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Spectrum OverLay through aggregation
of heterogeneous DispERsed Bands

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SOLDER

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

D2.1
Application Scenarios and Use Cases

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Abstract

This document presents a state-of-the-art survey on aggregation technologies, defines the application scenarios and use cases that the SOLDER project is considering, and discusses some of the challenges and opportunities for novel research that the project aims to address through those application scenarios and use cases. It is noted that the application scenarios and use cases may be adjusted somewhat throughout the duration of the project, if it transpires that it is beneficial to do so.

Keywords

SOLDER, state-of-the-art, use cases, scenarios, applications, aggregation, carrier aggregation, spectrum aggregation, channel aggregation, link aggregation

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Executive Summary

The aims of this Deliverable are threefold. First, it aims to present in considerable detail the current state-of-the-art of aggregation solutions as a key part of cutting-edge wireless systems such as LTE-Advanced (LTE-A). Second, it aims to describe application scenarios and use cases that SOLDER will consider, based on the current licensed-LTE context, and extending that significantly to aggregation involving heterogeneous radio access technologies (h-RATs) and heterogeneous spectrum bands (HetBands). Third and finally, it aims to give a clear overview of open challenges and opportunities in spectrum aggregation, and how the SOLDER project address some of those challenges and opportunities through its various aggregation solutions.

A good starting place in assessing the current situation in terms of aggregation technology in mobile communications is the roadmap set by 3GPP in the releases of LTE-A, and specifically as standardized in Releases 10, 11 and 12 of LTE-A. Further, some particular developments aiming to assist aggregation among different RATs and different types of spectrum can point the way forward in terms of how resources and links might potentially be combined at various layers of the Open Systems Interconnection (OSI) reference model. This Deliverable provides an extensive state-of-the-art study, and learns from that in order to define new application scenarios and use cases for possible implementation of aggregation. The scenarios take into account the possibility of aggregating resources among a range of different spectrum types (licensed spectrum, unlicensed spectrum, and TV white space) and aggregating among various RATs, including LTE-A, WiFi, and HSPA, among others. A number of benefits are intended through these aggregation scenarios, such as increases in achieved throughput and capacity area-density, reductions in energy consumption, and improvements in various measures of QoS, among others.

Given that aggregation is a very promising technique that has received insufficient attention to-date in wireless communications research, there are a number of open issues that challenge the SOLDER project in achieving its goals. For example, in HetNets, challenges include transceiver designs to operate in different HetBands and band combinations for small-cell/macrocells, operation of UEs in uplink in intra- or inter-band aggregation scenarios, interference cancelation techniques for mitigation of inter-cell interference, and link adaptation issues when a PCell/SCell serving the UE in a HetNet compose a set of real challenging issues. Other problems which challenge the implementation of aggregation in HetNets are channel measurements and feedback reporting capabilities of UEs for selecting the appropriate carriers for aggregation.

In h-RATs, major challenges exist due to aggregation being among various systems, technologies and spectrum types, around issues such as integration of functionalities and elements to achieve aggregation at as low OSI layer as possible for efficiency reasons (this is a SOLDER aspiration). Moreover, the SOLDER project aims to focus on some specific problems at the PHY/MAC layer, including multi-RAT aggregation where the aggregation should not only aggregate various carriers but also should overcome the problem of aggregation of different access technologies. Other challenging issues specific to utilization of particular types of systems in h-RATs are being addressed, such as utilization of LTE in unlicensed spectrum (LTE-U), recently being labeled as “Licensed-Assisted Access” (LAA). This is being understood by industry as the aggregation of licensed LTE and LTE in unlicensed spectrum (LTE licensed always being present), where interference issues exist in the unlicensed spectrum. Similar interference issues exist regarding the aggregation of resources involving TV white space. Hence, in general, radio resource management challenges must be addressed in providing dynamic allocation of resources and interference management in such license-exempt contexts, and more generally in 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, comparable with landline communications. Several key technologies have played a significant role towards this end, among them Aggregation. Aggregation has been introduced in 3GPP Long-Term Evolution (LTE) since Release 10 (LTE-Advanced—LTE-A), and is also used in recent Wireless Local-Area Networking (WLAN) systems, sometimes referred as channel or carrier bundling. Aggregation consists of aggregating several carriers to achieve very large bandwidths, and has the supplementary benefit of facilitating the use of fragmented spectrum for wireless operators. As a result, aggregation is becoming a hot topic, both from research perspectives and from the commercial deployment standpoint.

The SOLDER project aims at generalizing aggregation to consider the possibility of aggregating several bands utilised by the same system or several types of systems, as well as heterogeneous types of bands such as licensed bands, unlicensed bands, and TV White Space (TVWS). SOLDER is trying to bring a pragmatic step towards flexible spectrum usage.

Aggregation can be seen as achieved at different layers, and therefore parts of the network, as illustrated by the Figure 1. Radio Access Network (RAN)-based aggregation is mainly considered through Carrier Aggregation (CA) technologies, perhaps assisted by novel MAC and PHY schemes. At higher layers, it could be considered as achieved through the use of multi-homing transport protocols, among other solutions.

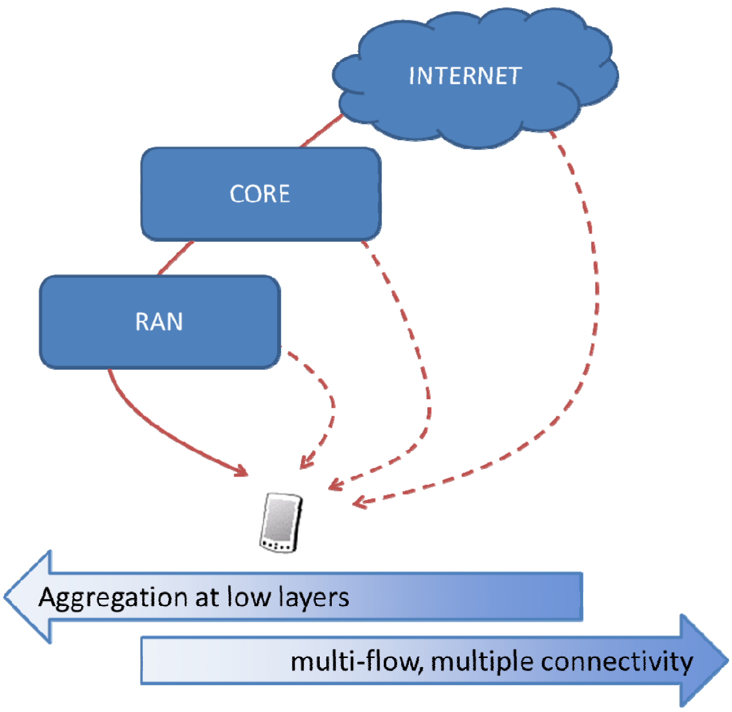

Figure 1: Options for aggregation at different levels in the network, and at different OSI layers.

For performance and efficiency reasons, SOLDER aims to achieve aggregation at a low a layer as possible, pushing towards aggregation at the PHY layer, although in reality in most scenarios the MAC layer will only be option for aggregation. In a small number of cases, aggregation at higher layers will be necessary as the solution. More specifically, in RANs, aggregation might be done at the PHY layer for contiguous spectrum resource or channels.

In non-contiguous aggregation cases it might still be done at the PHY layer through the RAT covering a wide bandwidth and “notching out” its interference to specific channels within that bandwidth, using advanced waveforms such as Filter-Bank Multi-Carrier (FBMC). Otherwise, non-contiguous aggregation seems likely to be handled by a MAC layer solution. Aggregation could be done at core network level through core data transport protocols, or using transport or application layer capabilities in the context of an IP-based network or collection of networks. Aggregation could also be done above the IP layer through multi-flow or multi-connectivity/homing techniques involving the split and merger of traffic in the Internet or at service end-points (the server and client/receiver).

As well as more generalized solutions such as alluded to above, SOLDER aims to strongly take into account particular scenarios based on releases and specifications of given standardization bodies and industrial proposals. Several advances in aggregation technology can be realised within such given constructs. The clearest example is the work on enhancing LTE-A, which is one key objective of SOLDER.

This Deliverable is structured as follows. Section 2 provides a state-of-the-art review on the topic of recent advances in aggregation in LTE-A, Heterogeneous Networks (HetNets) and Heterogeneous Radio Access Technologies (h-RATs). Some considerable detail on technical solutions is given, with a particular emphasis on solutions involving the lower layers. In particular, Section 2.1 provides a review of carrier aggregation in LTE-A, assuming primarily 3GPP Release 10 and later releases. Section 2.3 provides a review of carrier aggregation in HetNets. Both industrial and academic innovations are presented, i.e., patents and scientific publications. Similarly, Section 2.3 presents the state-of-the-art in h-RAT aggregation, covering a range of combinations of RATs and spectrum types. Although all layers are considered, Section 2.3 is quite strongly weighted to upper layers, as described above.

In Section 3, potential aggregation application scenarios and use cases for LTE-A, HetNets and h-RATs are presented, also providing a particular emphasis on the types of spectrum that are being aggregated. Section 4 provides a quick summary on some of the open issues and challenges that are identified in aggregation, touching on some of the interesting technical challenges and opportunities that SOLDER is working towards addressing. Finally, this Deliverable concludes in Section 5.

2. State-of-the-Art

The explosion of mobile data traffic, which is expected to grow by at least three orders of magnitude in the next decade, cannot be supported either by current radio technologies or by their envisioned enhancements. Conventional PHY techniques are no longer sufficient to increase 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 future wireless networks. More specifically, coordinated multipoint (CoMP) transmission and reception [2]-[3] 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 [4]. 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.

The 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 [5]. 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.

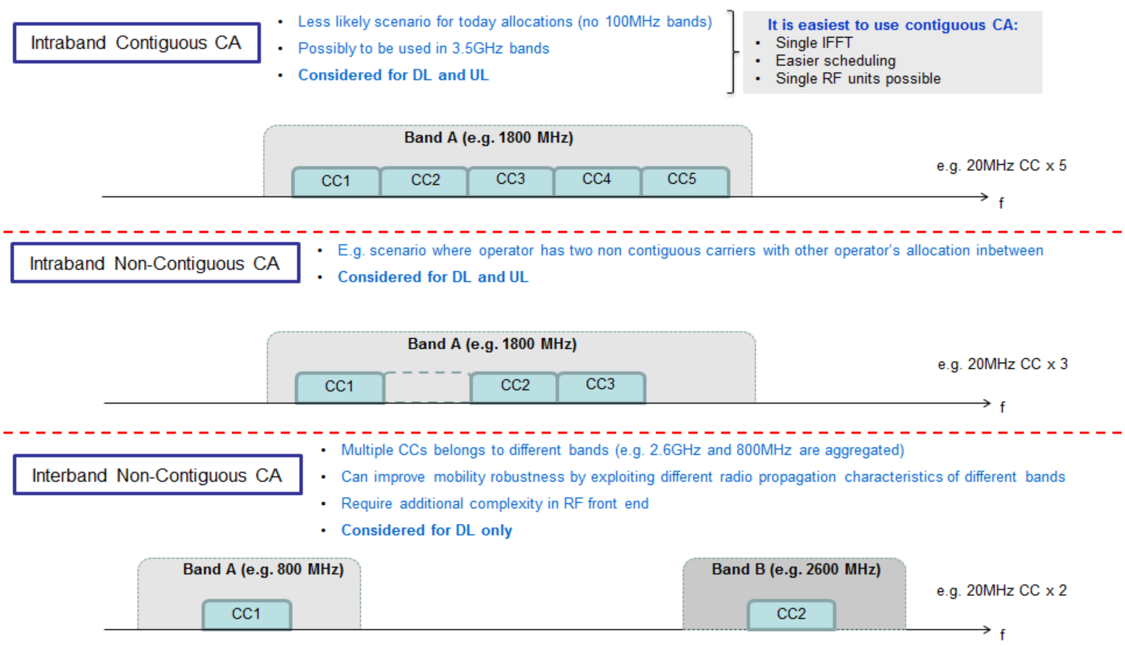

Figure 2: LTE-Advanced CA options.

2.1 Carrier Aggregation in 3GPP LTE-Advanced

Two types of CA approaches have been proposed in the context of 3GPP LTE-A, 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 [6], [7].

2.1.1 3GPP Release 10

The required spectral scaling for the future broadband wireless networks for both downlink (DL) and uplink (UL) 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 (CCs) is allowed. Each CC's bandwidth may have one of the following values: min=1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, and max.= 20 MHz.

For the intra-band and inter-band contiguous CA supported by LTE Rel-10, the combinations are listed in Table 1 and Table 2 below [8].

Table 1: Intra-band contiguous CA.

Band	E-UTRA Band	UL operating band BS receive / UE transmit FUL_low – FUL_high			DL operating band BS transmit / UE receive FDL_low – FDL_high			Duplex Mode
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 2: Inter-band non-contiguous CA.

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

2.1.2 3GPP Release 11

In LTE Rel-11, intra-band non-contiguous CA has been introduced (Reference: http://www.3gpp.org/specifications/releases/69-release-11)). In this case, the design solutions should care about the spurious emission and adjacent channel leakage.

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 [9] and [10].

2.1.3 RF Design

Figure 3 below depicts various Tx architectures for implementation for intra- inter- contiguous or non-contiguous CA scenarios [11]. The differences between the several architectures are the number of IFFT, DAC, mixer and PA receiver. For example, in contiguous CA scenario, the RF architecture has one PA. a zero-IF mixer, a wideband DAC and IFFT. For the intra-band non-contiguous (NC) CA, multiple IFFT and DAC are required and the difference is observed on the power combiner, that is employed either at IF or RF. Finally, for the inter-band CA, two different chains are used that can be combined, filtered before communicating to the antenna front-end.

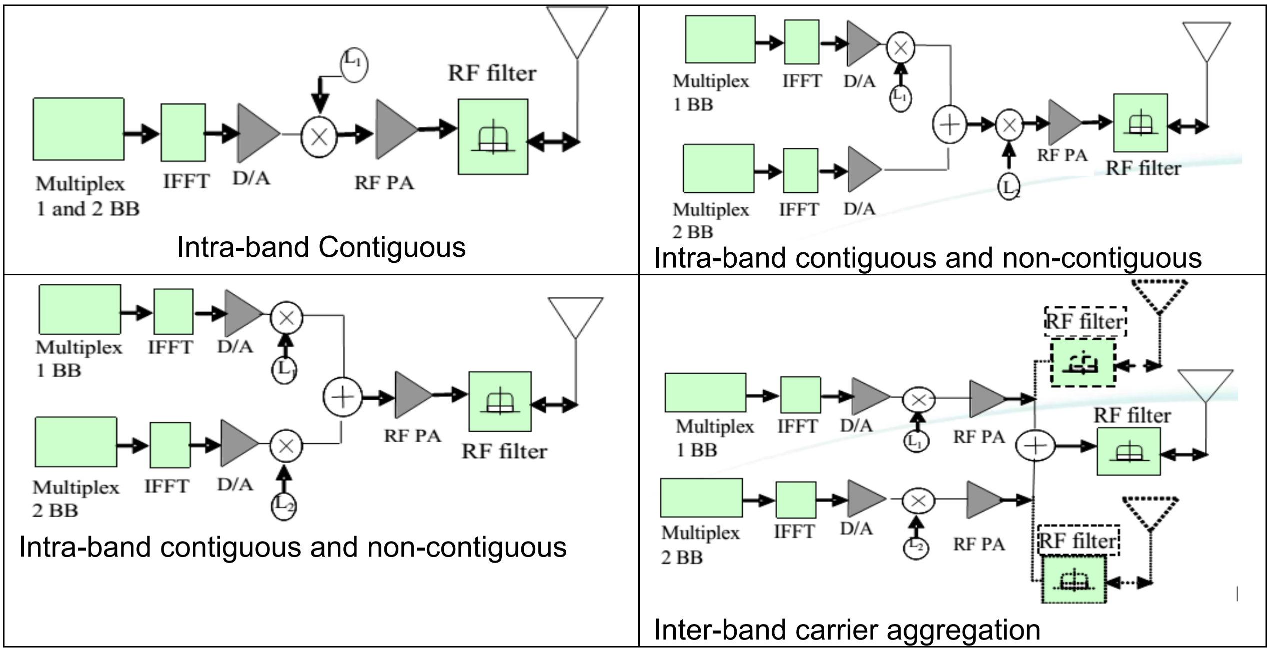

Figure 3: RF architectures according to 3GPP [11].

Thus, a good implementation example of such architectures can be found as a single-chip receiver architecture as shown in Figure 4 that includes a primary antenna and a secondary antenna [12]. This architecture is proposed relying on the inter-band CA scenario, wherein a first signal is received using a primary antenna and a second signal is received using a secondary antenna. For both RF chains, two different in-phase/quadrature (I/Q) signals are provided.

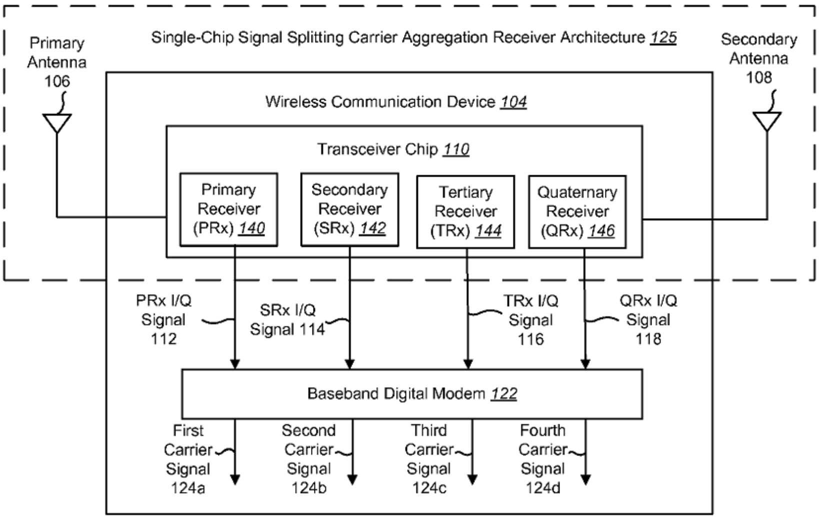

Figure 4: Single-chip receiver for CA [12].

All the above architectures are examples of CA receiver's designs without having the added functionality that could provide dynamic carrier aggregation using the Cognitive Radio (CR) principles. Moreover, other scenarios are not included like, tri-band CA, TDD-FDD CA and LTE with unlicensed. To this end, SOLDER project will investigate and propose the expansion in order to support aggregation between 3 bands, TDD-FDD and licensed with unlicensed (e.g. LTE-U). MIMO antenna implementation will be also an important aspect of our RF architecture. Regarding the dynamic CA provision as a challenge of SOLDER to address the heterogeneous channel statistics over multiple heterogeneous bands, spectrum sensing and activation/deactivation of the multiple RF chains will be provided. The RF architecture could combine a power detector added in the chains in order to build an algorithm to achieve the channel gain control on both on the transmitter and receiver chains, implementation of spectrum sensing technique in order to dynamically decide the number of aggregated carriers.

2.1.4 PHY Layer Design

Downlink channel quality is an important aspect for many PHY layer techniques in LTE and LTE-A system. In particular the channel quality is estimated at the UE and reported via the channel state information (CSI). For multiple CCs in CA, LTE Rel-10 adopts the same procedure; however, the existence of multiple CCs requires that Channel Quality Indicator (CQI) must be evaluated and reported back to BS for each CC individually when CA is active. To this end, one Physical Uplink Shared Channel (PUSCH) is utilized by the PCell and the overall control information for each CC is fed back to the BS via the PUCCH. The correct assignment of report information per CC at the BS is implemented through carrier indicator field (CIF) information bits [13].

Moreover, another important design for the PHY layer is the co-design of MIMO with CA. In particular, in [14] a device that provides MIMO with CA transmission is presented with two receivers. The key idea of this device to provide two MIMO CA receiver architectures, called first and second, that can separately forward two different CA receiver paths. However, this invention does not deal with issues related to codebook design, interference cancellation for heterogeneous fading channels and in addition to that it doesn't include any CR functionality for having knowledge about the channels' activities. Such a work would be one of the SOLDER's objectives.

2.1.5 MAC Layer Design

MAC layer is a very important layer for the CA technique since it behaves as a multiplexer for the aggregated CCs [13]. More specifically, the following processes are implemented at the MAC layer:

- Aggregation of different CCs and hence aggregation of data aggregation
- The separation of data and HARQ processes between different.

Figure 5 depicts the MAC Layer architecture with and without CA for comparison purposes.

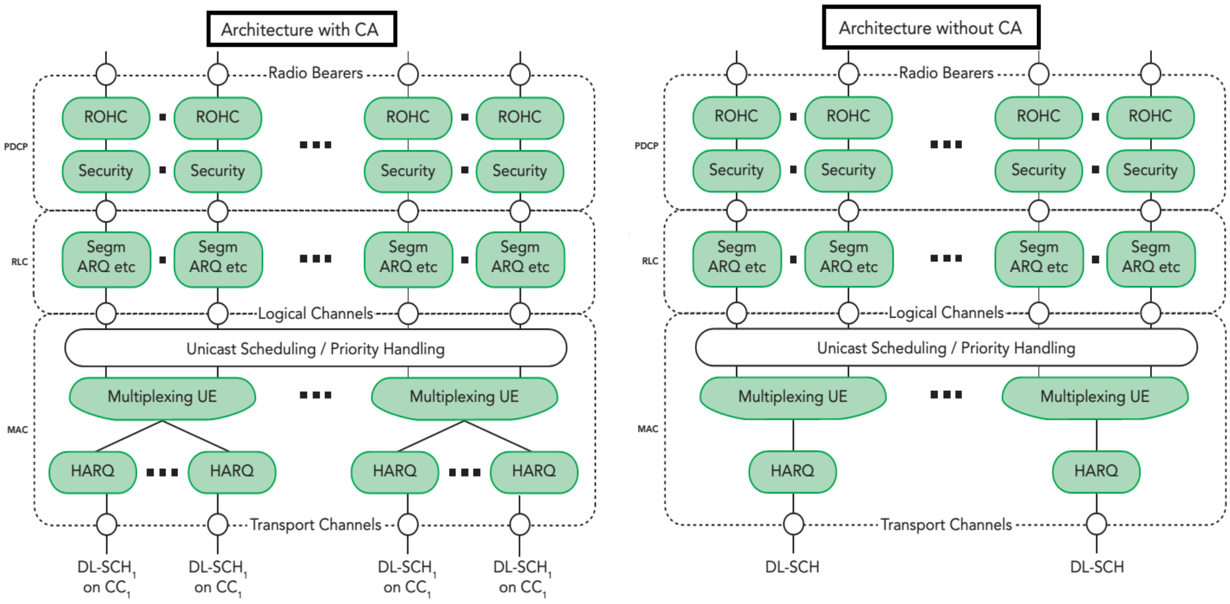

Figure 5 : Evolution of MAC for LTE-A CA [13].

Another important aspect of LTE-A (i.e. Rel.11) related to CA in heterogeneous networks (HetNets) is the multiple uplink Timing Advances (TAs). An indicative HetNet scenario is shown in Figure 6; macro-cells, which overlay small cells both simultaneously use the same CCs. In this use case, the PCell (i.e. macro BS) will provide bandwidth limited data transmission and control signalling in contrast to the SCell (i.e. micro BS) that will offer high data rates using higher frequencies. Due to the different locations of the two cells, the UE will experience different propagation delays and thereby, the TA cannot be homogeneous for all the CCs. The appropriate adaptation for having heterogeneous multiple TAs to provide CA in HetNets is really important.

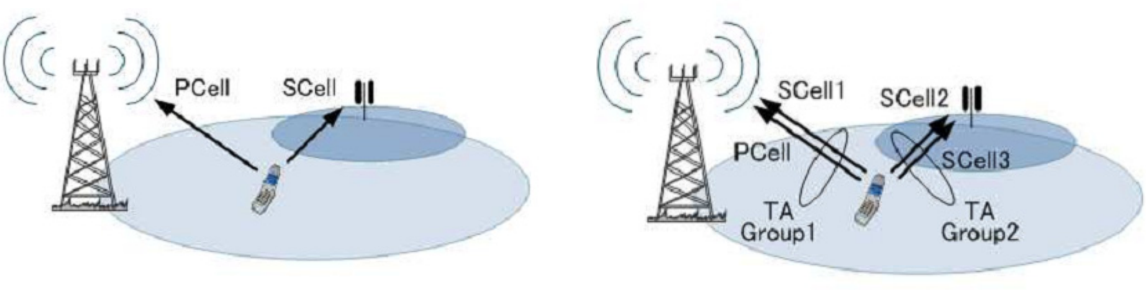

Figure 6: Single and multiple timing advance concepts [15], [16].

2.1.6 Radio Resource Management

2.1.6.1 Cell Configuration for Carrier Aggregation

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 7 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.

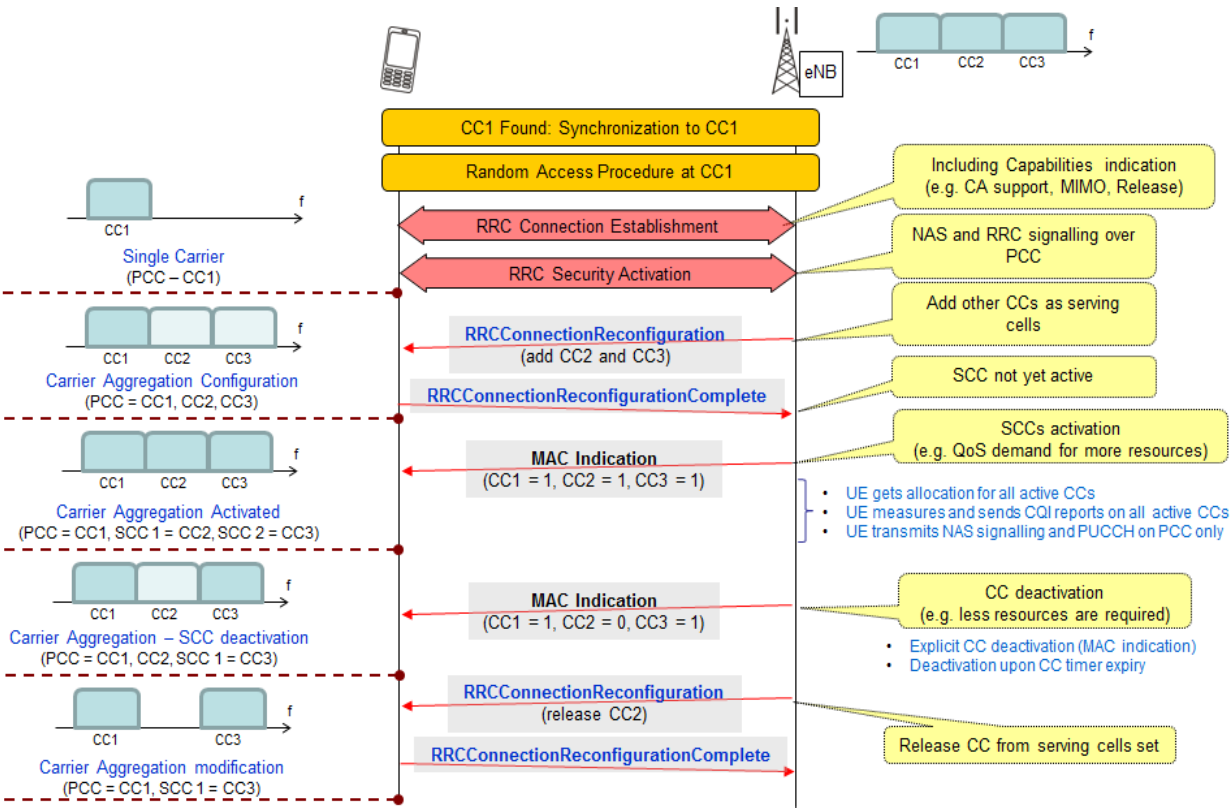

Figure 7: CA procedures: RRC control with CC activation and deactivation.

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.

2.1.6.2 Cross-Carrier Scheduling

Cross carrier scheduling encompasses the usage of control channel from the Primary cell to indicate the allocations for the Secondary cell. It has been introduced in 3GPP Rel. 10 and set as an optional UE feature. Figure 8 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 cell to know where exactly its data channels were scheduled. On the right side of the Figure, Cross carrier scheduling is used: the control channel of the Primary cell allocates data resources for both Primary and Secondary cell.

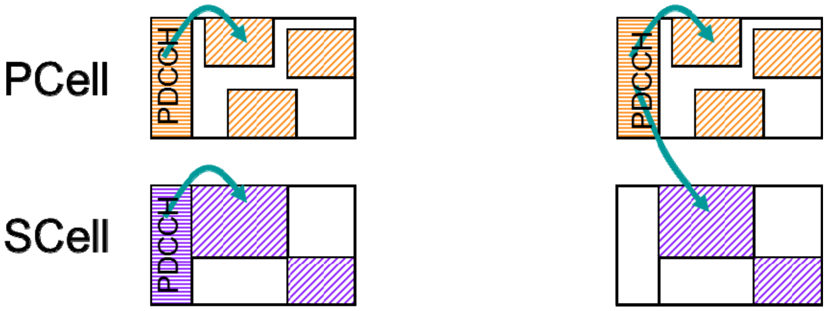

Figure 8: Illustration of cross carrier scheduling.

In addition to saving resources on the Secondary cell, Cross-carrier scheduling provides interference management for control channels. The goal is to reduce interference level in HetNets scenarios with CA where a combination of macro, small 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 interferences to CC1 of the pico cell. Thus, the pico cell uses CC2 for Physical Downlink Control Channel (PDCCH) messages to schedule PDSCH transmission on CC1.

2.1.7 Towards 5G Aggregation

Future 5G Physical layer shall face new issues in comparison to the current 4G solution. Among these challenges, opportunistic and dynamic spectrum access is of great importance [18]. Furthermore, 5G solution shall probably be more flexible in the way it performs the intra-band carrier aggregation [19]. Some companies use multiple radios to transmit/receive signals over different portions of the spectrums. Others suggest modulation and filtering of the aggregated spectra. These solutions are more expensive and less flexible than carrier aggregation with Physical Layer. Hence, one compelling reason to adopt new Physical layer in future standards may be the advantage that it has over OFDM.

The Physical layer of the 4G LTE is based on OFDM and its derivative for multiple access purposes (namely OFDMA and SC-FDMA which is a DFT-precoded OFDM). However OFDM based PHY layer is an undesirable solution for intra-band carrier aggregation. Indeed, OFDM is a poor fit because the filters associated with its synthesized subcarrier signals have relatively large side lobes and result in:

1) At the transmitter side: leakage of signal power among the bands of different users and/or services
2) At the 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 [20], these solutions are generally very limited in performance while they may add significant complexity to the transmitter and they will incur some loss in bandwidth efficiency.

The leakage, interference and synchronizations problems can be elegantly alleviated by the use of alternative multi-carriers Physical layer such as Universal Filtered Multicarrier (UFMC) [20], Generalized Multi Carrier (GFDM) [21] or FilterBank MultiCarrier (FBMC) [22].

In Universal Filtered Multi carrier (Figure 9) [20], the filtering operation is applied to a group of consecutive subcarriers instead of per subcarrier filtering. By using UFMC, the effect of sidelobe interference on the immediate adjacent subchannels can be significantly reduced.

This offers better inter carrier interference robustness and better suitability for fragmented spectrum operation. Moreover, UFMC technique uses shorter filter lengths compared to OFDM cyclic prefix lengths, which make it applicable for short bursts communication.

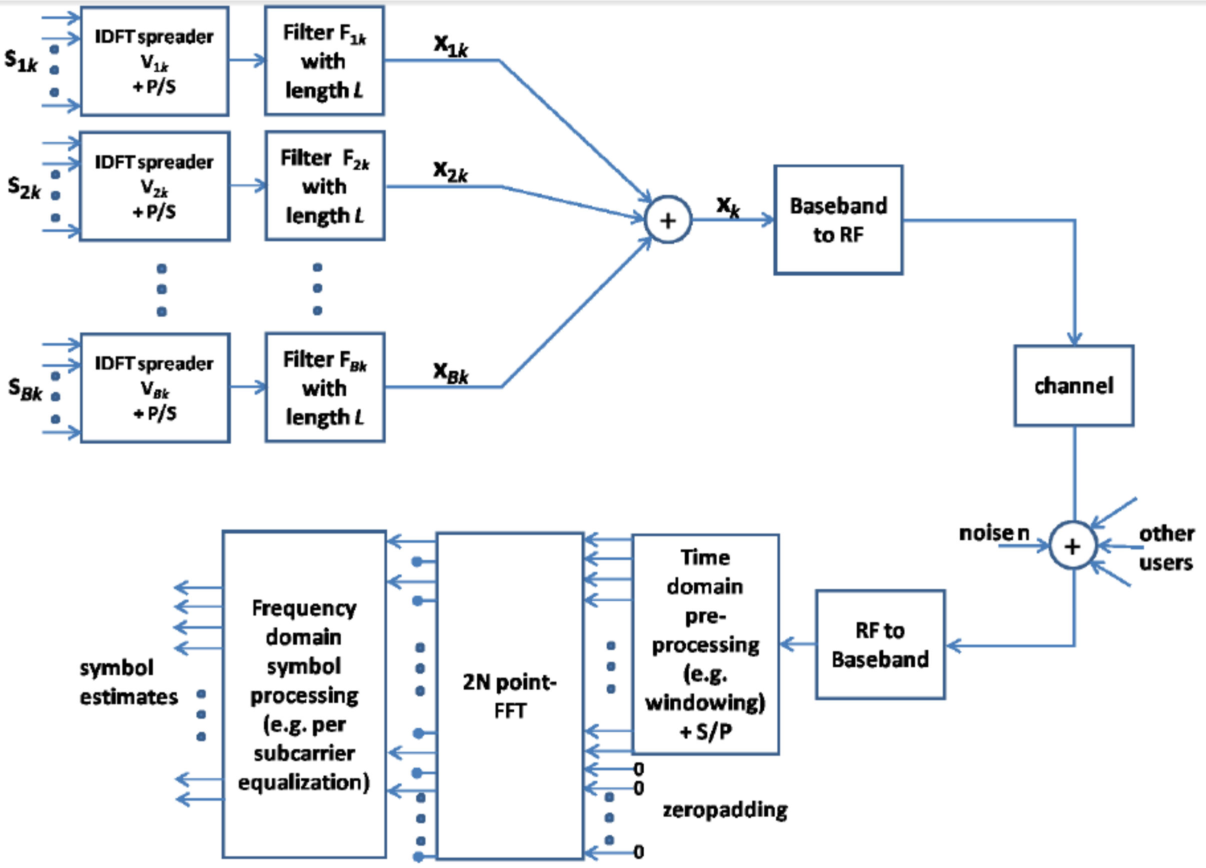

Figure 9: Block diagram of UFMC transceiver [23].

Generalized Frequency Division Multiplexing (GFDM) (Figure 10) [21] is based on the modulation of independent blocks, where each block consists of a number of subcarriers and subsymbols. The subcarriers are filtered with a prototype filter that is circularly shifted in time and frequency domain. This process reduces the out-of -band emissions, making fragmented spectrum and dynamic spectrum allocation feasible without severe interference in incumbent services or other users. The subcarrier filtering can result in non-orthogonal subcarriers and both inter-symbol interference and inter-carrier interference might arise. Nevertheless, efficient receiving techniques can eliminate this interference, i.e. a matched filter receiver with iterative interference cancellation can achieve the same symbol error rate performance as OFDM over different channel models.

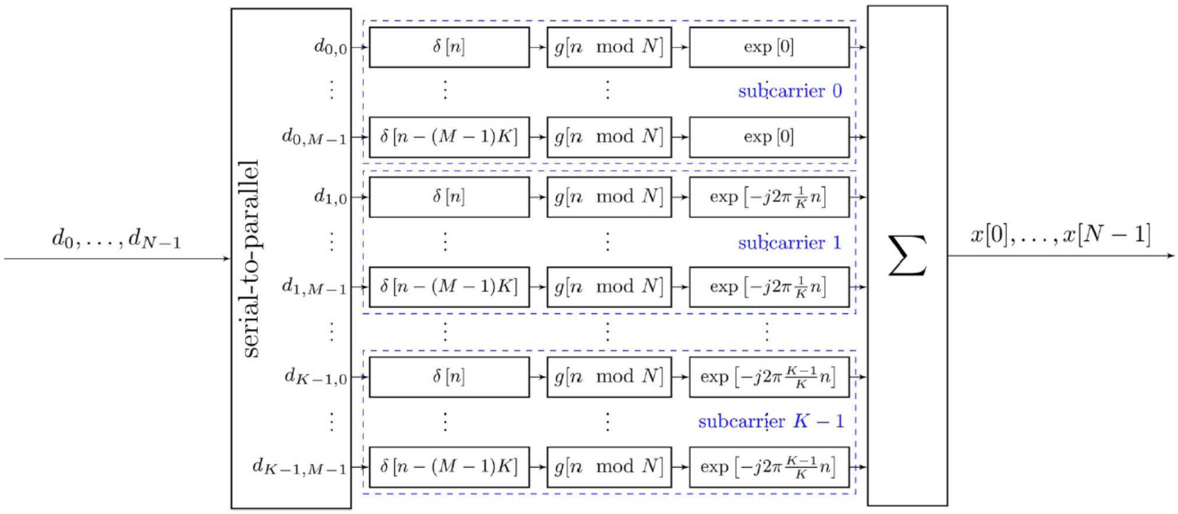

Figure 10: Block diagram of GFDM modulator [21].

Filter Bank Multi Carrier (FBMC) [22] applies a filtering functionality to each of the subcarriers (designed with arbitrarily small side lobes) in contrast to OFDM. So, with FBMC the side-lobes are much weaker and thus the interference and synchronization issues are by far less crucial than with OFDM. In FBMC, a set of parallel data symbols $s_k(t)$ are transmitted through a bank of modulated filters, as in Figure 11. 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.

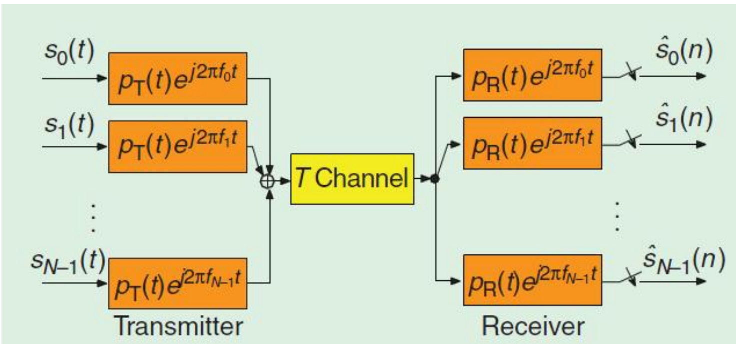

Figure 11: Block diagram of an FBMC transceiver [22].

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.

It is important to note that the inter-band carrier aggregation is not considered from a Physical layer point of view since it is not realistic fir the time being to process at the same time very distant frequency bands such as 800 MHz and 2.5 GHz.

2.2 Carrier Aggregation in HetNets

A HetNet comprises a different combination of macro-cells and smaller cells usually low-power nodes known as pico-cells and femto-cells (Figure 12) [24]-[29]. HetNets are based on the cooperative communications strategies where low power nodes are deployed in specific areas and collaborate each other in order to meet the demands of UE for high data rates or better signal reception [30], [31]. 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 [32]. Possible deployment of HetNets relies on the different frequencies that can be used with power control to enhance the data rates over heterogeneous channels to [33]. The differences on frequencies can be provided through the sub-band granularity and the resource blocks thereby. However, information feedback through the heterogeneous channels is required. On the other hand, interference coordination and timing adjustment between the UL/DL is also mandatory for taking benefits from the new HetNets technology.

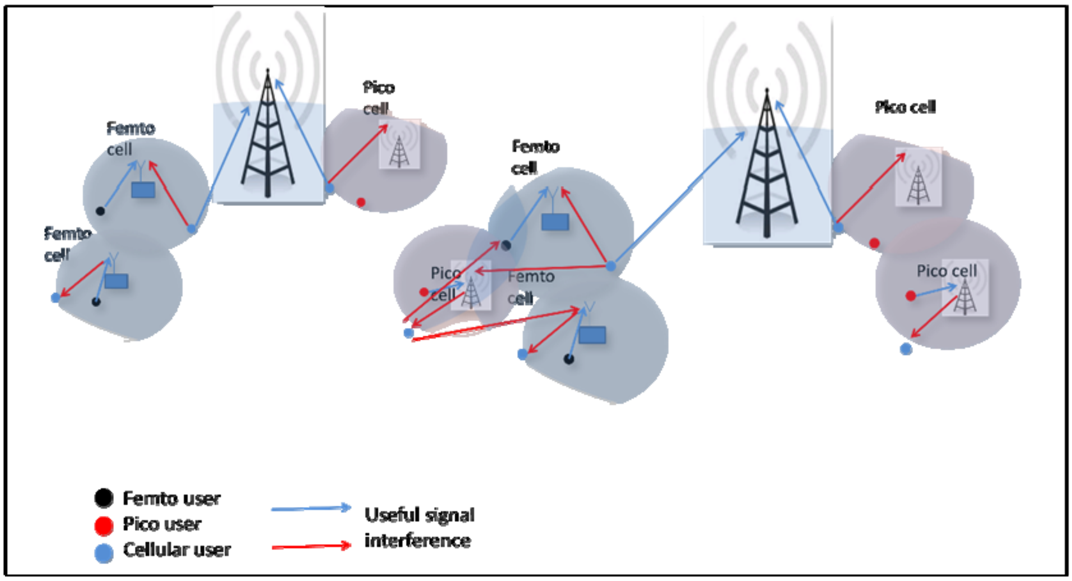

Figure 12: A two-tier HetNet.

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. For example, the Asia Pacific (APT700) MHz band that is widely used in the Asia Pacific region boosting enhanced services. Moreover, Rel-12 will support tri-band CA as an indicative application of CA in HetNets. Additional bands are also considered such as 3800-4200 MHz band.

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 [34]. In [34], the authors compared the differences between LTE FDD and TDD in control signalling and subframe timing. Also, they studied problems and propose solutions in the area of primary serving cell configuration and cross-carrier scheduling.. CA in higher bands (3.5/3.6 GHz) was indicated in [35], where a prototype five-CA technique for TD-LTE is referred.

Moreover, for HetNets deployment, wherein multiple resources of signals co-exist the interference mitigation plays an important role. For example, an important technique is the ICIC (Inter-cell Interference Coordination), which in Rel-10 was enhanced enabling interfering cells to configure subframes with almost no transmissions. This no transmission feature is 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 [36]. 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. [37]. 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 PHY Layer Design

2.2.2.1 RF Prototype

Searching for implementations that can provide CA in HetNets, we can find the solution above. In [38], a RF design prototype is presented for supporting MIMO and CA in devices using a single inverse FFT (IFFT) block. In this way, the complexity caused by FFT is reduced as well as to provide both intra and inter band CA (Figure 13). In this way, the Rx can support HetNets CA and it will be taken into account in SOLDER's designs.

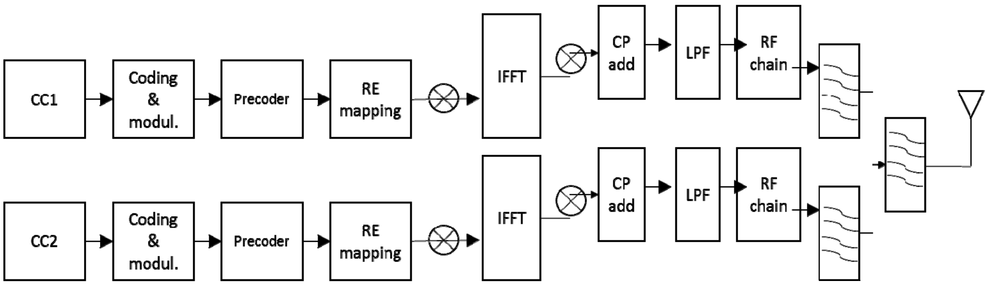

Figure 13: The RF design prototype proposed in [38].

Moreover, the authors in [39] present a single-chip receiver supporting both NC intra-band and inter-band CA with the capability to receive up to three carriers simultaneously (Figure 14). The latter one is considered as CA in HetNets RF design. Going into more detail, in [39] the authors propose two-component inter-band aggregation schemes where one band from one group is aggregated with one band from another group. In this way, the permutation is reduced of the aggregation schemes. The RF blocks, e.g. RF amplifiers can be adaptable in terms of frequencies. Moreover, it reduces the number of different required RF amplifiers.

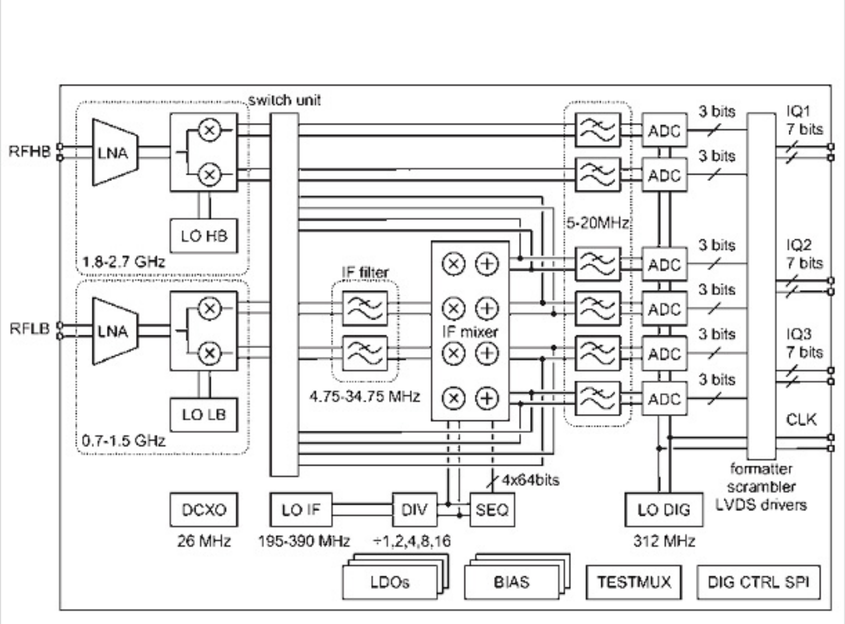

Figure 14: The receiver proposed in [39].

2.2.2.2 OFDM Schemes Supporting Carrier Aggregation

In CA systems, there is a high Peak-to-Average Power Ratio (PAPR). Therefore, PA at the transmitter should operate with sufficient power back-off to address large peaks. In [40], the authors reduce significantly the PAPR of the CA signal at the transmitter (no extra information at the receiver is transmitted) by proposing a two stages of Noise Shaping process . (Figure 15).

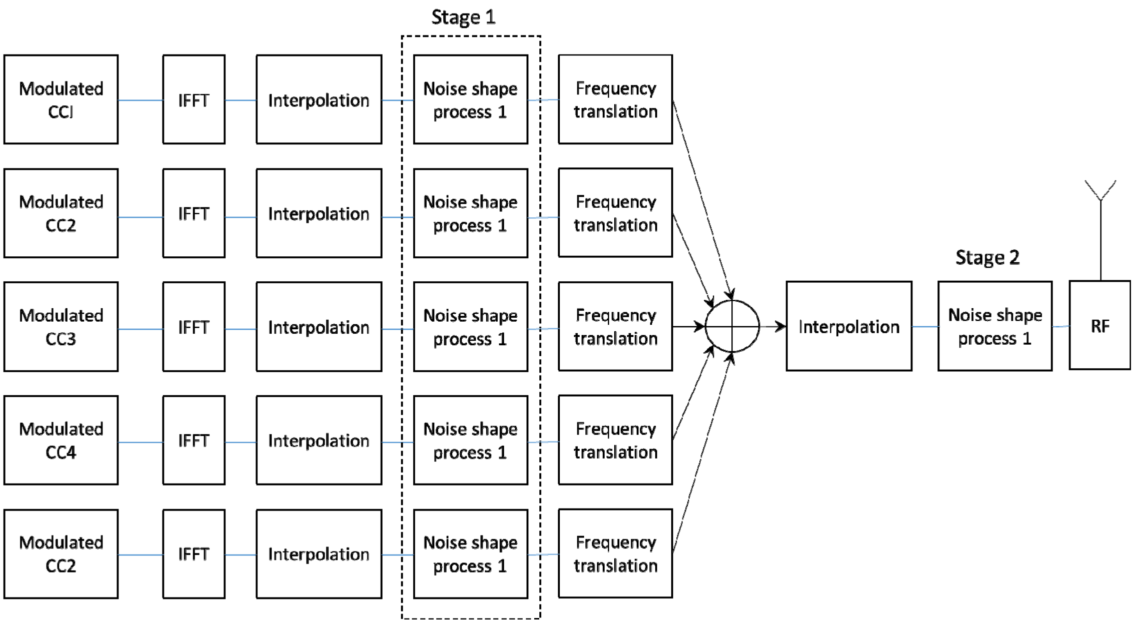

Figure 15: Transmitter architecture for N-x-OFDMA system [40].

A CA scheme is introduced in [41] for the case where two or more OFDM CC are transmitted and aggregated at the receiver.

In [42], the invention proposes a mechanism to aggregate different frequency resources continuous and non-continuous focusing on a technique to reduce the power amplifier metric in a LTE system. The method of transmitting modulation symbols on multiple component carriers is illustrated in Figure 16. Furthermore, the Non Contiguous Orthogonal Frequency division multiplexing (NC-OFDM) scheme has attracted considerable attention for CR systems and carrier aggregation [43], [44]. It is evident that the OFDM plays an important role in the CA system and adaptations or new designs are required. For example, the optimal tone selection for adapting the performance according to the delay and Doppler spreads of each user is proposed already in [45]. In SOLDER, we will investigate solutions for mitigating the different delay and Doppler shift for a bunch of subcarriers for one and multiple users that allocate aggregated component carriers.

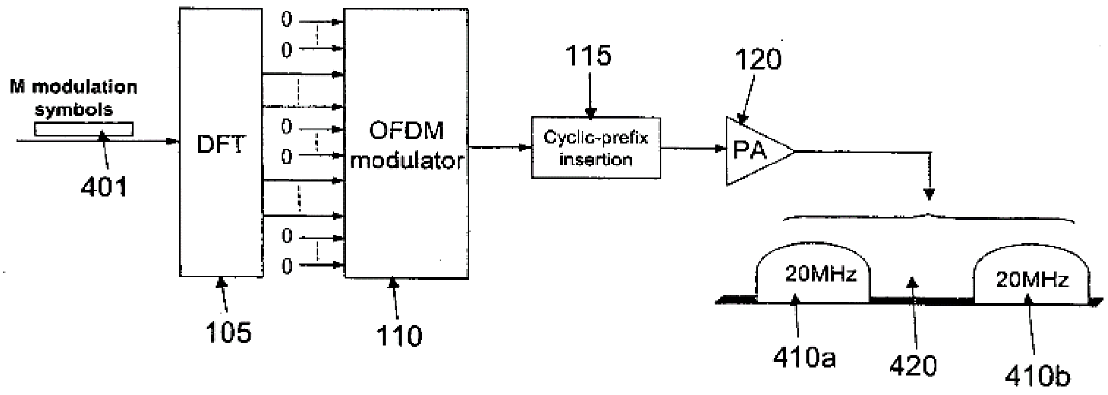

Figure 16: A modified OFDM scheme for CA in LTE-A systems [42].

2.2.2.3 Interference Cancellation

An important aspect of the HetNets and in a CA system implementation should be also revisited. This is important especially for the UE in HetNets that must cope with the interference from several heterogeneous resources. An Almost Blank Subframes (ABS) technique cannot solve this problem definitely. Base stations must transmit pilot signals to measure the quality of the channels, and cell acquisition signals on a predetermined schedule 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 [46]. To this end, the UE should always reports back information signals at the eNodeB. One possible approach for interference mitigation is to decode and suppress the interference from the useful signal. Such approach is non-linear and is called successive interference cancellation (SIC) [47], where decodes the strongest interfering signals are decoded and cancelled in a cascaded fashion. Some of the most important SIC techniques are presented in [48] such as:

- *Complexity Reduction Strategies based* on SIC methodology *Sliced-Processing Window Techniques.*
- *Zero forcing (ZF)*-SIC receivers in MIMO systems: *Complexity Reduced MIMO-SIC detectors.*
- *MIMO-SIC Detectors based on* cyclic redundancy check *(*CRC*) codes*.
- *Parallel SIC Implementation on MIMO-OFDM Systems.*
- *CCI Mitigation with MIMO-OFDM SIC Receivers*..

2.2.3 MAC Layer Design

2.2.3.1 Link Adaptation

Moreover, power control is another important technique for link adaptation provision. To this direction, the authors in [49] devise a method for UL power control signalling of a UE in conjunction with semi-persistent scheduling including CA. Operation of PDCCH configuration is used in to order to provide UL power control of a selected component carrier. Such a scheduling method can provide separate power control for each CC. However, the feedback mechanism using the PUSCH should provide minimisation of the UL control information as can be increased from the numbers of multiple CCs. Thereby, the minimization of signalling overhead is important for the CA in multiple CCs as also highlighted in [50]. Further to this topic, SOLDER will provide efficient link adaptation technique in order to provide the best possible adaptation of several channel measurements information as pointed out below.

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 [51]. 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 BS cannot easily adapt to fast time-domain channel variations. 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. This delay is getting cannot be ignored when the UE moves at high speed.. It Link adaptation performs better based on the measurements of the channel quality on a long-term. For estimation of the uplink channel conditions is not as straightforward at least in FDD, since there isn't y no reference signal transmitted by each UE [52]. The standard has however defined the Sounding Reference Signal (SRS) which could be used to sound the UL channels at the cost of overhead. On the other hand, for TDD systems, the estimation on uplink channel conditions are based from downlink measurements due to the reciprocity of the channels. [52]. In any case, the UE reports back to the BS CSI to inform the BS about the conditions of the channels. Then the BS adapts its transmission modulation and coding rate to the CSI received by the various UEs within its coverage area (or cell).

2.2.4 Radio Resource Management

RRM is a system level control in the eNodeB of radio resources such as user scheduling, link adaptation, handover, and transmit-power (see Figure 17) [53]. 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 SRSs 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.

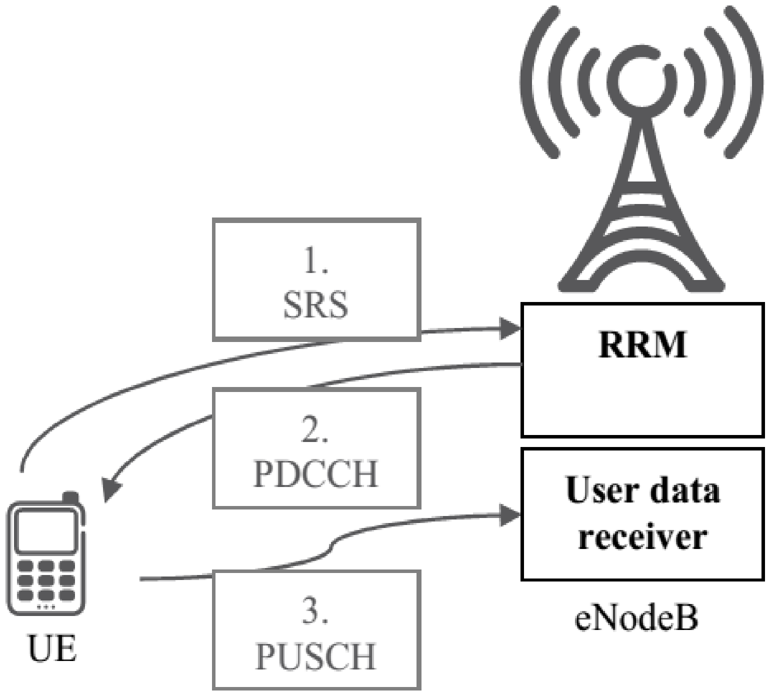

Figure 17: RRM and user data receiver in eNodeB [53].

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 [46].

- ***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 [46].
- ***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 [46].

2.2.4.1 Interference management in HetNets

In [54] a practical CA-based scheme is proposed to manage the interference between femtocells in a fair manner by assigning only one carrier to each femtocell based on inter-cell interference measurements. In [55] the authors proposed a new power scheme among femtocells to collaboratively adjust their transit powers and thus eliminate the overall intra-tier interference. 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 new method is proposed in [56] for mitigating the interference, by using a mapping function between the heterogeneous cells and the resources of the networks leading to a dynamic data scheduling.

2.2.5 Cognitive Radio Solutions for Aggregation in HetNets

Aggregation may be performed between the macro cell and small cells in different bands even using different types of spectrum. Moreover, aggregation in HetNets can often build on CR solutions in order to manage a number of considerations, some of which are covered above. Reference [57], for example, proposes a means to optimise the aggregation of channel opportunities in 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 [58]. 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 [59]. 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 [107].

2.3 Carrier Aggregation in h-RATs

Besides the HetNet concept, the cooperation of different RATs 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 [60]-[64].

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 [65]-[68]. Building more WiFi hot spots is significantly more cost efficient than network upgrades or small cells deployments. For example, the big number of

WiFi access points that are used everywhere corroborate the fact that dense networks are already deployed. Thus, relative initiatives from both IEEE 802.11 and 3GPP like the Extensible Authentication Protocol Subscriber Identity Module (EAP-SIM) protocol has been considered in order to provide WLAN APs for offloading cellular data [69]-[72].

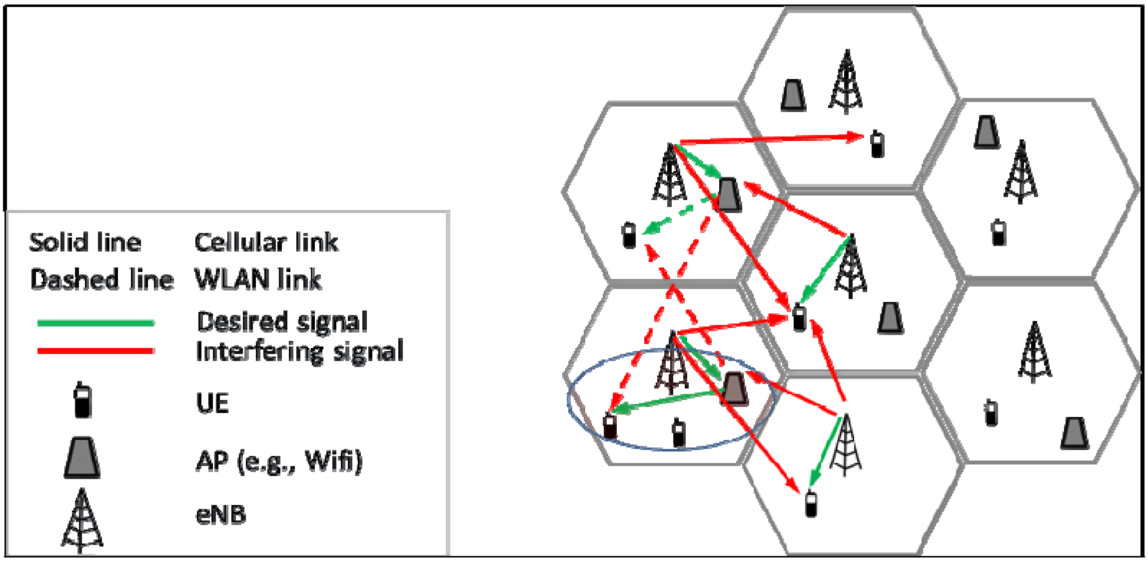

Figure 18: A multi-cell h-RAT network.

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 [73]. In general the cooperation of different radio technologies in terms of spectrum sharing, such as depicted in Figure 18, 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)

Another important issue for the aggregation of h-RATs is to identify and specify communication methods that can facilitate the aggregation of heterogeneous component carriers. Such a procedure can specify the aggregated heterogeneous access technologies and in which layer are aggregated, e.g. Layer 2 or below the Layer 2 in a protocol stack as highlighted in [73]. The appropriate physical channel resources organization and management should be incorporated into the overall solution corresponding to the heterogeneous access technologies and this is one of the scopes of SOLDER.

2.3.1 Multi-RAT Carrier Aggregation

Looking into the industrial scenarios of h-RATs aggregations, we can find out the multi-RAT CA with timing adjustment mechanism to be introduced in [74]. This is an interesting solution, wherein a common UL timing adjustment parameter value is estimated for UE transmissions in the multi-RAT communications networks. Multi-RAT can be assumed technologies that are managed by the operators, e.g. 3G and 4G. The required signalling is designed for all RATs that guarantee the connection with one or more UEs. Notably, a common timing adjustment can be also used for the DL reducing thereby the overhead. SOLDER project will look into solutions that can provide efficient multi-RAT CA in a cross-layer manner, wherein the efficient PHY/MAC layer can be adjusted through important signalling information.

The inventors in [75]. proposed also new protocols and entities, e.g. the intra-networking spectrum management entity, the Dynamic Spectrum Sharing (DSS) measurement control and signalling in order to make decisions on the available spectrum. In SOLDER, the management of resource blocks for multi-RAT technologies that are under control or are not under the control of the operators will be investigated and proposed with several kind of solutions at MAC layer.

Moreover, in [76] a multi-RAT CA for WWANs assisted by WLANs is proposed (Figure 19), where the services are mapped dynamically between the WWAN radio and the WLAN radio, according to the service requirements and the network conditions. In the proposed mulit-RAT scheme, WiFi radios are considered as virtual carriers by the operator’s access network. In this way, the multi-RAT CA could be led by different network traffic conditions though the dynamic spectrum aggregation among different technologies like 2G, 3G and 4G and this will be addressed in SOLDER.

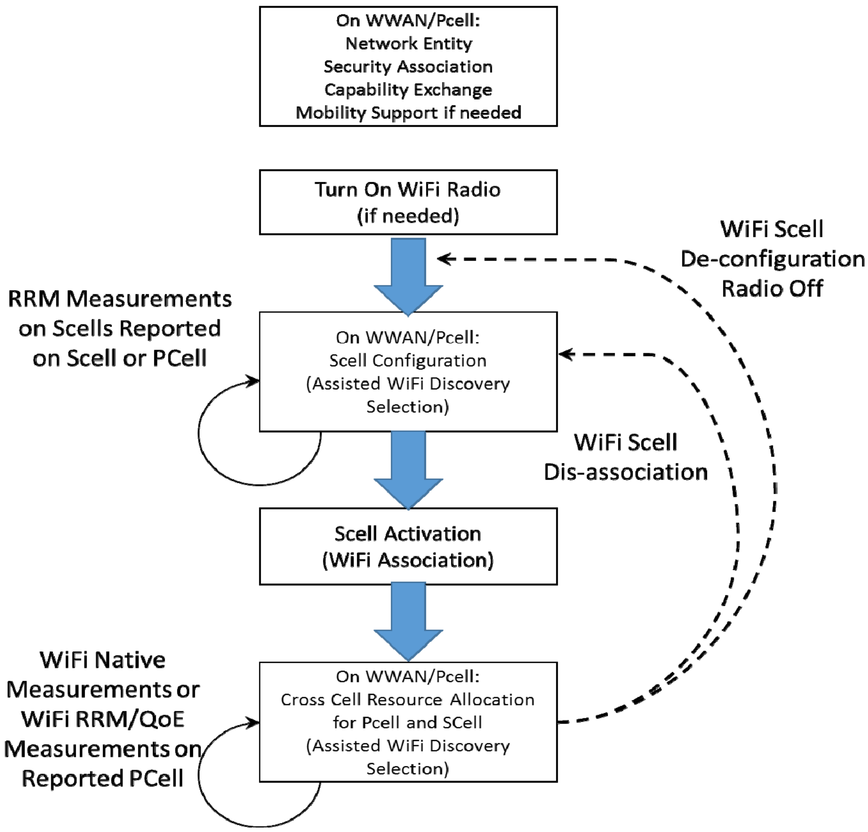

Figure 19: multi-RAT WWAN and WLAN aggregation [76].

2.3.2 LTE and WiFi

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 [77].

WiFi technology as defined by the family of IEEE 802.11 standards is the most popular technology that makes use of the unlicensed ISM bands. In fact most mobile phones today (especially smartphones) support both cellular and WiFi technology, making it particularly interesting to combine the two. WiFi offloading for example, uses WiFi technology for delivering data originally targeted for cellular networks and is considered a cost-efficient, easy to deploy solution for congested mobile networks [61]. Another effort to combine WiFi and LTE and other capabilities has been taken by the small cell forum, through the promotion of integrated WiFi Access Points with Femto-cells [65]. 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 [69], [70]. The 3GPP based Enhanced Generic Access Network [71] architecture couples WiFi and cellular networks even tighter as it specifies rerouting of cellular network signalling through Wi-Fi access networks. However, today no solution of real aggregation of WiFi and cellular traffic exists, where both technologies could be used in parallel.

In SOLDER we will consider the following two different approaches to aggregation of LTE and WiFi.

2.3.2.1 Aggregation using IEEE 802.21

The IEEE 802.21 standard (see Annex A) 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 (Layer 2 or even above IP). An overview of the basic services provided by the standard is given in Annex A.

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 [78]. 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 [79]. Some more examples on the use of 802.21 are given in [80]-[83].

2.3.3 LTE in Unlicensed Spectrum

Recently there has been a strong interest by both equipment manufacturers and operators to extend the use of LTE directly to unlicensed bands [84], [85], [86], [87]. This activity is also referred to as LTE-U and it is currently a study item in 3GPP Rel. 13 [88]. The main motivation is to complement existing licensed bands with these unlicensed bands to serve the increased traffic demands. Potential benefits include a more efficient use of the spectrum and a single network for both systems. The main use cases are operator-deployed small cells in indoor or outdoor hotspots. However, communications equipment operating in these unlicensed bands must tolerate any interference generated by ISM equipment and at the same time must not cause harmful interference to other ISM equipment. However, today LTE is not designed to do this and therefore the main challenge is to adapted LTE for this operation. One possible solution is the design of a special carrier type for operation in unlicensed spectrum that is being aggregated with a classical licensed LTE carrier responsible for keeping connectivity and control plane signalling.

2.3.4 LTE in TV White Space

TVWS is an excellent opportunity for many types of systems to obtain extra spectrum/capacity on an opportunistic basis, including potentially in cellular contexts such as depicted in Figure 20. 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 [89]-[94].

From the CA principle, 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. Both FDD and TDD are considered important since all operators provide both access modes.

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.

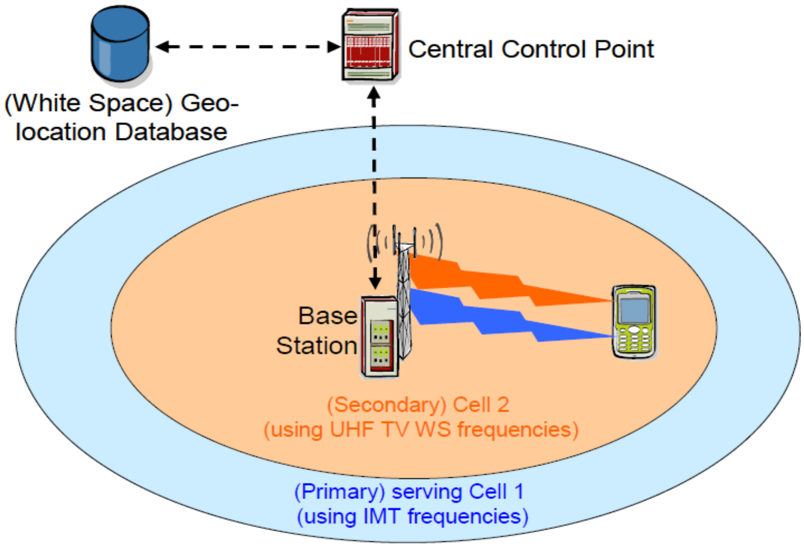

Figure 20: Carrier Aggregation of LTE band and UHF TV band.

The work in [95] 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 21). 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 [89], [90]), 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.

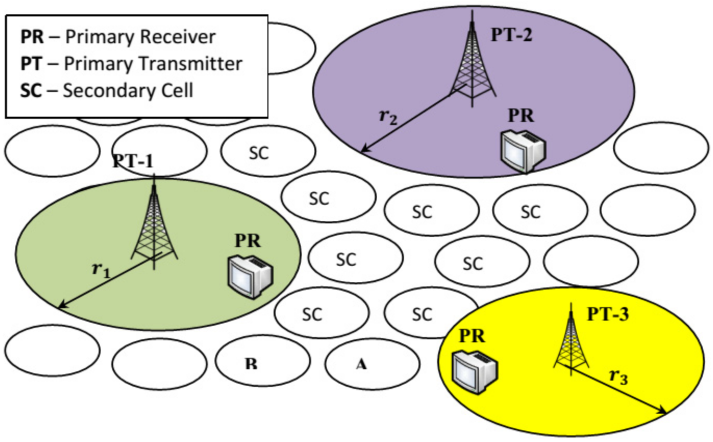

Figure 21: Coexistence of primary and secondary cellular networks [95]

A key area of recent progress in TVWS is the work at the UK regulator Ofcom to develop a framework for TVWS [91]-[93]. The Ofcom framework is far more “nuanced” than the US case. It encompasses the ability to vary the maximum allowed powers for white space devices, and for white space devices to comply with one of five possible spectrum mask class characteristics ranging from extremely challenging to relatively relaxed. The result of this is that white space devices under the UK framework can be used in vastly more locations than is the case under the US rules, and can still operate under a less challenging spectrum mask class even if their mask performance is not exceptionally good. It is noted that the key conformance testing-related aspects of the UK framework are captured in the ETSI standard 301 598 [94], thereby presenting a path to harmonisation of aspects of the framework across the EU level.

The details of TVWS operation in the EU/UK case are explained in Chapter 14 of reference [96]. A broad representation of the interactions of the white space devices with the various elements in the UK’s white spaces framework is given in Figure 22. Simplifying the description of this greatly for the purpose of this report, the master white space device must first query a “database of databases” hosted at Ofcom, and from the response of that select a geo-location database that it will use to obtain information on allowed TV channels and powers (Equivalent Isotropic Radiated Power, EIRP). The master device must then query the geo-location database that it chooses, sending information about itself to the database such as on its complying transmission mask quality (“Class”), its location and height above ground level, and other aspects such as is serial number and model ID. The geolocation database, which in the UK case has knowledge of the locations of TV receivers through the UK’s TV licensing system, and is aware of the locations of TV transmitters and propagation characteristics across the country, will calculate the highest power (EIRP) that the device can use, individually in each TV channel, causing less than a given allowable interference power to any TV receiver in the area. It then sends this information on allowed channels and maximum powers to the master white space device. The master white space device must decide on which channel(s) and power(s) it will use, inform the database, wait for confirmation from the database, then can start transmitting on those channels and powers.

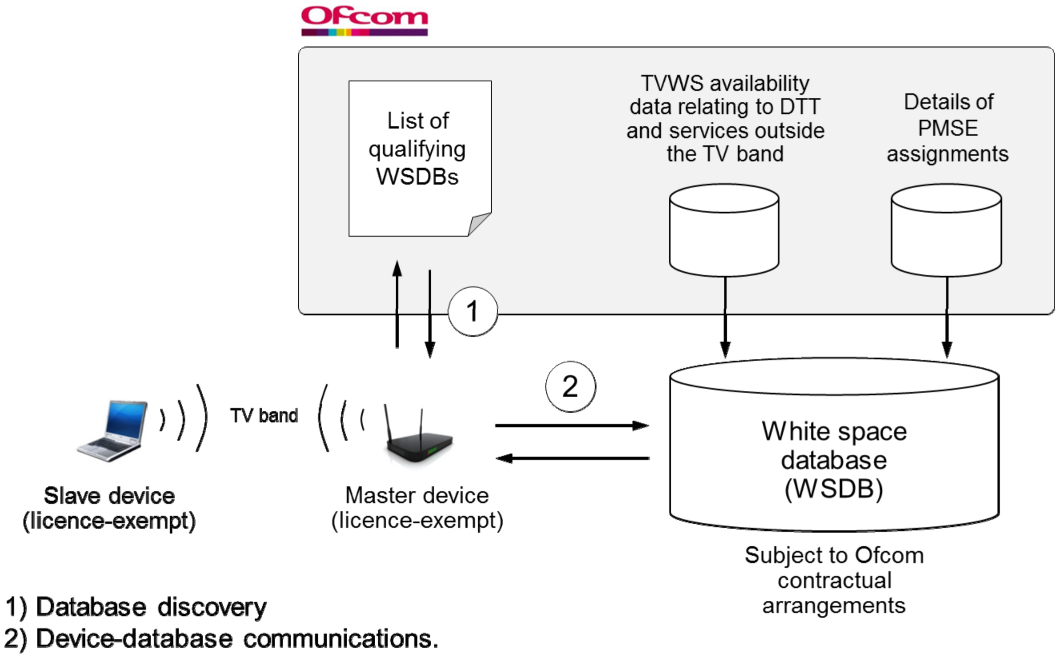

Figure 22: A high-level depiction of communication of white space devices with the various elements in the UK's TV White Spaces Framework [92].

The master device also, on behalf of "slave" devices (which are not Internet-connected), obtains "generic" slave parameters and "specific" slave parameters. Generic slave parameters are those that the slave devices can use without providing information on their location to the master device, i.e., they are the worst case lowest power for any location in the coverage area of the master (hence, taking into account any location that the slave could possibly be when it hears the broadcast of generic parameters from the master). The master forwards those generic parameters to the slave devices by broadcasting them. The slave device upon hearing the generic parameters, can then communicate with the master using those parameters and send its characteristics (location, height, etc.) to the master, whereby the master will then query the database for specific slave parameters based on this information. Spectrum slave parameters are linked to the exact location of the slave, and imply far high allowed maximum powers than the generic slave parameters.

3. Application Scenarios and Use Cases

This section discusses SOLDER application scenarios and use cases for aggregation, as summarised in Annex B of this Deliverable. 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 over the duration of the project, both within the project and based on external stimuli/developments.

3.1 Licensed LTE

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

3.1.1 Baseline LTE Aggregation Scenarios

We consider in this scenario the default scenario has originally motivated by 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.

Regarding motivation for such a scenario, it is noted that it 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).

This scenario is quite generic as it encompasses both homogeneous and heterogeneous deployments (when cells are overlaid: a macro cells being an umbrella to multiple small cells). In context of HetNets, CA provides also an easy mean for inter-cell interference management.

Finally, in terms of traffic served, in this scenario the carrier aggregation could be used to provide the same types of service as LTE without carrier aggregation, although with better availability, throughout and QoS thanks to the above mentioned benefits of CA.

3.1.2 TDD/FDD Aggregation Scenarios

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.. The main objective of this working item is to specify deployment scenarios for joint operation on FDD and TDD spectrum. Furthermore, that joint FDD/TDD operation must be provide by the network and UE. Some of the deployment scenarios for the FDD-TDD CA are described below:

- FDD+TDD co-located, and FDD+TDD non-co-located with ideal backhaul.
- FDD+TDD non-co-located with non-ideal backhaul.

The UE must be also able to operate as follows:

- To have access to both legacy FDD and legacy TDD in single mode carriers,
- To receive FDD and TDD carriers simultaneously (i.e. DL aggregation),
- To transmit simultaneously on FDD and TDD (i.e. UL aggregation)
- To transmit and receive simultaneously on FDD and TDD (i.e. full duplex)

However, since all the above required functionalities are expected to increase the complexity and the energy consumption of the UE, it is expected to provide the best possible design of the UE side for supporting the TDD-FDD CA. RF and baseband capabilities at the UE are among the requirements among the needs for this scenario. High-layer specification changes in order to fully support the FDD+TDD joint operation is also required. To this end, SOLDER is considered as an important application scenario for HetNets deployment providing solutions for adapting the layer functionality targeting to the following results:

- Frame adaptation for the DL/UL aggregation transmission
- Throughput analysis for possible scenarios

It is evident that the FDD+TDD scenarios will be one of potential application scenarios in future years, e.g. big companies such as NSN, Huawei and Vodafone have already demonstrated FDD+TDD scenarios in LTE-A CA technology. Therefore, SOLDER application scenarios could expand the use of more FDD+TDD carriers and find the optimum combination that improves dramatically the data rate speed.

3.1.3 Aggregation Among Multiple Operators

In addition to more conventional infrastructure-based scenarios, SOLDER is aspiring towards aggregation of capacity in challenging cases such as among the spectrum of multiple operators. Further, it is also touching on aspects such as ad-hoc and device-to-device (D2D) communications.

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 [97].

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 provisioning, 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)

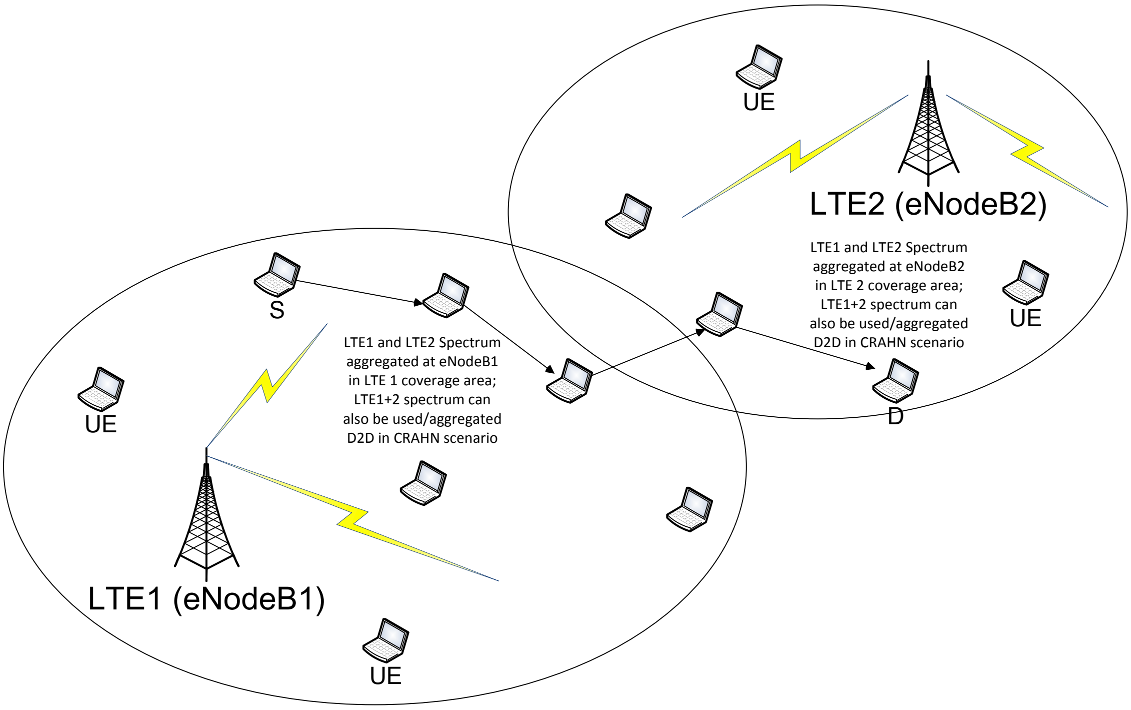

Figure 23: The multi-hop wireless cognitive radio ad-hoc network deployment scenario involving spectrum aggregation between a licensed LTE and licensed LTE system.

Figure 23 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

3.1.4 Towards 5G Aggregation

SOLDER strives to perform intra-band spectrum aggregation at the lowest possible layer considering a 5G candidate waveform. It is noted again that in the case of aggregation of two or possibly more carriers, operating intra-band, contiguously or non-contiguously using the same duplex method and in a single user point to point communication, CA could be achieved at the PHY layer by modifying current 4G PHY. For this particular scenario, we consider FBMC waveform only because we believe that it is the most mature technology compared to GFDM or UFMC: FBMC has been implemented for example in [22] and [98].

We expect that FBMC helps, when compared to other types of multicarrier communications such as OFDM schemes considered for 5G, in the following ways:

Increasing the spectral efficiency/thoughput: cyclic prefix required for OFDM can be seen as redundant information to be transmitted, whereas properly designed FBMC waveform does not require any cyclic prefix.

- Improving opportunistic spectrum access: current LTE carrier aggregation requires duplicating PHY layers: for instance, an intra-band non-contiguous carrier aggregation composed of two CC required two PHY layers. Excellent FBMC spectrum occupancy capabilities (low spectrum leakage) avoid duplication since the same PHY layer addresses fragmented spectrum without (or very limited) disturbance of already existing communications. Furthermore, FBMC is inherently highly efficient to exploit heavily fragmented spectrum.

- Improving energy efficiency: in order to benefit from the full potential of spectral containment of FBMC signal, it is necessary to linearize the power amplifier and to reduce the PAPR of the signal at the time. The joint use of linearization technique and PAPR reduction has the great advantage of reducing the power consumption of the power amplifier, implying an improvement of the energy efficiency.

3.2 Heterogeneous RATs and Bands

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

Aggregation at the IP layer and above (service aggregation)[1]**:** 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 [99].

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 24).

Heterogeneous radio access technologies (h-RATs) is an emerging research field with several applications. The concept is based on utilizing the spectrum that is not occupied by any UE working in kind of wireless systems. Different technologies can be connected using multiple wireless modems in a single device [100]. . Three indicative examples where carrier aggregation scenarios are deployed in various RATs is illustrated in Figure 24. The scenarios show aggregation in mixed licensed (LTE, HSPA, GSM) and unlicensed (WiFi) bands.

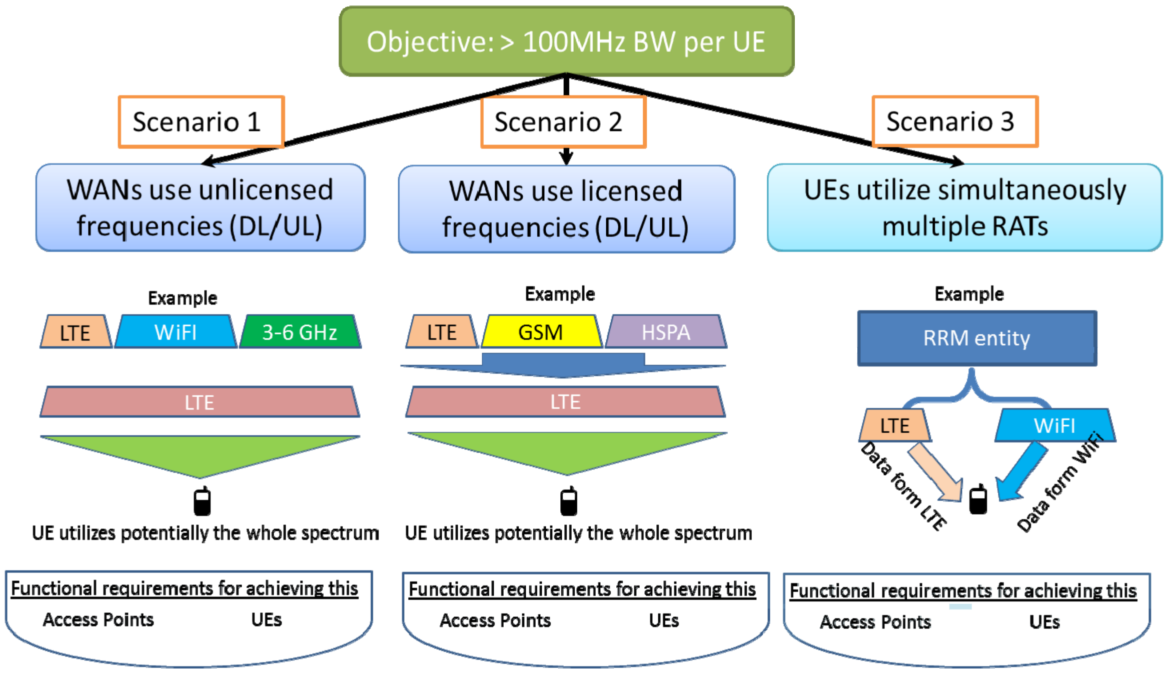

Figure 24: Basic aggregation scenarios in various RATs.

3.2.1 Licensed Spectrum with Licensed Spectrum Aggregation Scenarios

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

[1] To be considered as a last resort of aggregation in challenging h-RAT scenarios.

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 Multi-RAT Scenarios in LTE-A

The coexistence of multiple RATs introduces many operational coordination problems for network operators (see Figure 25). The co-existence of various RATs (i.e. 2G/3G/4G) requires several new adaptations in terms of coordination across the RATs in order to achieve better Quality of Experience (QoE), efficient resource usage and higher network capacity. 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.

Figure 25: Multi-RAT macro-macro & macro-pico scenario deployment.

Multi-RAT CA will be considered among the different access technologies that mobile operator can have under control and maintenance offering data services. Traffic can be mapped into the particular spectrum allocation and aggregation [101]. Dynamic Spectrum

Management (DSM) is essential technology to this end without significant architectural making them available as backward compatible to the previous and the next generation systems [102]. The DSM for CA in multi-RAT will be designed to provide spectrum overlay among the different systems. For example, overlaying the channels of system X on system Y can be practically provided either per subcarrier basis or PRB (Physical Resource Block) basis supporting better spectrum utilization. Moreover, spectrum utilization for the best possible CA in multi-RAT systems the bands allocation per best-effort UEs can be assumed. Control signaling overhead for each of the use cases to this application scenario will be measured and calculated. Energy consumption and efficiency might be also considered as QoS criteria for the CA approach. Optimization, near optimal and suboptimal of CA schemes will be devised and investigated. A multi-cell OFDMA multi-RAT network will be assumed for this application scenario with variant fading channels with different timing. Interference might also be considered depending on the spectrum refarming of the spectrum overlay system. Non-contiguous frequency bands will be considered comparing with the contiguous one. No spectrum sharing will be assumed for the considered system and only spectrum opportunities for CA will be devised. Depending on the priorities coming from the traffic variations, the spectrum overlay could be combined using LTE as a prime or another former system, e.g. HSPA or GSM.

3.2.2 Licensed Spectrum with Unlicensed Spectrum Aggregation Scenarios

The aggregation of licensed spectrum/link/carrier opportunities with unlicensed spectrum 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 (Licensed) – LTE (Unlicensed)

This section covers the scenario of the aggregation of LTE operated in a licensed band with a (possibly modified) LTE in an unlicensed band. Such scenario has been recently introduced in 3GPP (for the release 13) with the study item LAA (Licence Assisted Access).

The 3GPP has identified the 5GHz band as primary candidate for being considered in the LAA study item. This band is almost available worldwide (despite some variants in the regulatory context) and is unlicensed. As of today, the main legacy users of this band are the WLAN (Wifi) and some short range transmitters.

The principle of this scenario is to keep a carrier in the licenced spectrum (the primary carrier, Pcell) to provide a carrier-grade quality of service (including mobility management) and to consider secondary carrier (Scell) in the unlicensed spectrum on an ad-hoc basis, whenever need to boost the throughput.

In this scenario, the unlicensed spectrum is used for Downlink only and it is most likely that the waveform will not be classical LTE. Indeed, the LTE waveform is not compliant with the regulatory constraint of operating in a fair and coexistence spirit. The aggregation is done at the PHY level similarly to the LTE+LTE scenario.

Figure 26 depicts the LAA scenario. In the case represented in the figure, the licensed cell is originated say from a macro cell and the unlicensed cell is originated from a femto one, illustrating such LAA scenario in a HetNet deployment.

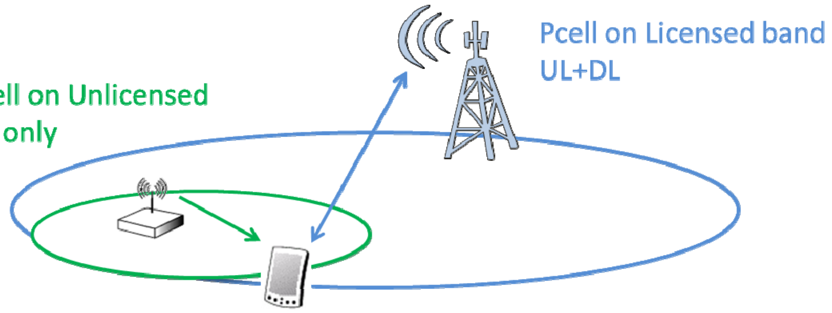

Figure 26: High level view of LAA scenario

The motivation of this scenario can be summarized by the Figure 27. Indeed, to face the mobile data growth, operators look at alternate bands such as the unlicensed one, used for instance by WLAN one. Unlicensed band is definitely of interest since it is free of charge! Operators argue that LTE has a better spectral efficiency than WiFI and therefore advocate for the use of LTE in such band. The use of a single technology could lead to economy of scale for the equipment and would require simple Operation and maintenance systems. All in all, it would lead to lower costs systems and devices, and a better use of the spectrum, whether licence or unlicensed.

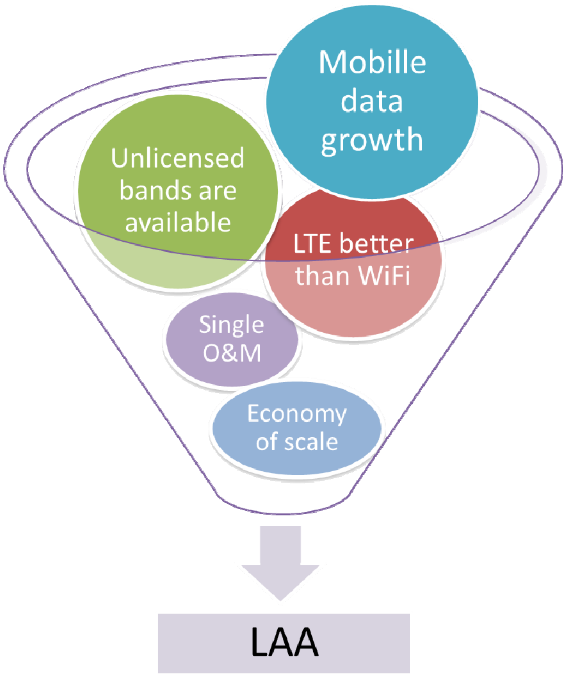

Figure 27: Illustration of motivation for Licenced / Unlicenced CA, a.k.a LAA

Finally considering the type of traffic that will be considered in such a scenario, the type of service offered by the CA is similar than the one that could be provided on regular LTE system. However, it should be noted that due to the nature of the unlicensed spectrum, it is most expected that the traffic operated on the unlicensed carrier will be best effort. Moreover the specificity of this scenario is not only about the overall throughput or capacity for the LTE system, but also on its ability to fairly share and coexist with alternate systems operating in the same unlicensed band.

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 [103]-[104]:

- The eNB can detect siginificant interference increase on unlicensed CCs. To this end, interference management is important for this application.
- In unlicensed band it could be proposed a new kind of “listen-before-talk” procedure that requires from the device to discontinue its transmission immediately on unlicensed spectrum when a WiFi system is trying to get access.
- A newdesign of MAC level signaling for the unlicensed spectrum CC based on more instantaneous characteristics of the unlicensed bands.
- Power allocation issues for CCs with different coverage area should be appropriately 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 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.

3.2.2.2 LTE (Licensed) – WiFi (Unlicensed)

In this scenario, a eNodeB (eNB)/access point (AP) can aggregate WiFi working in an unlicensed band and LTE working in a licensed band. We will call such a device an integrated LTE + WiFi (ILW) eNB. The above aggregation is feasible under the condition that the LTE eNB 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 [105]. 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 network, LTE is a fully-fledged cellular system with user and mobility management, roaming, etc integrated into the standard. On the 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 3.

Table 3: Comparison of WiFi and LTE

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

Aggregation of WiFi and LTE could be seen at different level as illustrated in Figure 1. 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 RAN.

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. However, initial studies will also be carried out with an aggregation at layer 3 but within the RAN.

3.2.3 TV White Space with Unlicensed Spectrum Aggregation Scenarios

3.2.3.1 LTE (TV White Space) – WiFi (Unlicensed)

TVWS devices, in this case the LTE systems that are being aggregated with WiFi, opportunistically reuse the available TV channels at a given location. An introduction to TVWS is provided in Section 2.3.4, so will not be covered again here.

Although LTE systems operating in TVWS will, in almost all cases covered under this scenario (and definitely in the demonstration work that will result), operate according to the conventional use of a geolocation database, this scenario does not rule out the use of spectrum sensing to determine available spectrum. Indeed, the FCC, for example, still allows spectrum sensing-only based access to TVWS with a very low transmission power (EIRP) limitation. Moreover, it is noted that the main focus of the scenario, definitely for demonstration purposes, is the provision of LTE eMBMS (evolved Multimedia Broadcast and Multicast Services) in TVWS supported by locally available WiFi provision. This scenario is therefore a form of "Augmented Broadcast" through aggregation, whereby examples key applications include layered video provision (e.g., local subscription to additional layers when WiFi is available), large-scale software download provisioning (e.g., for operating system updates), and others such as support for the well-known "Cognitive Pilot Channel" (CPC) concept [106].

Generally speaking, this scenario can work towards achieving throughput and energy consumption improvements. In that context, is may be extended to aggregation of TD-LTE in TVWS with WiFi in unlicensed spectrum at a later stage. However, the key purpose, particularly for demonstration, is at the application layer, with the enhancement of broadcast video provisioning and the shortening of large-scale background software download times (e.g., for operating system upgrades) being primary targets.

Regarding the deployment context for this scenario, the LTE TVWS system will likely be broadcast eMBMS, at least for "Augmented Broadcast" purposes, and the WiFi deployment will be sporadic with local area coverage, exactly as is the case for current WiFi. The coverage of the systems will be partially overlapping, likely with the WiFi systems covering subsets of the areas that are covered by LTE TVWS. As depicted in Figure 28, the LTE system will likely be mounted high on buildings or other structures, assisting coverage of a large area, and WiFi deployments will be as is currently the case.

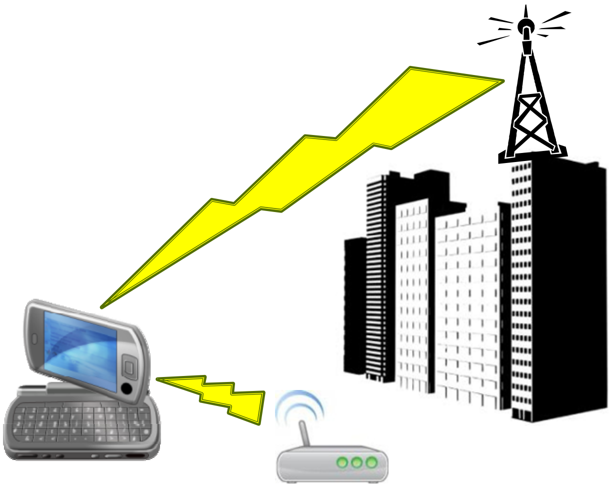

Figure 28: Core deployment context for LTE (TV White Space) – WiFi (Unlicensed) aggregation.

The consideration of the types of traffic that will be served in this scenario is inherent in the purposes of the scenario, but, essentially, the scenario will be aimed at broadcasts of video, software updates (coded at the packet-level), and CPC-like traffic. Possible other traffic types may be considered in the future, especially where the use of TD-LTE is considered.

3.2.4 Licensed Spectrum with TV White Space Spectrum Aggregation Scenarios

3.2.4.1 LTE (Licensed) – LTE (TV White Space)

LTE aggregation with LTE in TVWS can be considered as variation of the baseline LTE-LTE case argued in Section 3.1. 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. Third, the requirements on the RF performance are much more stringent in TVWS than in licensed LTE bands. Fourth, , the slave mode operation of user devices is more constrained.

Given all these constraints the most likely usage of TVWS together with LTE is for a supplemental downlink carrier. Such a carrier type is already supported by LTE Advanced. Like in the LAA case, all the radio resource management and control signalling is being done on the licensed carrier, while the supplemental DL carrier is only used for data-plane traffic if required.

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.

3.2.4.2 General Cellular Networks (Licensed) – General Cellular Networks (TV White Space)

The spectrum aggregation of licensed cellular networks with license-exempt 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 [107], [87]. 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 TVWS, whereby CR technologies might eventually assist the realization of such concepts. In Europe, Ofcom in the UK has developed rules for TVWS 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 [94]. 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 Digital Terrestrial Television (DTT) and Programme Making and Special Events (PMSE) applications.

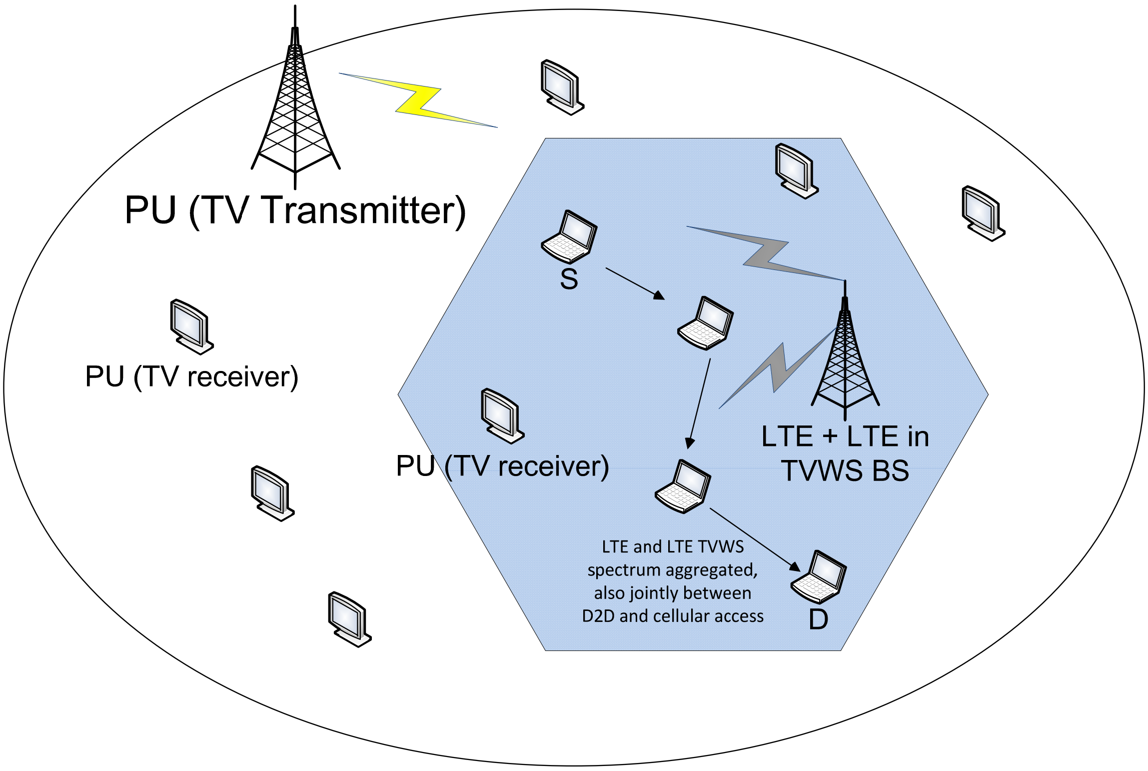

Figure 29: The multi-hop wireless cognitive radio ad-hoc networks deployment scenario: involving spectrum aggregation between cellular networks with licensed TV white space.

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 29 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 TVWS 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 TVWS 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 TVWS 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.

3.2.5 TV White Space with TV White Space Spectrum Aggregation Scenarios

TVWS work defines a pioneering framework aimed at taking advantage of locally-available TV channels (TVWS) for forms of wireless communication such as wireless broadband provisioning, and wireless local-area networking, among many others. The UK regulator Ofcom is the first country in Europe to implement and trial a TVWS framework [91]-[94], after a small number of other cases internationally such as TVWS deployments and trials in the US [89], [90] and Singapore [109]. SOLDER is leading (created under the ACROPOLIS project) one of the largest trials within the Ofcom TVWS Pilot [110].

Contrary to the other systems that are covered in Section 3.2 of this report, it is noted that many of the (e.g., database-assisted) aggregation solutions that are covered in this work can apply to any deployed radio interface in TVWS, as well as their combinations. Hence, sub-sections covering the systems being aggregated not provided here. However, it is noted that the vast majority of the work done in SOLDER outside of the scope of the database management of aggregation, at least for demonstration purposes, will likely only involve LTE carriers being aggregated in TVWS.

Crucially, under the geo-location database concept introduced through TVWS, very detailed information is maintained about the white space devices that are opportunistic accessing TVWS, on aspects such as their IDs, technical characteristics, and locations, among others. Moreover, the database decides on the allowed transmission powers of the white space devices. This implies that the geo-location database could, if it wished to, manage the spectrum coordination among the white space devices through varying their allowed channels/powers, even though that is not its original purpose. Further, the database could manage aggregation of channels by secondary devices, or at least the determination of which channels the white space devices might aggregate and which channels other non-aggregation capable white space devices might use. This capability is essential in the context of coexistence of white space devices. For example, it would be very easy for a non-aggregation capable white space device under the current framework to accidentally select a channel that ruined the potential for aggregation by aggregation-capable devices through causing interference on a channel that might be one of the only ones available that the device might be able to aggregate under its aggregation profile.

Regarding the layer at which aggregation could be done in TVWS, this could be at the PHY or MAC layer. In the case of contiguous channels being aggregated, it is possible to switch to a different waveform or extend a waveform (e.g., using additional sub-carriers in an OFDM case) to cover the contiguous channels. This implies aggregation at the PHY layer. In the case of aggregation in non-contiguous channels, it is likely that a MAC solution will be employed, or as a very rudimentary initial solution, radios might access the channels independently and aggregation be undertaken at IP level.

Regarding the purposes for aggregation in this scenario, it is noted that TVWS is a clear example where the benefits of aggregation can be strongly felt. This is because there are typically a large number of TV channels available (i.e., white space) that might be aggregated depending on location, and there are often challenges with using some particular white space channels in their own right. For instance, the SOLDER-supported participation in the Ofcom TVWS Pilot has shown clear issues with the realisation of some particular pioneering use cases, such as long-distance backhaul provisioning in TVWS, linked to interference from distant primary systems that are not meant to be covering the area; this will likely be compounded by issues with interference or coexistence issues among the secondary systems that are using TVWS in future deployments. Indeed, if a single TV channel is used in such aggregation cases, it is easily observed that the interference from distant primary systems is serious enough to stop that channel being viable for low-received signal level above-rooftop cases, quickly causing the received SINR to drop to negative (dB values) [111]. Aggregation of channels is one solution that can mitigate such issues.

Extrapolating to the overall effect, the purpose for aggregation in the TVWS case is to enhance throughput/capacity achievable through in TVWS deployments, and mitigate the extremely high variance interference effects that are seen among TVWS channels.

Finally, considering the deployment context for such an aggregation scenario, it is noted that conventional mobile and wireless communications system deployment scenarios will be relevant for the aggregation work. These include point-to-multi-point cellular provisioning, and wireless local area networking, among others. Within the LTE context, the work will concentrate particularly on point-to-multi-point cellular provisioning, and MBMS broadcast given our heavy emphasis on MBMS broadcast in TVWS contexts. Moreover, in cases other than our work on database management for aggregation purposes, we assume that all of the RATs in channels being aggregated in TVWS are of the same type (i.e., the work is perhaps not so related to h-RATs in this particular case).

The systems being aggregated in the TVWS case, especially in the case of relatively stationary deployments (e.g., on the base station side) can be assumed to be either fully or partially overlapping. In the case where mobility is involved (e.g., the use of TVWS for uplink purposes) it is safest to assume that the systems are fully overlapping, although it is noted that the TVWS framework does also allow the specification of “areas” rather than precise locations for white space devices’ localities, linked to the given white space rules (e.g., allocated channels/powers). Hence, the intersections between these areas might be ascertained in order to manage aggregation of different systems in TVWS on a area basis where mobility is concerned.

Regarding the traffic and services that might be served under this scenario, a key factor is again mobility. In cases where deployments are stationary, it is often possible to have a relatively good certainty on the quality of the channels you have access to, hence, such stationary scenarios could be somewhat suited to all traffic/service types, both reliable and best-effort. However, the ability to find good channels might not be the case in above-rooftop deployments due to distant interference as mentioned previously, and interference among the secondary systems will likely be an issue in the future as the density of white space device deployments increases thereby increasing the variability in channel quality even in the most stable channels. Indeed, such interference among secondary devices is a key aspect of the work covered under this scenario. In mobile scenarios, the availability of the TV channels for white space device usage will change as the white space device moves, although this depends on the characteristics of TV channels usage in the area and the level of mobility. For example, in the most challenging case of TVWS usage at the Strand, King’s College London for example (due to the extent of PMSE usage nearby with theatres, concert halls, television production facilities, etc.), moving only approximately 880m West-SouthWest to the Strand campus, for a Class 3 device at 6m height, results in the difference between 20 TV channels being available for white space device usage at maximum power according to the framework (36 dBm) and numerous others at slightly below maximum power, to only 3 channels being available all at reduced power (31 dBm or lower) at the Strand, one of those channels being at significantly reduced power (20 dBm). This case is illustrated in Figure 30. In many such cases, therefore, TVWS aggregation under mobility might be best suited to only best-effort traffic, such as web browsing and background downloads (e.g., for operating system upgrades).

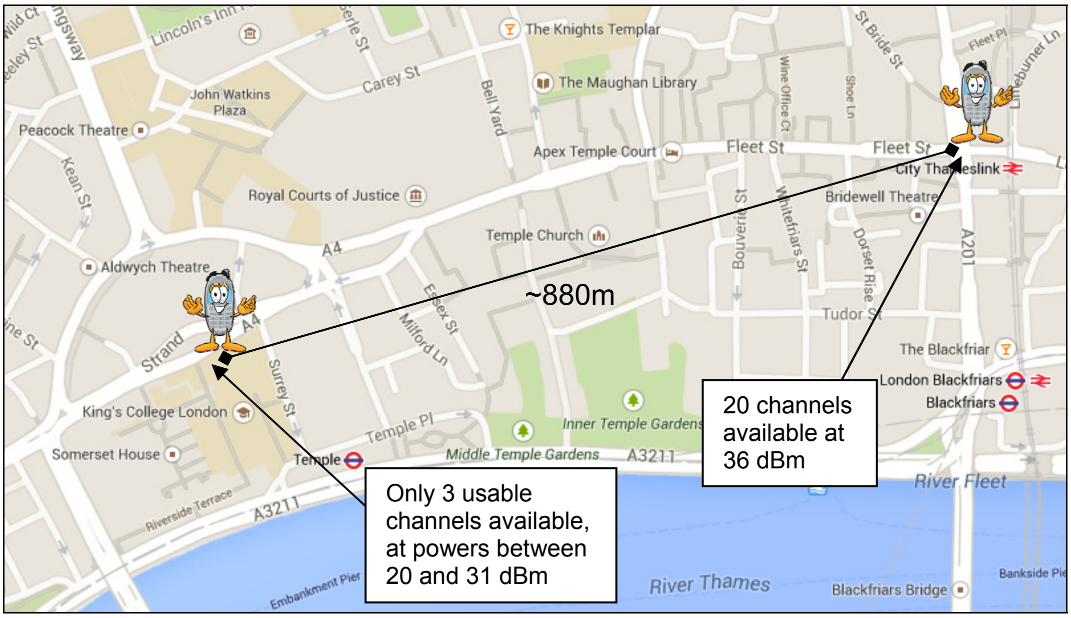

Figure 30: Illustration of how spatially rapidly the availability of TV white space can change, for a Central London scenario. This is for a Class 3 white space device at 6m above ground level.

4. Open Challenges and Opportunities

Several challenges persist in all of the above forms of aggregation, and there are various opportunities to enhance the range of aggregation 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 view of 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 for Carrier Aggregation in HetNets

There is an opportunity to enhance aggregation 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 prototype for aggregation in 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 with tri-band aggregation provision. Unlicensed bands will be also incorporated with a combination of LTE Licensed bands such as Bands, 3, 7 and 20 in Europe. The above challenges on RF & UE design could be quantified by studying performance metrics such as: new interference mitigation techniques, power amplifier and backoff, performance in fading/shadowing environment etc. Dynamic aggregation provision is the main scope of this work.

UE in Intra-band aggregation 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 aggregation Scenarios: the inter-band aggregation requires multiple simultaneous receive chains and multiple simultaneous transmit chains in case of UL aggregation. 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 technique 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. On the other hand, the licensed/unlicensed carrier aggregation brings new challenges for the eNodeB and UE in order to be capable to manage the interference from a systems that is not managed by the former. The interference on each sub-carrier can be cancelled by employing a null space based technique. To that end both the Tx and the Rx of a user must design appropriately the pre- and post-coding matrix, receptively. Therefore both the base station and the UE must listen to the available sub-carriers in order to estimate in a blind manner (without training symbols) the aforementioned matrices by the null-space of the interfering signals. 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 UE are adopted, such as: the received-power dependent Interference Cancellation (IC), and the decision-directed channel estimation and IC-assisted channel estimation.

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:

- Heterogeneous channel feedback and reporting, i.e. 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.
- Multiple timing issues in multi-CCs environment for synchronization of UL transmissions both in contiguous or non-contiguous aggregation schemes especially in multi-RAT application.

Heterogeneous 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. Specifically, channel measurements and feedback reporting could address the following issues:

- Channel measurements per cell and CC in conjunction with feedback reporting will be incorporated to the LA scheme.
- The measurement and reporting is related to the network and the particular CCs candidate for being aggregated.
- 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.

Multi-Band aggregation: Multi-Band LTE aggregation considers the aggregation 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.

Alternate waveform (FBMC): SOLDER will investigate alternate waveform (FBMC) in context of intra-band aggregation 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 for Carrier Aggregation in h-RATs

Many opportunities exist for aggregation 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. Thus, 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.

The SOLDER project will concentrate on specific problem in PHY/MAC layer aiming to highlight how beneficial aggregation 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-RAT aggregation: 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. For such a design, the following will be studied in the course of SOLDER:

- o And, PHY/MAC layer issues when the UE connect simultaneously to different RATs and thus to different CCs.
- o To cope with the spectrum overlay among the 2G, 3G and 4G technologies, providing the physical resource blocks efficiently.

The metrics that could be analyzed in Multi-RAT aggregation 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:

- The heterogeneity of the various CCs in licensed and unlicensed spectrum makes the implementation of aggregation in PHY/MAC layer a real challenging problem.
- UE transmission power problems due to the necessity of multiplexing CCs in different spectrum bands.
- Blind interference nulling for strong interference scenario.
- Sensing strategy such as Listen Before Talk (LBT)

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 aggregation 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.

TV White Space: Aggregation involving TVWS presents a number of challenges and opportunities. First, there is the opportunity that differently from aggregation in unlicensed spectrum, there is an entity or entities (geolocation databases) in TVWS that maintain a large amount of information on the white space devices and might potentially be enhanced for purposes such as managing the aggregation and coordinating among the white space devices. There is immense opportunity to build such capabilities within SOLDER. Second, there are challenges presented by uncontrolled interference situations in TVWS, leading to the need to carefully assess which scenarios and traffic would be most appropriate for taking advantage of TVWS. Such an assessment particularly applies when white space access is being aggregated with other systems outside of TVWS. SOLDER is keeping in mind this challenge and aiming to develop its solutions in ways that take into account the interference situation in TVWS.

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 Annex A), 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 aggregation 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 aggregation-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 Deliverable has presented a State-Of-The-Art (SOTA) review of aggregation techniques as originally standardized by the 3GPP, and as discussed in various research papers and other works such as patents. The detailed analysis of current and past research presented herein has revealed that aggregation in Heterogeneous Networks (HetNets—as defined by the 3GPP), and h-RATs, will be one of the most challenging areas of interest in coming years. The SOTA in this Deliverable has provided a necessary overview of the challenges towards the realization of associated solutions. Furthermore, it has clearly shown the current aggregation capabilities of systems and research efforts, and set a clear context in which potential application scenarios, use cases and requirements will be developed as the basis upon which SOLDER work will be undertaken.

Application scenarios that SOLDER will investigate, extending LTE-Advanced and in HetNets and h-RATs, have been presented highlighting the significance of aggregation in future wireless networks and the ground-breaking objectives of SOLDER. Moreover, in each of the presented scenarios, a set of specific performance metrics has been given. The applications for which aggregation might be applied have been presented in a broad sense showing that aggregation is not only a new technique, but it also opens new horizons in wireless networks. However, it is prominently noted that SOLDER will keep is application scenarios and use cases under review, and will consider adapting them if necessary should it transpire as being beneficial to do so. Such a situation might arise, for example, due to a major development occurring in research or industry, or a change in regulation affecting the potential for certain aggregation solutions to be pursued.

Finally, open research issues which can be explored through SOLDER have been analysed both for HetNets and h-RATs. The combinations of technologies, such as LTE, HSPA, WiFi, TV white space systems, and the variety of spectrum bands that might be used in a contiguous or non-contiguous mode has revealed wide potential of aggregation solutions in future wireless networks and their tremendous effect on the increase of UE’s data rate.

SOLDER will not only investigate the performance of the proposed aggregation solutions by prototyping, simulation, and analytical/paper work, but it also aims to provide forward guidance on the use of aggregation to research engineers of future wireless networks. Such guidance is inherent in the project’s recommendations for aggregation in the various application scenarios and use cases.

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List of Acronyms and Abbreviations

Acronym/Abbreviation	Meaning
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
ABS	Almost Blank Subframes
AP	Access Point
BER	Bit Error Rate
BS	Base Station
BSC	Base Station Controller
CA	Carrier Aggregation
CC	Component Carrier
CIF	Carrier Indicator Field
CoMP	Coordinated MultiPoint
CPC	Cognitive Pilot Channel
CQI	Channel Quality Indicator
CR	Cognitive Radio
CRS	Cell-specific Reference Signal
CSI	Channel State Information
D2D	Device-to-Device
DAC	Digital to Analog Converter
DFT	Discrete Fourier Transform
DL	Downlink
DRS	Demodulation Reference Signal
DSM	Dynamic Spectrum Management
DSS	Dynamic Spectrum Sharing
DTT	Digital Terrestrial Television
EAP-SIM	Extensible Authentication Protocol Subscriber Identity Module
eICIC	Evolved Intercell Interference Coordination
EIRP	Equivalent Isotropic Radiated Power
eNB	evolved NodeB
E-UTRA	Evolved UMTS Terrestrial Radio Access
FBMC	Filter Bank Multi-Carrier
FCC	Federal Communications Commission
FDD	Frequency-Division Duplex
FFT	Fast Fourier Transform
GFDM	Generalized Frequency-Division Multiplexing
HARQ	Hybrid Automatic Repeat Request
HetNet	Heterogeneous Network
h-RAT	heterogeneous RAT
HSPA	High Speed Packet Access
IFFT	Inverse FFT
ILW	Integrated LTE and WiFi
IP	Internet Protocol
ISM	Industrial Scientific and Medical
LA	Link Adaptation
LAA	Licensed-Assisted Access
LPN	Low Power Node
LQM	Link Quality Metrics

LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
LTE-U	LTE in Unlicensed spectrum
MAC	Medium Access Control
MAI	Multiple Access Interference
MBB	Mobile BroadBand
MBMS	Multimedia Broadcast/Multicast Service
MFCN	Mobile/Fixed Communications Networks
MIH	Media-Independent Handover
MIHF	Media-Independent Handover Function
MIMO	Multiple-Input Multiple-Output
MSS	Mobile Satellite Services
MT	Mobile Terminal
MU	Multi-User
NAS	Non-Access Stratum
NC	Non-Contiguous
NC-OFDM	Non-Contiguous Orthogonal Frequency-Division Multiplexing
NE	Network Element
OFDM	Orthogonal Frequency-Division multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OSI	Open-Systems Interconnection
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
PCC	Primary Component Carrier
PCell	Primary Cell
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PHY	Physical Layer
PMI	Precoding Matrix Indicator
PMSE	Programme Making and Special Events
PRB	Physical Resource Block
PU	Primary User
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio-Frequency
RI	Rank Indicator
RRC	Radio-Resource Control
RRH	Remote Radio Head
RRM	Radio-Resource Management
RSRP	Reference Signal Received Power
SAP	Service Access Point
SAW	Surface Acoustic Wave
SCC	Secondary Component Carrier
SCell	Secondary Cell
SC-FDMA	Single-Carrier FDMA
SINR	Signal-to-Interference- Plus-Noise Ratio
SME	Spectrum Management Entity

SOTA	State-Of-The-Art
SRS	Sounding Reference Signal
SU	Secondary User
TA	Timing Advance
TDD	Time-Division Duplex
TDM	Time-Division Multiplexing
TVWS	TV White Space
UCI	User Control Information
UE	User Equipment
UFMC	Universal Filtered Multi-Carrier
UL	Uplink
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local-Area Network
WWAN	Wireless Wide-Area Network

Annex A: Background information on the IEEE 802.21 Media Independent Handover 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).

A.1 Media Independent Handover

The MIH as defined in the IEEE 802.21-2008 specification [83] 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 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.

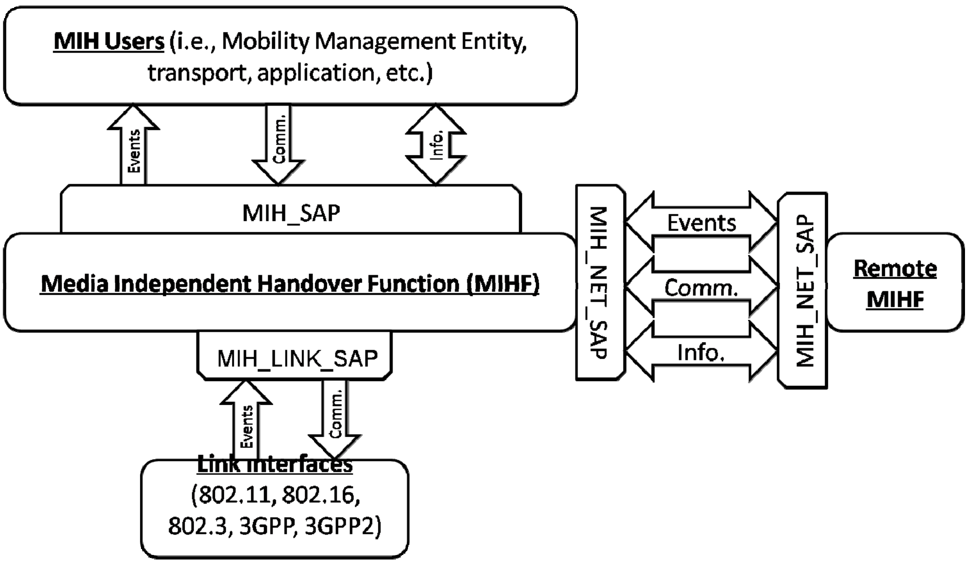

Figure 31: MIH Architecture.

A.2 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.

A.3 Service Access Points

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.

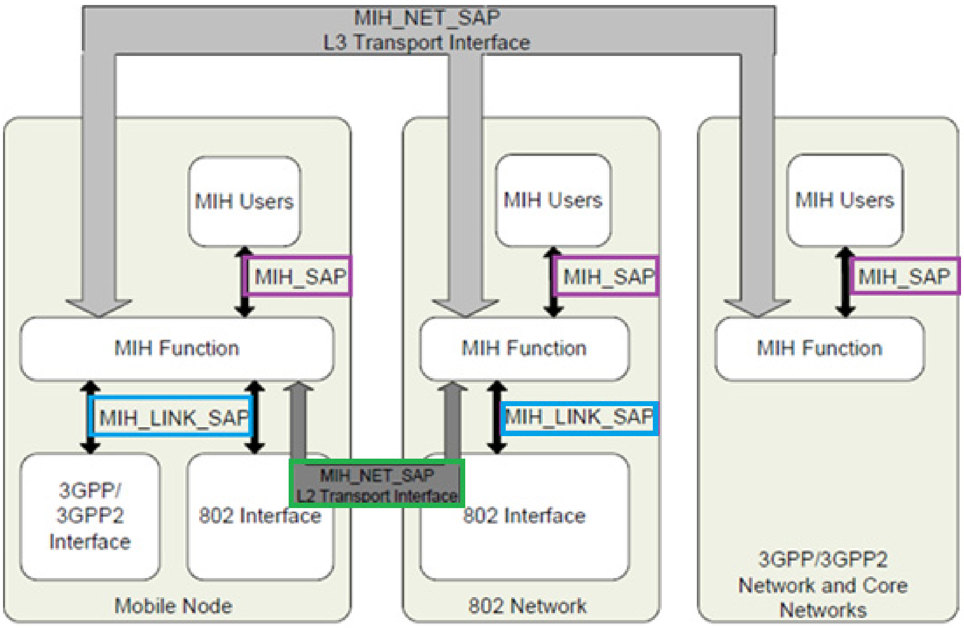

Figure 32: Types of SAP defined in MIH protocol.

Annex B: Technical Summary of Application Scenarios and Use Cases

In this Annex, a summary of the application scenarios and use cases considered by SOLDER is provided. This summary addresses a number of technical aspects, including the spectrum types that are being aggregated, the systems in that spectrum that are being aggregated, the likely layers at which aggregation will be undertaken, the deployment contexts being considered, the expected benefits of the aggregation (e.g., higher capacity), the traffic types that are addressed (this is left blank if it is uncertain, or if the scenario applies to multiple traffic types), detail on some of the research and technology challenges that are addressed, and the methodology through which the work will be undertaken (prototyping, simulation, or paper work). This summary also provides references to the sections in this Deliverable in which the associated use cases and scenarios are discussed.

Scenario number	Scenario name	Spectrum to be aggregated	Radio access technologies to be aggregated	Layer at which aggregation occurs	Application Scenario/Use Case	Expected benefits	Type of traffic to be aggregated	Research & technology challenges addressed	Partners involved	Methodology	Other comments	D2.1 section in which covered
1	LTE Carrier Aggregation	Licensed + Licensed or Licensed Shared Access	LTE FDD + LTE FDD or LTE FDD + LTE TDD	Layer 1 and Layer 2	Classical LTE network, using/sharing the spectrum of single or multiple operators, homogeneous or heterogeneous network (HetNet, as defined in the scope of LTE), multi-user	• Aggregation of multiple Carriers to reach higher throughput or capacity • Better usage of fragmented spectrum and easier dynamic resource management • Aggregation of multiple Carriers to mitigate operator spectrum fragmentation • Dynamic CA in HetNets DL and UL transmissions over TDD and FDD aggregated channels • Aggregation of multiple Carriers to reduce energy consumption	Same as legacy LTE	• RRM mechanisms to optimize network throughput and efficiency • Efficient implementation of inter-band CA • Efficient co-existence and cooperation between various types of cells. • Dynamic CA based on channel measurements criteria of MIMO LA • Frame format adaptation	SEQ, KCL, EUR, IS-Wireless, ISI	Prototyping, simulation, paper work		3.1
2	LTE in Unlicensed Bands	Licensed + Unlicensed	LTE + LTE-U	Layer 1 and Layer 2	LTE Rel 13, single operator, heterogeneous network, multi-user	• Aggregation of multiple heterogeneous carriers for higher network and user throughput • Aggregation of Unlicensed bands at 5GHz applying cognitive radio principles		• How to make LTE fair under the rules of unlicensed spectrum access. • Co-existence studies with WiFi. • Efficient unlicensed spectrum usage using cognitive radio techniques, e.g. LBT, carrier selection	EUR, ISI, SEQ	Paper work, simulation, prototyping		3.2.2.1
3	LTE Supplemental Downlink Carrier in TV White Space	Licensed + TV white space	LTE + LTE	Layer 2	Classical LTE network using additional DL-only carriers in TV white space, single operator, homogeneous network, multi-user	• Aggregation of multiple heterogeneous carriers for higher network and user throughput	TV white spaces part may be most suited to best-effort traffic where high mobility applies, but could also be used for reliable traffic in a relatively stationary scenario if good TV channels are available	• Extending LTE to TV white space	EUR, KCL, SEQ	Prototyping? & simulation	Problem demonstrating due to licensing issues of the licensed carrier. An addition to scenario 1. Probably not to be demonstrated at end	3.2.4.1
4	TV White Space Aggregation	TV white space + TV white space	LTE + LTE	Layer 1 or Layer 2	ETSI 301598-compliant TV white space deployment. Multi-user, homogeneous or heterogeneous network, one or more operators, or used outside of the scope of an operator	• Better addressing primary system and other secondary system interference in aggregation • Increased capacity and throughput, and reduced interference among coexisting secondary systems	Most suited to best-effort traffic, such as web browsing, background downloads, etc. Can also be used for reliable traffic, particularly if good TV channels are available locally and there is limited/no mobility	• MAC and PHY decisions for aggregating TV white space • Optimal channel selection algorithms for aggregation • Extending LTE to TV white space	KCL	Prototyping & simulation		3.2.5
5	LTE-WiFi Aggregation	Licensed + Unlicensed	LTE + WiFi	Layer 3	LTE + WiFi offloading, single operator, heterogeneous network, multi-user	• Better network throughput		• How to provide efficient aggregation of two heterogeneous systems. • What are the gains in terms of network performance?	EUR	Simulation		3.2.2.2
6	Augmented Broadcast	TV white space + Unlicensed	LTE + WiFi	Layer 3	Augmenting broadcast through MBMS by aggregating with locally-available resource, multi-user, heterogeneous network, one operator or service provider	• Better service quality through additional video layers or extra capacity to assist large-scale software downloads (e.g., OS updates?) or broadcast signalling requirements (e.g., CPC-like concepts)	Layered video or software downloads; broadcast signalling traffic	• Decision making on when/where to aggregate (e.g., QoS interactions) • Packet-level coding and coded packet distribution approaches supporting aggregation at high layers	KCL, EUR	Prototyping		3.2.3.1
7	5G Waveforms	Licensed + Licensed	5G + 5G	Layer 2	Single-user point-to-point	• Better opportunistic access through better ACLR • Better energy efficiency		• CA (MultiBand) Power Amplifier linearization/PAPR mitigation for FBMC schemes	TCL	Simulation & prototyping		3.1.4
8	Multi-RAT Aggregation	Licensed + Licensed	3G + 4G + 5G	Layer 2	single operator, heterogeneous network, multi-user	• Required signaling and adaptation for CA within multi-RAT of a single operator		• Timing issues • MAC layer adaptation is required for multi-RAT CA	ISI	Simulation		3.2.1.1