interference mitigation in HetNets networks is a critical challenge. Capacity and coverage gains with such deployments can only be realized with proper interference management to mitigate cross-tier interference. In LTE Rel-11, performance requirements for linear inter-cell interference have been defined. In parallel, more advanced receivers with partial inter-cell interference cancellation and mitigation of cell-specific reference signals, for example, are being defined. The primary motivation for such advanced receivers in Rel-12 and beyond is to enhance the support for offloading in heterogeneous deployments, using even larger cell-selection offsets than is possible with existing receiver algorithms. At the same time, such receivers are also expected to provide user-data-rate benefits in macro deployments at typical low to medium loads. Advanced receivers, for further mitigation of intra- and inter-cell interference coming from control and data transmission, are a natural evolution of the current ones. As conventional receivers with channel estimation based on the interfered Cell-specific Reference Symbol (CRSs) fail to work properly, advanced interference mitigation schemes for user equipment (UE) are adopted, such as: the received-power dependent interference cancellation (IC), and the decision-directed channel estimation and IC-assisted channel estimation. An associated applicable scenario for interference avoidance from reference signals is the NCT.

MIMO link adaptation: Considering a network with primary serving cells (PCells) and secondary serving cells (SCells) the UE is able to aggregate carriers from different serving cells, by performing radio link monitoring and choosing those carriers that provide the most ubiquitous coverage and/or best overall signal quality. The challenges of link adaptation comprise the following aspects, which are related to the LA performance in systems employing OFDM and MIMO antenna technology:

- o Adaptation on power and coding to mitigate interference and increase code rate, respectively.
- o Investigation of important Link Quality Metrics (LQMs)such as Precoding Matrix Indicator (PMI), Rank Indicator (RI) and Channel Quality Indicator (CQI) in different HetNet scenarios where LA is applied
- o Answer the question on how much the LA is affected by inter-cell interference and possible trade-offs metrics.
- o Multiple timing issues in multi-CCs environment for synchronization of UL transmissions both in contiguous or non-contiguous CA schemes.

Channel measurements and feedback reporting*:* SOLDER will implement measurements and reporting techniques to support basic mobility management, CC selection and link adaptation. The UE must perform the appropriate measurements and reporting to support the selection of component carriers, as specified in the 3GPP standardization. The measurements could be supported by the interference mitigation as mentioned previously.

The measurements could be extended to cover the h-RAT case (see section 2.4.2). Specifically, channel measurements and feedback reporting could address the following issues:

- o Channel measurements per cell and CC in conjunction with feedback reporting will be incorporated to the LA scheme.
- o Detection of primary and secondary cells (PCells/SCells, micro/pico) using the interference cancellation will be exploited by the interference-cancellation-capable receiver.
- o The measurement and reporting is related to the network and the particular CCs candidate for being aggregated.
- o UE will be able to autonomously select the PCell/SCell and their CCs. Feedback reporting is related to the indicators, PMI, CQI and RI of the LA.

Channel measurements should be also adapted to NCT scenario for reducing the signaling overhead.

Alternate waveform (FBMC): SOLDER will investigate alternate waveform (FBMC) in context of intra-band CA scenarios. In order to validate a step forward in the use of FBMC as an alternate waveform, the following issues have to be addressed:

- Efficient and low complexity instantaneous power fluctuation reduction (PAPR reduction) for FBMC
- Power amplifier linearization

These issues will be addressed in SOLDER thanks to the use of radiofrequency-baseband co-design. These digital processing algorithms will take place at the interface of the PHY layer and the RF front-end. The performance of the proposed algorithms will be assessed with the following "performance indicators":

- Power Amplifier Efficiency
- Out-of-band Radiation

4.2 Challenges to be addressed in CA over h-RATs

Many opportunities exist for CA in h-RATs. They involve aggregation of opportunities that exist in a range of different types of spectrum, including licensed spectrum, unlicensed spectrum (WiFi) and emerging forms of spectrum such as TV white space and spectrum freed by concepts such as authorised/licensed shared access. Aggregation of different types of systems in the same type of spectrum or even in the same band is also an interesting topic with much ongoing research. Indeed, the broad application of aggregation is a hot topic as a means to cope with increasing fragmentation in spectrum usage. There are also many challenges and considerations that have to be addressed in aggregation scenarios in the context of h-RATS as follows:

- The significant variety of aggregation scenarios among different types of systems (i.e., LTE, HSPA, WiFi, TVWS spectrum opportunities, etc.); multiplicity of solutions and combinations of systems (e.g., combinations of licensed-licensed and licensed-unlicensed), as well as challenges in merging the differing capabilities of each pair of systems in the most efficient way possible. Many of the combinations of systems will have different requirements (e.g., spectrum mask characteristics) making aggregation at lower layers challenging, or at higher layer will have traffic QoS challenges.
- Cross-layer implications, in terms of satisfying user traffic demands as well as the interactions among users considering the fairness of resource allocation in scheduling among different systems. By aggregating different types of systems, there are numerous challenges in performing aggregation at the PHY layer due to unpredictability of interactions of the associated waveforms, and, besides that, at the MAC layer

challenges persist due to the different temporal-spectral patterns with which MAC resources are used among the systems.

- If different carriers of the same type of system are being aggregated, it is likely that medium access can/will be synchronised, and other access patterns being simpler, make it more realistic to avoid interference among the carriers. Given this, aggregation involving these different systems may in some cases have to take place in higher layers, involving the aggregation of links or flows rather than carriers. This may also be the case where the different systems are in different, non-contiguous spectrum bands, given that they will not share the medium in such cases.

Considering all the above challenges, SOLDER will investigate the behaviour of the prototype in PHY and MAC-Layers in the context of h-RAT scenarios.

Moreover, it is the broad objective of SOLDER to drive towards aggregation at the lowest layer possible, with likely the MAC being a common layer for many aggregation solutions noting that the MAC is usually in software and thereby is easily implemented in systems, and can be updated in systems in the field to support aggregation solutions. On the other hand, one area that has received significant attention from the research community over recent years is the ability for systems to aggregate resources in unlicensed spectrum or among chunks of opportunistically used spectrum which might be made available by technologies such as cognitive radio, noting that there are already examples of such opportunistic spectrum usage being made possible in the regulatory domain through concepts such as TV white space. Spectrum opportunities that are aggregated under such concepts might further be aggregated with licensed spectrum systems and/or communications in other types of spectrum, in order to maximise resource usage. This aggregation may involve innovating spectrum licensing concepts such as ASA/LSA, in addition to unlicensed spectrum.
The SOLDER project will concentrate on specific problem in PHY/MAC layer aiming to highlight how beneficial CA could be for the operation of UE in the context of h-RAT. Specific challenging issues that can be studied during the can be categorized as:

Multi-Band CA: Multi-Band LTE CA considers the CA of licensed-licensed spectrum where each of CC utilizes a specific LTE band. An open issue is the aggregation of more than two CCs and also the study up-to the theoretical limit as imposed by 3GPP, i.e. five component carriers. Performance analysis in both PHY and MAC Layer is an open issue for multiband LTE CCs and specifically the SOLDER project can provide the research community outcomes in average DL throughput, spectral efficiency of multiband systems, and effective capacity per UE etc.

M*ulti-RAT CA*: The co-existence of multiple RATs and coordination of various technologies will be one of the future trends in wireless mobile communications. Apparently, from an operator point-of-view, the coordination between different access technologies is absolutely necessary. From a UE perspective the question is: What are the challenges that may be arise of a UE working in the above multi-RAT environment?

- o For example, optimal and smooth operation of UE in different RATs in macro-pico scenarios.
- o And, PHY/MAC layer issues when the UE connect simultaneously to different RATs and thus to different CCs.
- o And, Inter-Layer load balancing.

The metrics that could be analyzed in Multi-RAT CA open problem are the effective capacity per user and interference among macro-macro and macro-pico scenarios.

Licensed-Unlicensed: By deploying LTE in unlicensed spectrum (LTE-U), LTE could occupy and utilize channels form the unlicensed spectrum for the benefit of UE. Therefore a mixture of various CCs from Licensed LTE, unlicensed/licensed TVWS and unlicensed WLAN spectrum is challenging task. It is easy to understand that major technical issues challenging the operation of UE in licensed-unlicensed bands as follows:

- o The heterogeneity of the various CCs in licensed and unlicensed spectrum makes the implementation of CA in PHY/MAC layer a real challenging problem.
- o UE transmission power problems due to the necessity of multiplexing CCs in different spectrum bands.
- o Strong interference.
- o Power allocation issues in unlicensed spectrum since CCs are shared among the unlicensed users.

To address the above problems and in different scenarios could help us to evaluate the overall received capacity for aggregated CCs, to optimize the total sum rate and to study traditional performance metrics in PHY/MAC layer.

LTE-WiFi: The CA between LTE and WiFi is the most challenging issue in h-RATs. Obviously there are many differences between Licensed LTE and unlicensed WiFi which is also shared with other users. PHY/MAC issues by concurrently use of LTE and WiFi bands by a UE. Critical interference issues in UE receiver by co-existence of LTE and WiFi in adjacent or overlapping radio spectrums.

RRM related challenges: The main RRM challenges for h-RATs are the dynamic allocation of resources, interference management, and load-balancing of the traffic between the different aggregated resources. In order to do this the RRM needs to rely on measurements from both the base station and the users. However, different RATs provide different kind of measurements thus making RRM very complex. One way to solve this issue is by using the media independent handover functions defined in IEEE 802.21 (see A1), which provide (amongst other functionality) an abstraction layer to the measurements provided by different RATs. In the SOLDER project we plan to implement 802.21 for both LTE and WiFi, using a set of common measurements that allows the RRM to efficiently and dynamically aggregate traffic on both RATs. Moreover, other RRM challenge is the scheduler design that is resulting from the fact of having multiple CCs vs single CC. They are explained in short below:

- More feedback is required.
- Backwards compatibility requires that the design of the scheduler needs to take into account different UE types (e.g. Rel-8 and Rel-10).
- Using various bands for non-contiguous inter-band carrier aggregation will result in very different channel conditions in each – thus requiring different AMC/PC/MIMO for different CCs for a single UE (which adds more complexity also for the UE receiver).
- Additional procedures (CC activation/deactivation) at MAC layer are giving more degrees of freedom while allocating resources.

Other challenges to be addressed under RRM framework within CA application could also include:

- Hybrid scheduling mechanisms and dynamic resource allocation with application specific approach.
- Hybrid scheduling mechanisms for various UE types, e.g. combination of scheduling mechanisms according to UE mobility.
- Simple scheduling mechanisms for CA-capable and legacy Rel. 8 UEs Handover procedures among various LTE CCs and h-RAT CCs.
- Optimization algorithms for aggregated h-RAT resources (e.g. load balancing, handover optimization).

Therefore, SOLDER will investigate techniques for h-RAT aggregation, encompassing radio resource management techniques, architecture and design that should allow maximum backward compatibility with LTE.

5. Conclusions

This document presented a thorough state-of-the-art (SOTA) of CA technique as originally standardized by 3GPP body. The detailed analysis of the current research bibliography, patents and white papers revealed that the utilization of CA by UE moving in hetNets or h-RATs will be one of the most challenging problems in coming years. The SOTA provided the necessary overview of the challenges towards the realization of associated solutions. Furthermore, SOTA clearly showed us the current capabilities of CA and set also critical questions about potential application scenarios, use cases and requirements being the basis upon which SOLDER will be deployed. The SOTA analysed through the originally release of standardization of CA i.e., Rel-10 and expanded through Rel-12, the next version of LTE-A.

Considering the above, application scenarios in HetNets and h-RATs were presented highlighting the significance of CA in future wireless networks. More, in each of the presented scenario, a set of specific performance metrics were given. The applications that might CA be applied were given in a more broad sense showing that CA is not only a new technique but opens new horizons in wireless networks. However, all the scenarios presented above might be not implemented in the context of SOLDER project due to time limitations imposed by project durations.

Finally, open research issues which can be explored through SOLDER were analysed both for HetNets and h-RATs being a useful guide to our team. The combinations of technologies such as LTE, HSPA, WiFi, TVWS and the variation of spectrum bands in a contiguous or non-contiguous mode revealed the usefulness of CA in future wireless networks and its tremendously effect on the increase of UE's data rate.

SOLDER will not only investigate the performance of the proposed prototype in PHY and MAC-Layers in the context of HetNets and h-RAT scenarios concentrating on specific problems but also will be a useful tool to research engineers for the design CA applications in future wireless networks.

Appendix

A1. Background information on IEEE 802.21 MIH Protocol

The IEEE has standardized the 802.21 framework for media-independent handovers (MIH) which facilitates handover between heterogeneous access networks by exchanging information and defining commands and event triggers to assist in the handover decision making process. Specifically the standard consists of a framework that enables service continuity while a MN (Mobile Node) transitions between heterogeneous link-layer technologies. Also, it defines a new logical entity created there in called the media independent handover function (MIHF).

1.1 MIH (Media Independent Handover)

The MIH as defined in the IEEE 802.21-2008 specification [2] is a framework designed at IEEE to facilitate handover between heterogeneous network technologies. The architecture of the framework revolved around making relevant information available to both the MN and the network elements (NE). Depending on the available information, both the MN and NE can then take intelligent decision on handover to another network technology. The types of information include the presence of neighbouring networks, their link status and type, their characteristics, strength, QoS, and services that are supported. This information helps the core element of MIH, namely MIH User, to take decision about the necessity and timing of handover. Besides taking the responsibility of making decisions, MIHF also defines a communication model between the link layer and the upper layers of OSI protocol stack,
To improve handover performance in heterogeneous environments, IEEE decided to standardize a media-independent handover (MIH) framework under the name of 802.21.
It defines mechanisms for exchanging handover-related events, commands, and information. Handover initiation and handover preparation are covered but not the actual handover execution.

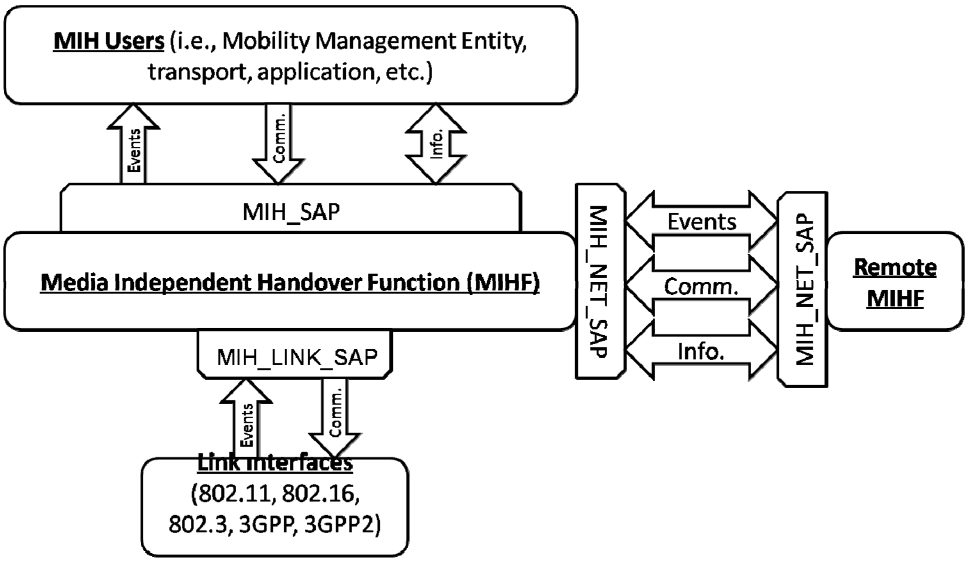

Figure 43: MIH Architecture.

1.2 MIHF (Media Independent Handover Function)

The MIHF is the central entity of the emerging IEEE 802.21 standard. Its primary roles are to facilitate handovers and provide intelligence to the network selector entity. The MIHF is located both in the mobile node (MN) and the network protocol stack and provides three types of services:

- Event services
- Command services
- Information services

These services help the MIH users maintaining service continuity, quality of service monitoring, battery life conservation, and network discovery and link selection.

1.3 Service Access Points (SAP)

SAPs are the link between the lower layers (1 and 2) from ISO model and higher layer(3+). There are three types of SAPs defined in the MIH protocol:

- MIH-SAP :the interface between MIH Users and the MIH Function.
- MIH_LINK_SAP :the interface between MIHF and the lower layers which is generic to all access technologies.
- MIH_NET_SAP :the interface defining the exchange of messages between MIH entities.

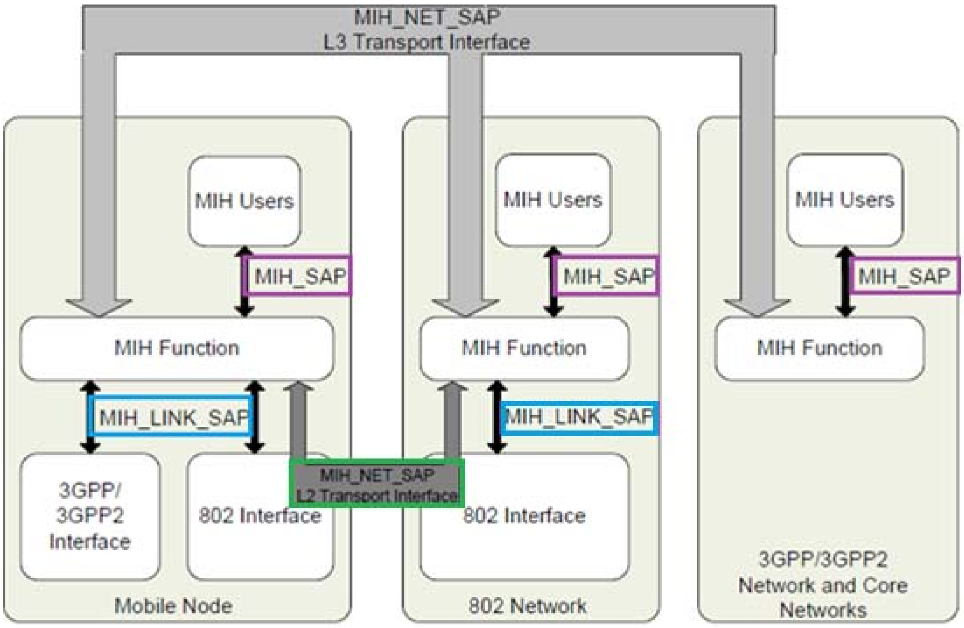

Figure 44: Types of SAP defined in MIH protocol.

List of Acronyms

Acronym	Meaning
3GPP	3rd Generation Partnership Project
4G	4th Generation
ABS	Almost Blank Subframes
AP	Access Point
BER	Bit Error Rate
BS	Base Station
CA	Carrier Aggregation
CC	Component Carrier
CIF	Carrier Indicator Field
CSI	Channel State Information
CoMP	Coordinated MultiPoint
CQI	Channel Quality Indicator
CR	Cognitive Radio
DSM	Dynamic Spectrum Sharing
DL	DownLink
HetNet	Heterogeneous Network
EAP-SIM	Extensible Authentication Protocol Subscriber Identity Module
eICIC	Evolved Intercell Interference Coordination
eNB	Evolved node B
E-UTRA	Evolved UMTS Terrestrial Radio Access
FBMC	Filter Bank MultiCarrier
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
HARQ	Hybrid Automatic Repeat Request
HSPA	High Speed Packet Access
IFFT	Inverse FFT
IP	Internet Protocol
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
LPN	Low Power Node
MAC	Media Access Control
MAI	Multiple Access Interference
MIMO	Multiple Input Multiple Output
MIH	Media Independent Handover
MT	Mobile Terminal
MU	Multi-User
NC-OFDM	Non Contiguous Orthogonal Frequency division multiplexing
MBB	Mobile BroadBand
NC	Non-Contiguous
NAS	Non-Access Stratum
OFDM	Orthogonal Frequency division multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio

PCC	Primary Component Carrier
PCell	Primary Cell
PDSCH	Physical Downlink Shared Channel
PHY	Physical Layer
PUSCH	Physical Uplink Shared Channel
PU	Primary User
RRC	Radio Resource Control
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RRH	Remote Radio Head
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
SAW	Surface Acoustic Wave
SAP	Service Access Point
SCC	Secondary Component Carrier
SCell	Secondary Cell
SINR	Signal-to-Interference- Plus-Noise Ratio (SINR)
SME	Spectrum Management Entity
SU	Secondary User
TA	Timing Advance
TDM	Time Division Multiplexing
TDD	Time Division Duplex
TVWS	TeleVision White Space
UCI	User Control Information
UE	User Equipment
UL	UpLink
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network

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