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# SOLDER
Spectrum OverLay through aggregation
of heterogeneous DispERsed bands

## FP7 Contract Number: 619687

SOLDER

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

### D2.3
### System-Level Requirements for Scenarios and Use Cases

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| **Abstract** | This Deliverable presents the system-level requirements for the SOLDER scenarios and use cases, as introduced in Deliverable 2.1. Further, this Deliverable presents system-level architectural viewpoints to act as a basis and reference for the discussion on system-level requirements. |
| **Keywords** | SOLDER, aggregation, system-level, architectural requirements, functional requirements, QoS requirements, KPI expectations |

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## Executive Summary

Aggregation solutions require careful design and assessment of necessary capabilities. In addition to assessment at the component level as discussed in Deliverable 2.2, this assessment progresses to the system-level, where design considerations involve multiple different entities implemented at different locations in the overarching composite architecture, those entities being required in order to achieve aggregation of various communication standards potentially operating in a range of spectrum bands. Further, in the context of LTE-only aggregation for example, additional functionalities and capabilities are necessary outside of the current relatively-simplistic channel combinations envisaged in LTE aggregation scenarios. The complexity of such cases is emphasised by heterogeneous forms of LTE-only aggregation being possible, such as aggregation among different operators using a common band, and aggregation among licensed LTE and LTE in unlicensed spectrum, among others.

Aggregation at the system-level requires a good understanding of the baseline architecture that will be assumed and worked with. Such an architecture can ultimately progress to the definition of the various functionalities and protocols at different layers, in consideration of whether the underlying purpose of the resulting communication is data or control related. This is often most achievable in the context of aggregation involving only one type of system, and aggregation scenarios involving only different instances of and variations on that well-known system—such as the case of LTE-LTE aggregation scenarios in the SOLDER context. However, a generalisation of such functionality can also apply, often being necessary if the aggregation is among different types of systems with different characteristics.

In a number of cases where the differences in the systems being aggregated push aggregation solutions to higher layers by necessity, the best way forward might be the definition of a management architecture among the systems that are being aggregated. For example, such an architecture might define which resources should be used where, and why, and how the necessary context information is obtained in order to make appropriate aggregation decisions. Such a management architecture might further be necessary in the context of different types of systems being aggregated that aren't designed to talk to each other or otherwise coordinate. Of course, in the context of different instances of an individual system/standard such as LTE being aggregated (even in heterogeneous scenarios, such as among different operators, among different types of spectrum in which LTE might be deployed, etc.), or in the context of coordinated systems being aggregated, such management aspects are in a large part already defined or can be relatively-easily derived by the selection and combination of compatible capabilities in the already existing systems.

In view of the above, this Deliverable provides detail on the system-level requirements for the various aggregation scenarios and use-cases that are defined in the scope of SOLDER in Deliverable 2.1. Moreover, it aims to provide a good grounding in terms of the system-level architectural aspects as a basis on which the various scenarios and use cases are built. Section 2 of this Deliverable provides this architectural grounding, approaching the issue from the point of view of LTE-only aggregation (based on an extrapolation from LTE architecture) and heterogeneous system aggregation, with a strong emphasis on management aspects which are key to progress in such cases. Further, it aims to weight some effort on the combining of solutions towards an all-inclusive SOLDER architecture serving the aggregation scenarios considered in the project. Section 3 assesses the system-level aggregation requirements on a per-scenario basis, those scenarios being as outlined in Annex B of Deliverable 2.1. In particular, for each scenario, it assesses the system-level assumptions, system-level architectural requirements, system-level functional requirements, and system-level QoS requirements and KPI expectations. Finally, this Deliverable concludes in Section 4, providing thoughts on future use of its content and the wrap-up of work package 2.

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# 1. Introduction

A communications "system" generally follows one of two key definitions. One definition is the combination of elements in order to create a single physical entity, e.g., a radio device with all necessary capabilities at the various OSI layers implemented in hardware or software in order to create the functional device or "system". The other definition is the combination of entities, often logical or spaced in distributed locations, that serve all of the capabilities that are necessary in order to achieve a particular communication application—a mobile network as an example. Both of these definitions are widely-used and relevant to the capabilities that SOLDER must address in order to achieve its aggregation objectives. Hence, in addressing system-level requirements, SOLDER takes into account both visions on what is defined as a "system".

System-level requirements can be reflected in the context of architecture, i.e., which entities have to be included on the system-level and how they are interfaced (architectural requirements), the necessary functions of those entities to achieve aggregation (functional requirements), and requirements in terms of  Quality of Service (QoS) and Key Performance Indicators (KPIs). The latter, from a system-level viewpoint, can be seen as related to distributed combinations of elements, or an assessment on an area basis. For example, a capacity calculation as a KPI on a system-level might be what can be achieved per unit area, e.g., $b/s/Hz/km^2$, as is a common representation of area-capacity. An energy efficiency calculation might be seen as the power consumption per unit area to achieve a given objective area-capacity, as opposed to the consumption of an individual entity or element (e.g., a base station) to achieve a given capacity for that entity or element.

Aggregation must be built on an architecture and functional capabilities. Moreover, serving the counter-intuitive objective of further harmonisation and integration of mobile communications at a time when they are being seen a likely served by heterogeneity, e.g., through the combinations of a range of heterogeneous systems and spectrum types to the 5G concept, it helps if such an architecture can be all-encompassing, or at least aim to serve common/integrated purposes through a generalisation. Indeed, in the cases where there are very different types of systems being aggregated that were not designed to operate together or in a coordinated way, such a generalisation of architecture is the best way forward—it might also be tailored to encompass architectural capabilities assisting aspects that are not served by the individual systems that are being aggregated. To such an end, the architecture can aim to serve higher-layer aspects assisting the purpose of aggregation, such as the management of the systems that are being aggregated or the management of how the aggregation is appropriated, e.g., how it is decided which traffic demands are served by which underlying radio system types and spectrum availabilities, and particularly which sets of those should be selected and combined to achieve the given rate demand of an application taking into account system-level implications.

Keeping in mind all of the above, Section 2 of this Deliverable aims to first define some broad architectures that the system-level requirements will refer to. In particular, it defines a general architecture, which is heavily based on management in view of management being a key aspect that can be addressed among different systems—even if it is not feasible to integrate them for aggregation purposes. It also defines a specific LTE-related architecture, which is able to go into more detail across the layers given that integration in such cases typically is possible, or is even commonly happening. It then presents a viewpoint on how these architectures could be merged together.

In Section 3, this Deliverable then attempts to address the system-level requirements for scenarios and use cases, progressing in the same order as the list of scenarios summarised in Annex B of Deliverable 2.1 [1]. For each of the scenarios, it considers the system-level assumptions, system-level architectural requirements, system-level functional requirements, and system-level QoS requirements and KPI expectations. The viewpoint of a system as a distributed collection of elements/entities is the emphasis for much of this analysis, however, where appropriate it does in some cases take into account the vision of a system as a collection of capabilities within a single element or device, thereby achieving that element or device as a system. This Deliverable then concludes in Section 4.

# 2. High-Level System Architectural Viewpoints

In order to provide a basis for the analysis of the aggregation scenarios on a system-level, it is necessary to refer to architectures that will apply. To assist the harmonisation and integration/compatibility of the SOLDER aggregation solutions, common architectures should be derived as much as is possible for usage among the scenarios. In some cases, particularly where very different types of systems and spectrum are being aggregated, it is necessary for such commonalities to be in the form of a generalisation of the architecture or a solution such as a management architecture being applied (e.g., deciding which flows should be aggregated to serve which traffic demands). In the most challenging of such cases, management among systems may be the best form of integration that can be achieved. In other scenarios, such as in LTE-only aggregation cases that are being extended by the SOLDER work, a common architecture can delve right down to the elements and functionalities that are involved at the different layers of a communication system.

In view of this, this section has developed two architectural viewpoints that might serve the aggregation scenarios considered in SOLDER, and that the analysis of the aggregation scenarios cross-references. The two architectural viewpoints are (i) serving aggregation in the case of heterogeneous types of RATs (h-RATs) and spectrum opportunities (HetBands) being aggregated, and (ii) serving LTE aggregation scenarios specifically, i.e., applicable to SOLDER Scenarios 1 to 3 in Annex B of Deliverable 2.1. The former has a strong emphasis on management of aggregation, whereas the latter has more emphasis on the elements that are building up the communication and network realisation on a system-level given that management is already inherent in the LTE system(s) being aggregated and that the common design of LTE realisations allows such a deep level of integration. Further, the presentation of the latter LTE case gives some thought on the combining of the approaches in order to drive forward a coordinated architecture in SOLDER.

## 2.1 High-Level System Architecture Supporting Aggregation of Heterogeneous RATs and Spectrum Opportunities

First assessing the case of an architecture for h-RATs and HetBands, and inspired by the IEEE 1900.4 standard [2] which a SOLDER contributor has been instrumental in developing, we present a system-level architecture along with a detailed description of various types of information exchange between different functional entities.

The underlying approach in our proposed IEEE 1900.4 based system level framework is to design a management system that decides on a set of actions required to optimize spectrum usage. This framework provides a management architecture as an overlay for fulfilling the spectrum aggregation requirements.

There are two key management entities in the proposed framework: the network aggregation manager (NAM), and the terminal aggregation manager (TAM). In line with this, we assume a distributed approach to spectrum aggregation wherein the terminals assist the network in optimising the spectrum aggregation decision.

The proposed architecture is shown in Figure 1. It comprises five entities on the network side, in addition to a Centralized Spectrum Aggregation Controller (CSAC). Similarly, the architecture comprises four entities on the terminal side.
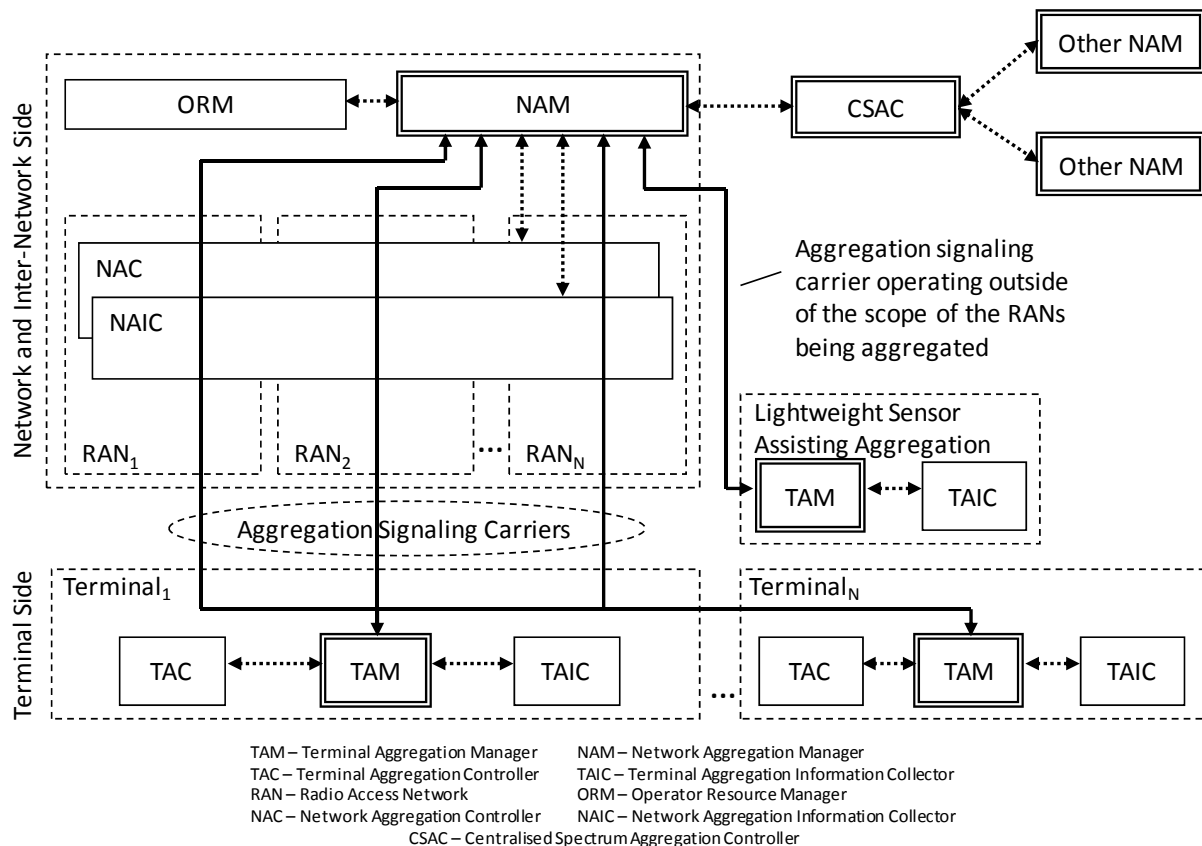
Figure 1: The h-RAT/HetBand aggregation-supporting architecture.

This architecture enables the management of aggregation among the range of RATs that have access to a range of different spectrum opportunities. It encompasses the necessary functionality to manage and implement aggregation decisions both on the network side and the terminal side, to convey decisions and constraints from the network side to the terminal side, and to obtain context information from the terminal side and RANs that is necessary to make aggregation decisions.

The key functionalities of different entities are introduced as follows.

Centralized Spectrum Aggregation Controller (CSAC)

This entity has global visibility of spectrum usage of different networks. It plays the pivotal role in spectrum aggregation decisions in the context of h-RAT scenarios where multiple NAMs might exist in the scope of different owners or decision makers.

Network Aggregation Manager (NAM)

This entity obtains information from the range of RATs, carriers and spectrum opportunities that are available, as well as (indirectly, from the TAM) information from the terminal side on the aggregation opportunities locally available there, the traffic demands of the user, and other information such as the current interference situation in spectrum that might be aggregated. It uses this information to make decisions about which resources should be provided and aggregated among different terminals in order to satisfy the traffic demand to each of the terminals. It creates aggregation instructions or policies, and conveys them to the RANs and the TAM at which points they are implemented.

It is noted that multiple instances of the NAM might exist elsewhere in different networks or under different spheres of control. In such cases where multiple instances do exist and the NAMs are collaborating, collaborative decisions will be taken among the NAMs via the CSAC.

Terminal Aggregation Manager (TAM)

This entity obtains aggregation instructions and policies from the NAM, and implements those aggregation instructions or policies. Importantly, the aggregation policies might leave some scope for this entity to make its own aggregation decisions on the terminal side, based on the local situation. The TAM instructs the TAC to implement the aggregation, and requests context information from the TAIC which is then forwarded to the NAM. The NAM might also specifically request context information to assist its aggregation decisions and formation of aggregation policies via the TAM/TAIC.

Operator Resource Manager (ORM)

This is the entity responsible for conventional resource management decisions on the operator side, including decisions on resources that should be aggregated for a particular user. Of course, the NAM has to take into account the policies of this entity, and perhaps negotiate with this entity in making an aggregation decision.

Network Aggregation Controller (NAC)

This entity obtains the aggregation instructions from the NAM, and implements them in/among RANs.

Network Aggregation Information Collector (NAIC)

This entity obtains the context information requests from the NAM, and gathers context information and forwards it back to the NAM.

Terminal Aggregation Controller (TAC)

This entity obtains the aggregation instructions from the NAM, via the TAM (incorporating also the possibility in some cases for the instructions to originate at the TAM), and implements the aggregation instructions on the terminal side.

Terminal Aggregation Information Collector (TAIC)

This entity obtains the context information requests from the NAM, via the TAM (incorporating also the possibility in some cases for the context information requests to originate at the TAM), and gathers context information and forwards it back to the TAM (which then, when/as required, forwards this information to the NAM).

Radio Access Network (RAN)

The RANs can be different RANs within the same network, or RANs in different networks operating the same RAT, or RANs in different networks operating different RATs.

### 2.1.1   Network-Side Functional Requirements

Referring to Figure 2, the NAM performs five distinct functions: spectrum policy derivation, spectrum assignment evaluation, spectrum information extraction, collection, and storage, spectrum aggregation decision and control, and spectrum selection.

1. The *spectrum policy derivation* function generates spectrum selection policies that guide TAMs in terminals' spectrum aggregation decisions. These policies are derived using spectrum and context information from the information extraction, collection, and storage function.

2. The *spectrum aggregation decision and control* function makes decisions on spectrum aggregation compliant with spectrum aggregation policies received from the ORM and the CSAC. This is also illustrated in Figure 3 for the case of LTE – LTE aggregation wherein a connection request (for either D2D communications or for a conventional UE) is received from a terminal. After this, the spectrum aggregation decision and control function sends a *spectrum aggregation request* (SAR) to the CSAC. The CSAC will allocate different bands/channels from different networks based on its spectrum assignment policies and sends back a SAR grant with the information of different bands/channels. Based on the SAR grant, the spectrum aggregation decision is made and corresponding reconfiguration commands are sent to the NAC and the ORM.

3. The *spectrum assignment evaluation* function evaluates the efficiency of the spectrum usage under the current spectrum assignment. Evaluation results are used by the spectrum aggregation decision and control function.

4. The *spectrum information extraction, collection, and storage* function receives, stores, and processes different types of spectrum measurements (e.g., information on channel state of different bands/channels) and context information. For the network side, this information is received from the NAIC. On the terminal side, the TAIC provides the required information.

5. The *spectrum selection* function selects the spectrum for exchanging radio resource selection policies between the NAM and the TAM.

### 2.1.2   Terminal-Side Functional Requirements

Referring to Figure 2, the TAM performs three distinct functions: including spectrum information extraction, collection, and storage, terminal aggregation decision and control, and spectrum selection.

1. The *spectrum information extraction, collection, and storage* function receives, stores, and processes terminal spectrum and context information received from the TAIC.

2. The *terminal aggregation decision and control function* makes decisions on terminal reconfiguration for spectrum aggregation. These decisions are made within the framework determined by the spectrum selection policies received from the NAM. After making the decision, this function sends reconfiguration commands to the TAC.

3. The *spectrum selection* function selects the spectrum for exchanging radio resource selection policies between the NAM and the TAM.

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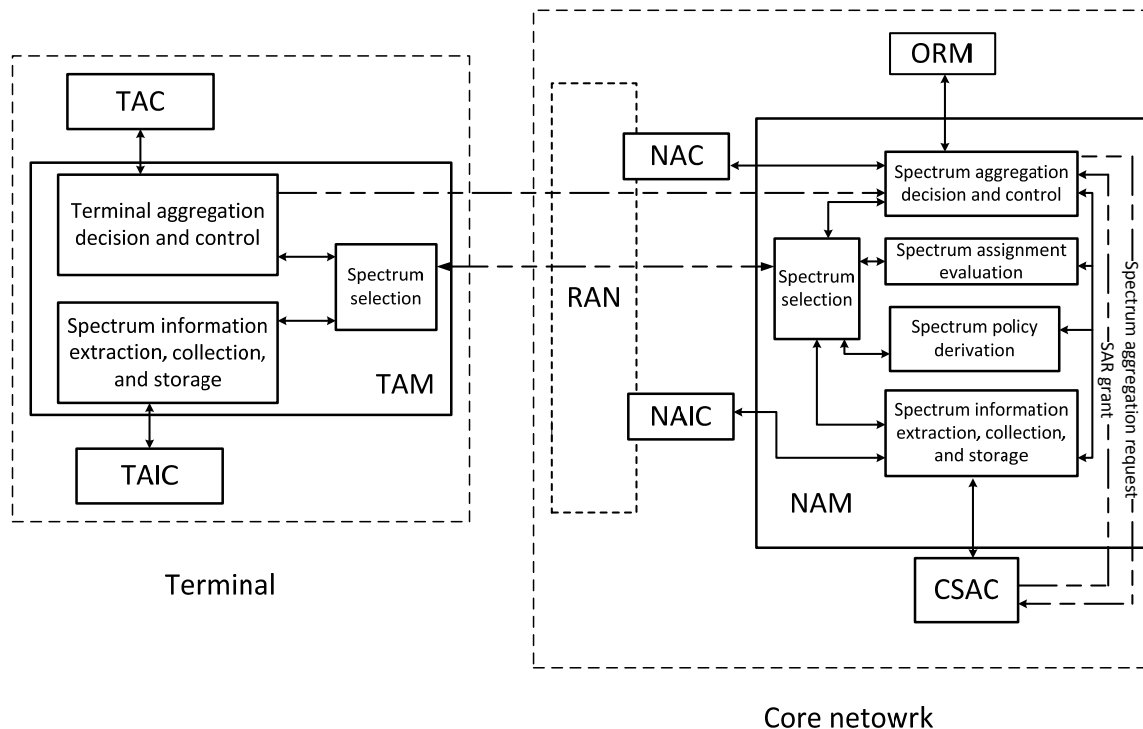
Figure 2: An illustration of the proposed functional architecture for the h-RAT/HetBand aggregation scenario.

## 2.2 LTE-Only Aggregation Example

The architecture described above is a management architecture and thus only describes the control plane. It does not specify how the actual aggregation should be done. In this section we show how this architecture can be applied to an LTE-Advanced system that naturally supports carrier aggregation. Typically, LTE-Advanced systems operate in licensed bands only and therefore do not employ any opportunistic access that would necessitate an architecture described above. In SOLDER however, we will use LTE also in unlicensed or license-exempt bands (such as TV white spaces—TVWS) in addition to licensed bands. Such a scenario can greatly benefit from combination of the two architectures.

A high level view of an overlay management architecture for LTE-LTE aggregation is given in Figure 3. The eNB application shall provide the interfaces NAC and NAIC to the NAM and shall be responsible for implementing the corresponding primitives. The NAM shall communicate with the TAM through a special radio bearer (to be defined in more detail). At the terminal side a UE application shall provide the interface between the TAC and TAIC and the TAM, which shall be responsible for implementing the corresponding primitives.

The architecture described above could be further simplified. LTE already has extensive functionality for management of aggregation. Almost all the IEEE 1900.4 management functionality at the terminal side could be handled by standard RRC signaling within LTE. The only thing that remains are the management entities at the network side. Instead of the link of the NAM with the TAM, we should rather add an interface of the NAM with the RRC at the eNB that implements all the spectrum decisions.
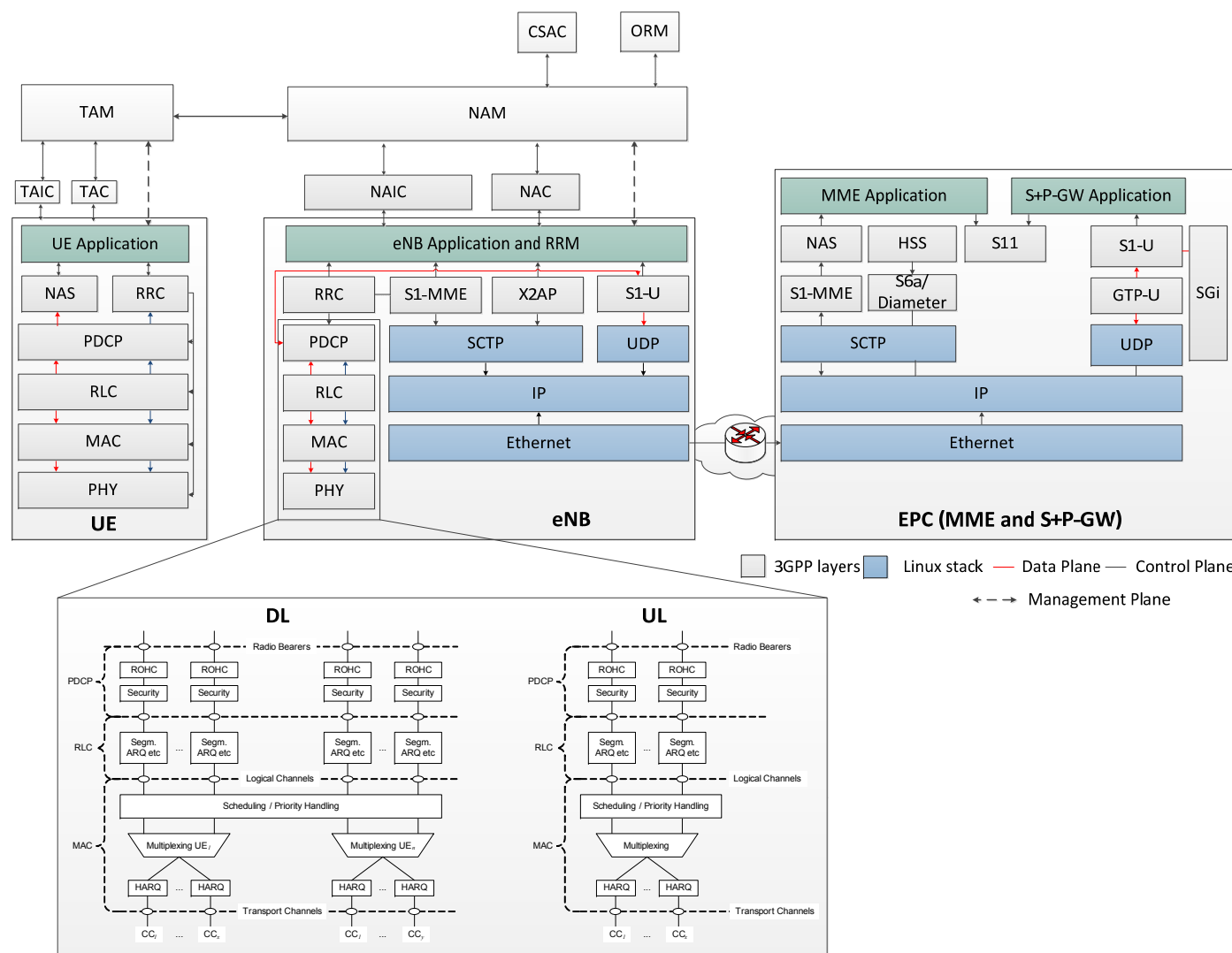
Figure 3: Example of system-level overlay management architecture for LTE-only aggregation, merging in the management entities of Figure 1.

# 3. System-Level Requirements for Scenarios and Use Cases

Having introduced the system-level architectural viewpoints for the aggregation solutions in SOLDER, this Deliverable now analyses system-level requirements taking into account and in reference to those viewpoints, where appropriate/necessary. It analyses the SOLDER aggregation scenarios in the same order that they are presented in Annex B of Deliverable 2.1 [1].

## 3.1 LTE Licensed Aggregation

This scenario is quite broad since it takes into account a number of different aggregation options involving licensed LTE spectrum usage (e.g., aggregation in homogeneous deployments, aggregation involving HetNets, aggregation among FDD/TDD spectrum usage, etc.). However, it does not take into account scenarios in which LTE is aggregated with different RATs (h-RATs) or is aggregated among different types of spectrum bands (HetBands). Given the wide-ranging nature of this scenario, the system-level requirements are addressed methodically on a case-by-case basis for each of the licensed LTE-only sub-scenarios.

### 3.1.1 System-Level Assumptions

Homogeneous Deployments

First considering LTE in homogeneous deployments, a key assumption is that there are terminals (UEs) capable of receiving data on more than one Component Carrier (CC). They co-exist with legacy User Equipment, which still handles just a single frequency CC in a single scheduling period (i.e., TTI). It is also assumed that a set of available frequency channels (i.e., CCs) is fixed for a certain eNB. The UE can be assigned a subset of it or—in the most favourable conditions—the entire set.

Regarding the architecture in Section 2, it is noted that in this scenario the terminal incorporates the TAM, TAC and TAIC as depicted in Figure 1 and in Figure 2. In practice, these elements are functionally split into the LTE protocol architecture, mostly within the RRC and MAC layers as introduced in Section 2.2.

HetNet Deployments

Regarding HetNet deployments, an initial assumption is that within the same geographic area base stations of distinctive characteristics co-exist. In particular, an environment comprising one centrally-located macro-cell base station and several surrounding pico-cells are considered. Further, it is assumed that UEs can be served by all types of base stations. The presence of femto-cells with Closed Subscriber Group (CSG) is not assumed. It is also assumed that few UEs might be able to take advantage of Multi-site Carrier Aggregation (i.e. simultaneously receive data streams from two or more physically separated eNBs).

Considering dynamic CA in cognitive HetNets, the following system-level assumptions are taken into account:

1. A UE is able to estimate the channel statistics of three bands of heterogeneous cells (i.e., macro-/micro-/pico-) and their corresponding CCs. The CCs bandiwdths could vary among the different bands depending on the regulatory assumptions.

2. The channel estimation statistics will be used from the UE to calculate PMI/RI and CQI feddback reports with different granularities per feedback type, i.e. CQI or PMI, and per CC.
3. The UE is able to provide decision about the CC selection and switching of the transmission to particular selected CCs for a particular period of time.

FDD-TDD Aggregation

Next considering FDD-TDD CA, which in our case is specifically applied to HetNets, the following are the system-level assumptions:

1. An LTE-A system is deployed, consisting of one primary serving cell (PCell) and one secondary serving call (SCell) as a HetNet deployment.
2. The eNodeB in the PCell owns a pair of FDD frequencies for FDD duplex mode, and one TDD frequency. Two eNodeBs the different modes is also possible to consider according to 3GPP [3].
3. The UE is able to transmit and receive through TDD duplex mode and via a pair of FDD frequencies for DL and UL. Symmetric aggregated traffic and non-continuous CA is considered. It is assumed that PCell is a macro cell and SCell is a pico cell as a HetNet deployment [4].

Aggregation of the Licensed LTE Spectrum of Different Operators

Finally, considering aggregation in LTE involving the spectrum of different operators, the following are our system-level assumptions:

1. The two LTE systems have been deployed in the licensed bands, belong to different operators and provide coverage in the same area. Considering Figures 1-3, they would each have separate NAMs and would require a CSAC to interface between the NAMs.
2. The LTE system aggregating the resources acts as the primary user of its owned spectrum; however, it acts as a secondary user for the other licensed band.
3. Spectrum availability is determined through either spectrum sensing or spectrum databases (and therefore different architectural requirements arise for the two cases).

### 3.1.2  System-Level Architectural Requirements

Homogeneous Deployments

Regarding system-level architectural requirements, and first considering the case of homogeneous deployments, CA in LTE Homogeneous environment does not introduce significant architectural modifications, as depicted in Figure 3. MAC/RRC  sublayers are the only entity fully aware of the usage of CA. The MAC layer is responsible for scheduling, prioritization and multiplexing data streams, which are forwarded towards Layer 1 (in case of the downlink).

HetNet Deployments and FDD-TDD Aggregation

Considering the case of HetNets, a key architectural requirement is that a prerequisite of efficient eNB cooperation in the HetNets scenario is a robust X2 interface, which links base stations. Further, X2 interface handles both Control Plane and User Plane, and is established between macro- and pico-cell base stations. However, it does not have to be present

between macro- and femto-cells. Dynamic cognitive CA in HetNets is provided through the TAIC and SS entities. The TAIC controls the aggregation information procedure, and the SS controls the spectrum selection procedure.

A further architectural requirement is that the UE is able to receive and transmit TDD and FDD modes by one eNodeB or two eNodeBs on the network side. In both scenarios, the UE is able to aggregate the two different types of frame formats at the MAC layer using the TAM and TAC. In the case of one eNodeB serving both modes, the eNodeB is able to aggregate the two different frame formats incorporated by NAM and NAC.

Aggregation of the Licensed LTE Spectrum of Different Operators

Finally, considering aggregation in LTE involving the spectrum of different operators, no major additional architectural requirements arise in this case. However:

1. To assist the detection of channel availability information (e.g., as might be fed from the NMC to the NAM in Figures 1-3, and used for the spectrum information collection, abstraction, and storage functionality in Figure 3), base stations might be equipped with wideband transceivers employing spectrum sensing.
2. In the case where channel availability information might be assisted through spectrum databases (notably quite relevant given recent advancements such as Licensed Shared Access—LSA), the proposed management architecture can be considered as an overlay for the LTE system as shown in Figure 3.

### 3.1.3 System-Level Functional Requirements

Homogeneous and HetNet Deployments

First considering homogeneous deployments, a key functional requirement is that the MAC sub-layer shall have the capability to manage radio resources for all aggregated Component Carriers (CCs). In particular, MAC sublayer shall be in charge of efficient scheduling (PRB distribution) among various types of users (i.e. CA-capable and non-capable). Additionally,

1. MAC sublayer shall be responsible for Activation and Deactivation of SCells. RRC sublayer is responsible of configuration/Deconfiguration of CCs
2. Separate HARQ processes shall be run for each CC.
3. CC assignment shall not be fixed for the entire transmission time. Contrarily, periodical reallocation of CC subsets should be feasible.

Having calculated the heterogeneous channel feedback reports for each CC in terms of granularity for different CC bandwidth and CC channel statistics, the system provides the following procedures:

1. Minimization of the CSI feedback: the minimization can be done by using different feedback granularities for both the CQI and PMI/RI.
2. Targeting an aggregated throughput over the different CQI and PMI/RI granularities and the bandwidths for each CC.
3. Minimization of the complexity reports calculation in multiple CCs scenario.

Notably, an approach for the heterogeneous feedback design provision was recently proposed in [5] to align feedback to channel statistics among different users. Our proposed heterogeneous feedback differs as follows:

1. CC selection varying the total aggregated bandwidth for each user;
2. Sub-band size adaptation changing the number of PRBs.

FDD-TDD Aggregation

Considering FDD-TDD CA, for efficiency the following functional requirements are specified for each frame structure:

1. FDD is implemented on a paired spectrum where DL and UL transmissions are sent on separate frequencies. The 3GPP frame structure used in FDD carriers contains 10 subframes within a radio frame with DL or UL sub frames depending on the link direction [3], [4].
2. TDD is implemented on an unpaired spectrum, using only one frequency for both channels, i.e. UL and DL. A single bandwidth is shared between UL and DL, with the sharing being performed by allotting different periods of time to UL and DL.

Figure 4 depicts the frame structures for TDD, where 7 different patterns of UL-DL switching, termed uplink-downlink configurations 0 through 6. The distribution of DL/UL subframes is asymmetric. The DL:UL ratios of the above TDD configurations are also provided. The down-link part (DwPTS) of the special subframe of a radio frame could also be part of a DL aggregation with FDD flow, whereas the uplink part (UpPTS) is not taken into consideration.

The cross-layer design (CLD) for the aggregation of the two different frame structures, i.e. FDD and TDD will be provided. The CLD solution will incorporate the QoS requirements from the upper layer for a file transmission and the same layer in terms of feedback delay. Dynamic selection of different TDD configuration will be provided based on the CLD.

| 3GPP UL / DL Frame Configurations | Legend: | | | DL | UL | Special | | | | DL:UL Ratios |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | D#0 | D#1 | D#2 | D#3 | D#4 | D#5 | D#6 | D#7 | D#8 D#9 | 2:3 (40% DL – 60% UL) |
| 1 | D#0 | D#1 | D#2 | D#3 | D#4 | D#5 | D#6 | D#7 | D#8 D#9 | 3:2 (60% DL – 40% UL) |
| 2 | D#0 | D#1 | D#2 | D#3 | D#4 | D#5 | D#6 | D#7 | D#8 D#9 | 4:1 (80% DL – 20% UL) |
| 3 | D#0 | D#1 | D#2 | D#3 | D#4 | D#5 | D#6 | D#7 | D#8 D#9 | 7:3 (70% DL - 30% UL) |
| 4 | D#0 | D#1 | D#2 | D#3 | D#4 | D#5 | D#6 | D#7 | D#8 D#9 | 8:2 (80% DL – 20% UL) |
| 5 | D#0 | D#1 | D#2 | D#3 | D#4 | D#5 | D#6 | D#7 | D#8 D#9 | 9:1 (90% DL – 10% UL) |
| 6 | D#0 | D#1 | D#2 | D#3 | D#4 | D#5 | D#6 | D#7 | D#8 D#9 | 5:5 (50% DL – 50% UL) |

Figure 4: LTE sub-frame configurations for TDD [4], [5].

Aggregation of the Licensed LTE Spectrum of Different Operators

Finally, considering aggregation in LTE involving the spectrum of different operators, the following system-level functional requirements are anticipated:

1. The aggregation is performed as a MAC-layer functional capability as discussed in Section 3.1.3 of D2.1.
2. In case of channel availability information being assisted through spectrum sensing, there must be an interval during which the LTE base station schedules sensing. Moreover, control and data transmission must be muted during this interval. Such si-

lencing capability could be managed through functions and actions implemented in the NAM and NAC in Figures 1-3; the sensing itself would be managed by the NAIC.

3. In the other case of channel availability information being assisted by databases (which is far more likely at least in the short term, given developments such as LSA), the proposed management architecture provides overlay functionality for the LTE system. In this case, protocol interactions between different entities take place. For example, the NAM obtains the channel availability information for the LTE base station through the CSAC which has global visibility of spectrum usage for the two LTE systems in question. The NAM obtains different types of channel state and context information through the PHY layer, which are fed to the NAM through the NAIC. Based on this information, the most appropriate aggregation plan is selected. The NAC conveys this information to the MAC layer where aggregation is performed.

### 3.1.4 System-Level QoS Requirements and KPI Expectations

<u>Homogeneous and HetNet Deployments</u>

Considering both heterogeneous deployments and HetNets, the most straightforward expectation associated with KPIs is an increased user throughput. However, this benefit might not be evident in highly congested cells where the advantage of having additional bandwidth will be shared among too many simultaneous users (UEs). Hence, appropriately to the system-level and within the area of achievable data rates – it is anticipated system throughput would be also increased as cumulatively more bits per second will be transmitted in the range of a cell.

Cell-edge throughput will also be enhanced – especially in the scenario comprising CCs from diverse bands. Cell-edge UEs can be prioritized within the pool of PRBs originating from a CC with noticeably better propagation conditions. It should yield improved data rates at cell edge.

"CC activation and deactivation" is a new procedure associated with additional frequency resources. However, the procedure itself usually does not last for more than 8-10 ms (MAC Control Information exchange) so its influence is rather negligible to the overall system latency. As such, CA could be seen as a quick and efficient way of performing load balancing. Nevertheless, the number activations and deactivations should be limited as much as possible.

The usage of additional CCs imposes signaling overhead due to the necessity to report separate CQI, PMI and RI for each active CC. The negative impact of signaling can be mitigated in various ways – for example via new uplink control formats.

In view of this, the most interesting KPIs that can be evaluated through simulation will be:

1. Average user throughput.
2. More specifically to the system-level, average cell throughput.

We should also consider that CA may increase the imbalance between UL and DL resource. Indeed, the initial scenarios of CA consider say 2 DL CC while still having 1 UL CC. Collateral impact of this imbalance could be the limitation of TCP throughput due to the limited UL rate (ACK/NACK would then limit the DL). Simulation should evaluate if such impact is purely theoretical or could happen in realistic traffic case.

The signaling overhead will be minimized in order to achieve a target aggregated throughput. A low complexity optimization process will provide the best possible solution based on short

and long-term channel statistics. Bandwidth selection for each CC will be also provided in order to maximize the overall aggregated (i.e. overall system) throughput.

<u>FDD-TDD Aggregation</u>

Concerning FDD/TDD aggregation, it is noted that the TDD frame configuration, which will be used in order to be aggregated with a FDD flow and boost UE data rate depends on the following parameters:

1. Traffic generation rate inside the cell in which TDD/FDD flows is aggregated.
2. QoS constraints from upper layers, e.g. file size related to TCP transmission.

Moreover, a cross-layer aware MAC protocol will efficiently combine the TDD configuration with an available FDD carrier.

The reconfiguration of a DL:UL ratio will be accomplished in a dynamic way. The measured KPI in this case is:

1. UE throughput.

<u>Aggregation of the Licensed LTE Spectrum of Different Operators</u>

Finally, it is expected that the LTE-LTE aggregation in the licensed spectrum will mainly result in improving the system-level throughput and ultimately the user experience. In addition to this, extra acquired bandwidth may also be used in improving the energy efficiency (based on the infamous power-bandwidth relationship) for mobile terminals. Therefore, improvement in the following system-level KPIs is expected:

1. Area spectral efficiency.
2. Bits-per-second-per-Watt area capacity.

It is noted that these KPIs can be easily measured through system-level simulation or analysis.

## 3.2 LTE Licensed with LTE Unlicensed Aggregation

This scenario has received a lot of attention in 3GPP, which used to be called LTE-U and more recently is called Licensed Assisted Access (LAA) [13]. The idea is to aggregate licensed LTE spectrum with unlicensed spectrum is the U-NII 5GHz band. The carrier in the licensed spectrum serves as an anchor point and all control plane traffic will be handled there. The carrier in the unlicensed spectrum will serve as a secondary component carrier for user-plane data only.

In SOLDER we will work on two important aspects of LAA: (a) carrier selection, and (b) interference mitigation. The system-level assumptions and requirements are described as follows.

### 3.2.1 System-Level Assumptions

Carrier Selection

To support the carrier selection in the LTE-Unlicensed CA application scenarios the following assumptions are made:

1. A scenario of co-located LTE-U with downlink CA in the presence of Wi-Fi users is analyzed and studied on the PHY layer.
2. Carrier Selection and Listen Before Talk (LBT) can be controlled by the NAIC and instructions to the NAC from the NAM in terms of the architectural generalisation in Figures 1 and 2 of Section 2. The algorithm aims at maximizing the total UE throughput and minimizing interference issues with Wi-Fi users.
3. The total sum rate of downlink CA based on maximum tolerant interference level perceived by a Wi-Fi receiver.
4. Fairness operating issues of the LTE-U. LTE-U carrier is a direct threat to Wi-Fi users and seize unlicensed bands for its own benefit. Therefore, *discontinuous transmission* (DTX) should be applied in the LTE-U band assuring fairness in the system.

Interference Mitigation

A Licensed transmitter with MIMO capabilities can aggregate the unlicensed CC providing interference mitigation for protecting the primary tranmission, i.e. the unlicensed one. Interference mitigation is applied on space direction through interference nulling. A blind learning is also assumed for learning the signals without interaction with the unlicensed system.

### 3.2.2 System-Level Architectural Requirements

Carrier Selection

The architectural requitements for the LTE-U deployment are considered UE-assisted with the TAIC and SS entities involved and they are summarized as follows:

1. LBT requires the application of a clear channel assessment (CCA) check before using the channel. Carrier sensing is a fair way of sharing spectrum in the unlicensed band where other systems operate along with LTE-U.
2. DTX on a carrier with limited maximum transmission duration. The maximum transmission duration is limited on certain regions such as Europe.
3. Carrier selection, so that LTE-U nodes can use carriers with low interference.
4. Transmission Power Control (TPC) is a regulatory requirement in some regions by which the transmitting device should be able to reduce the transmit power in some proportion to the maximum allowed.

Interference Mitigation

We assume a licensed Tx/Rx pair and multile unlicensed Tx/Rx pairs into the architectural model. The lisenced eNodeB is able to listen the available sub-carriers from the unlicensed side. Based on the interference signals, the UE estimates a post-coding matrix that nulls out the interference generated by the other UE occupying the the same sub-carrier.

### 3.2.3  System-Level Functional Requirements

Carrier Selection

Concerning LTE-A and Wi-Fi  PHY layer compatibility, the channel raster that defines the set of possible center frequencies is 300 KHz and 100 KHz for LTE-A and Wi-Fi respectively. This means that the center frequency must be an integer multiple of the channel raster. Consequently, LTE-A is compatible with Wi-Fi because the set of LTE-A center frequencies is a subset of those of Wi-Fi. LTE and Wi-Fi infrastructures shall coordinate, and when available, the LTE system can borrow spectrum from the Wi-Fi bands and allocate them to LTE-U UEs for aggregation. In terms of band and bandwidth specifications, the set of defined Wi-Fi bandwidths is a subset of the LTE bandwidth set.

A collocated LTE-U CA system is illustrated in Figure 5. The LTE (primary cell) and LTE-U band (secondary cell) are co-located and accessed by the same eNodeB. LTE operates in 7 or 20 LTE band as defined by the 3GPP, whereas LTE-U is deployed in Band C, i.e. near 5.8 GHz. Hence, the LTE UE can exploit the benefit of downlink CA by receiving data via LTE and LTE-U frequency bands concurrently. In the small-cell area there are also a number of $M$ Wi-Fi users which have privileged access to 5 GHz band and thus are perceived interference from the transmission of eNodeB in unlicensed spectrum. The interference generated by the eNodeB on each one of M users should remain below the interference threshold, $I_{th}$, which is the maximum peak interference level at which the Wi-Fi transceiver maintains the QoS. The eNodeB performs energy detection carrier sensing in all of the unlicensed channels. The channel with the lowest activity is selected for LTE-U transmissions. Therefore, carrier selection is based on the Wi-Fi activity and the carrier with the lowest activity is chosen for aggregation. The channel's activity will determine the portion of time for which the unlicensed channel will be used. So when the eNodeB selects a carrier starts immediately the LBT procedure to check if the channel is occupied by a Wi-Fi user or not. If the channel is not busy, a downlink transmission in this band can be started.
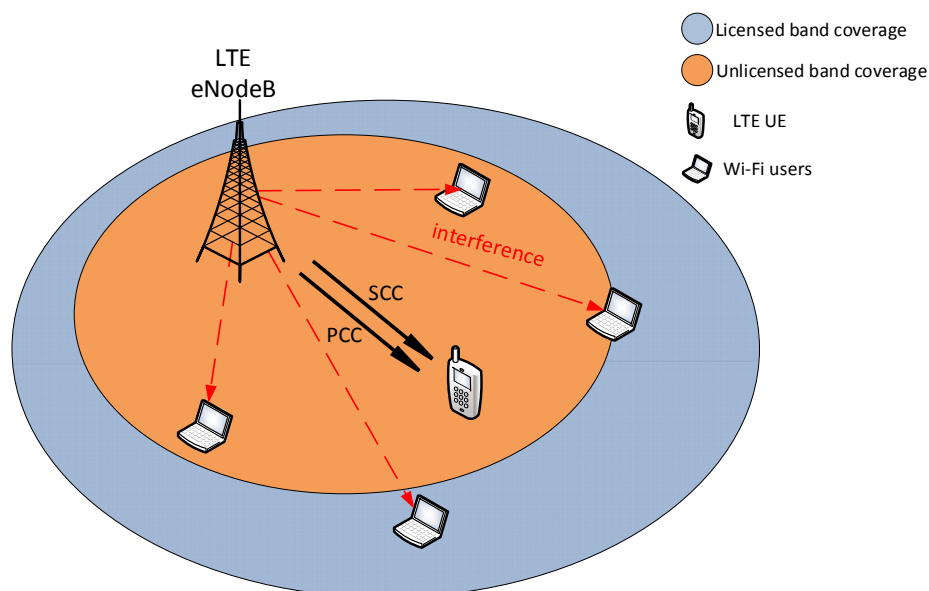


Figure 5: A collocated LTE-U scenario with Wi-Fi users.

Wi-Fi systems require the determination of a Clear Channel Assessment (CCA) before transmission. This involves the waiting for a duration of DCF Inter-Frame Space (DIFS), which is 34 µs plus a random backoff time expressed in multiples of a Wi-Fi slot (typically 9µs). This means that during an LTE frame (10ms) several Wi-Fi transmissions can be made and a continuous LTE-U transmission of that duration will postpone any of them. For fairness reasons, it is assumed that the number of subframes during which LTE-U transmissions can be enabled is limited based on the Wi-Fi traffic load. To this end, Wi-Fi users perceive this number of subframes as a high load period. LBT should be implemented at the beginning of the LTE frame for a period of time at least equal to DIFS of Wi-Fi. Frame Based Equipment (FBE) [6] proposes that CCA period is 20µs and if the channel is sensed as idle, a transmission for a fixed amount of time can start. This will potentially cause problems to Wi-Fi users because their traffic load is not considered to decide how long an LTE-U transmission will last. Instead we propose an adaptive FBE mechanism where, the duration of LTE-U transmission is based on the current Wi-Fi Channel Occupancy Time (COT).

Interference Mitigation

The licensed eNodeB employs a conventional water-filling (WF) algorithm over the available degrees of freedom via which the optimal power allocation is given. The aim is to provide a joint rate maximization and interference mitigation incoroporating unmlicensed bands into its own transmission. The functionalities of the proposed transceiver are presented in the diagram of Figure 6. The whole procedure will be applied periodically in order to detect a possible change in the licensed user's activity and to update the pre-/post-coding matrices according to channel variations.



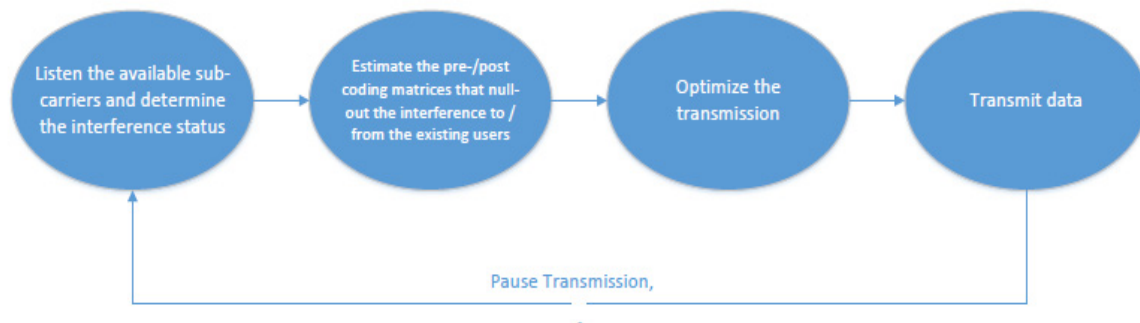Figure 6: The functional requirements for interference mitigation in unlicensed bands aggregation.

### 3.2.4 System-Level QoS Requirements and KPI Expectations

Carrier Selection

Regarding carrier selection, an improved throughput of the UE as a result of CA between licensed and unlicensed carriers is anticipated. The impact on the U-NII bands activity as well as a potential impact on signalling overhead will be also evaluated.

Interference Mitigation

Regarding interference mitigation, the achievable capacity of the UE under the proposed approach will be calculated and measured for the perfect and the imperfect CSI cases. In the imperfect CSI case we will also provide results concerning the interference generated to the un-licensed bands due to the imperfect estimation.

## 3.3 LTE Licensed with LTE TVWS Aggregation

The scenario for aggregation of LTE in licensed bands with LTE in TVWS has been introduced in Section 3.2.4.1 of D2.1, as is often seen as being useful for the deployment of a supplemental downlink of LTE in TVWS. Moreover, this scenario is essentially similar to the LTE (licensed) – LTE (licensed) aggregation scenario, with some key exceptions.

### 3.3.1 System-Level Assumptions

The following system-level assumptions are derived in this case:
1. At the system-level it is assumed that the LTE BS operating in TVWS has Internet connectivity in order be able to query a geolocation database.
2. The two LTE systems (potentially belonging to different operators) provide coverage in the same area. Due to better propagation characteristics of TVWS, the LTE (TVWS) system will provide coverage in a larger area compared to the LTE (licensed) system.

### 3.3.2 System-Level Architectural Requirements

The following system-level architectural requirements are derived:
1. There must be a geolocation database that assesses TVWS availability dependent on location.
   a. According to the current TVWS rules, it is the LTE BS that must directly access this through the Internet, and not a network management entity within the LTE standard. This may not be fully in line with LTE architecture, depending on the level to which the TVWS support is integrated within LTE. However, it is anticipated that there will be flexibility in white space rules if a degree of system reliability/security in the implementation is demonstrated, such as through a standard (e.g., LTE/LTE-A). In this case, it may be possible for the system to query the database on behalf of the LTE base station itself.

### 3.3.3 System-Level Functional Requirements

The following system-level functional requirements are assessed:
1. The aggregation would be performed at the MAC layer as described earlier.
2. An illustration of the management architecture for aggregation in this case is shown in Figure 7. The functional requirements are generally the same as described for the LTE (licensed) + LTE (licensed) scenario. For the LTE (TVWS) system, the NAM derives spectrum policies based on the guidelines from the TVWS database.
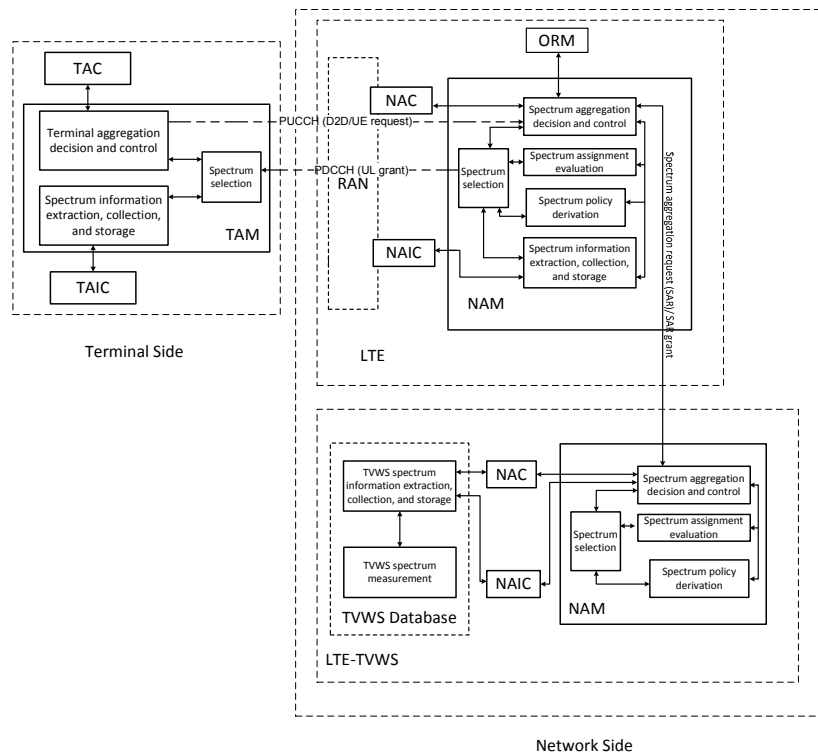
Figure 7: Management architecture for LTE licensed with LTE TVWS aggregation.

### 3.3.4 System-Level QoS Requirements and KPI Expectations

It is expected that aggregation in this scenario will mainly result in improving the system-level throughput and ultimately the user experience. In addition to this, extra acquired bandwidth may also be used in improving the energy efficiency (based on the infamous power-bandwidth relationship) for mobile terminals. Besides, this scheme will particularly improve the user experience for indoor users.

## 3.4 TVWS with TVWS Aggregation

As stated in Deliverable 2.1 [1], it is clear that much of the work we do on aggregation of TVWS with TVWS channels can apply to a wide range of radio interfaces being deployed in TVWS, including mixtures of radio interfaces over different aggregated channels—hence TVWS aggregation being considered under the h-RATs classification in SOLDER. This is because the aggregation solution is driven by the geolocation database as a management system. However, for some aspects, such as prototyping of the concept at the device side (noting that prototyping also looks likely to be done in terms of improvements to databases), the solutions being aggregated in TVWS will almost certainly all be LTE. This work proceeds based on such an assumption.

### 3.4.1 System-Level Assumptions

The following system-level assumptions are derived in this case:

1. It is assumed that the white space devices have Internet connectivity to be able to query a geolocation database. Such connectivity is, of course, standard for LTE and the vast majority of other possible systems to which this work can apply.
2. Regarding coverage on the system level, it is assumed that this scenario can apply to a range of possible mixtures of systems being aggregated in different TV channels, or

the same system (e.g., LTE) being aggregated among the channels. If the two systems being combined are both LTE, then it is assumed that their coverages will be similar, and ideally the same white space device will be serving the channels being aggregated. The solutions under consideration for TVWS aggregation can also apply to cases where the coverages are not precisely matching, which is beneficial to serve cases where different systems are being aggregated among the TV channels.

3. Relatively stationary deployment cases often be most suitable for TVWS, as referred to in Section 3.2.5 of Deliverable 2.1. This is for reasons such as spatial interference variability on channels, but can also be for other reasons such as (in some cases) the necessary sizes of equipment (e.g., antennas) that are used. It is therefore assumed that the deployments will in most cases be relatively stationary (with little mobility).

### 3.4.2   System-Level Architectural Requirements

The following system-level architectural requirements are derived:

1. There will be a geolocation database that is bi-directionally interfaced to white space devices over the Internet, and will be accessible via conventional protocols (typically HTTPS over TCP over IP) by the white space devices. Interaction with the geolocation database should be through the NAM or CSAC in Section 2.

2. There must be either:
   a. Radio elements deployed at both ends of the aggregated link (e.g., base station and terminal) that can access more than one TV channel contiguously, accessible (for control purposes) through the NAC and TAC in Section 2, and/or,
   b. Radio elements deployed at both ends of the aggregated link (e.g., base station and terminal) that can access more than one TV channel non-contiguously, e.g., through employing multiple RF front-ends over the TV channels, again accessible through the NAC and TAC, and/or,
   c. Radio elements deployed at both ends of the aggregated link (e.g., base station and terminal) that implement different or merged standards, e.g., LTE and Wi-Fi, such as through employing multiple radios in devices. These radio elements links could be in entirely separate (e.g., not co-located), at one but not at both ends of the aggregated link. They will again be accessible through the NAC and TAC.

### 3.4.3   System-Level Functional Requirements

The following system-level functional requirements are assessed:

1. The geolocation database must be capable of making or accessing decisions on which TV channels can be used at which powers by white space devices, based on white space devices' information provided to the database on their capabilities. This will be realised through the Spectrum Aggregation Decision and Control functionality in Figure 2, in conjunction with the other functions.
   a. The geolocation database will also make decisions to coordinate white space usage among the white space devices (e.g., allocating channels/powers to avoid interference among them). The authors of this Deliverable see such a capability as likely being essential to the future of TVWS; moreover, work towards such ends has already been initiated in some realms such as ETSI-RRS [7].

2. In order to serve some possible scenarios where there are different RATs are being aggregated in TVWS and some cases where LTE is aggregated using different radio elements operating among the TV channels, at each end of the link (i.e., the receiver

of the content, and the server from which the content originates), packet-level coding/decoding must apply such as described in Section 3.6.3.

    a. Again, it is possible for such coding to be implemented at an intermediary in the network (Figure 9).

    b. Such coding would be implemented in the CSAC/NAM and TAM, respectively through the Spectrum Aggregation, Decision and Control function and the Terminal Aggregation, Decision and Control function in Section 2.

3. Also in cases where different RATs or LTE deployments are being aggregated, there will likely need to be a multi-stream functionality again as described in Section 3.6.3.

4. In cases where the aggregation is within the same system or coordinated systems, there must be a MAC functionality that assesses which contiguous channels should be aggregated, which non-contiguous channels, and distributes the link layer information among the various PHY accesses of the channels of contiguous combinations of channels, as well as combining that link layer information at reception.

Figure 8 gives an example of a software tool that we have developed that queries one of the geolocation databases deployed for the Ofcom TV White Spaces Pilot, and from the response assesses which TV channels have to be aggregated in order to achieve a given rate requirement at the receiver. This is an example of a functionality that will be significantly extended or the purpose of aggregation in TVWS, although the particular example in this case is a decision that can be taken at the white space device side. This decision is sub-optimal, as it doesn't take into account the channel quality (e.g., interference from other white space devices and from distant primary systems). On the database side, allocations to receivers can take into account aggregation capabilities, avoiding cases where an allocation to one white space device will interfere with the possibility of another white space device to aggregate available channels. Alternatively, individual white space devices might take into account aggregation and coexistence by, for example, (i) sensing interference levels before making channel selections, or (ii) making careful choices in channel selections in order to avoid accidentally interfering with other radios possibilities of aggregating contiguous channels.



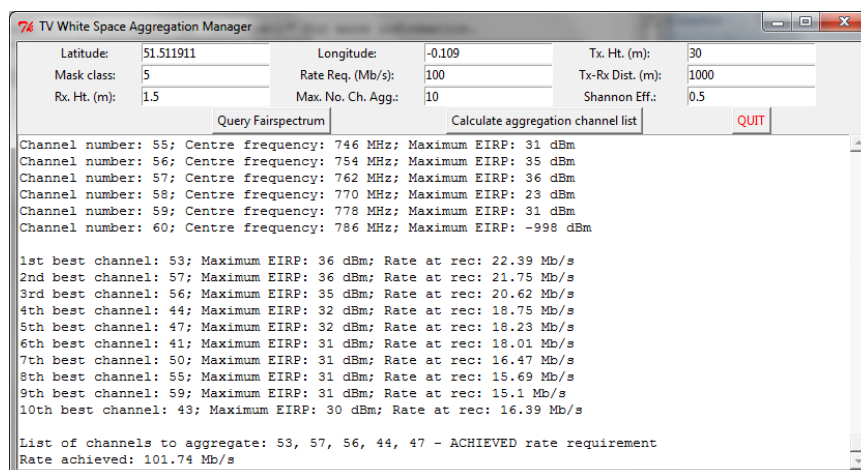Figure 8: Software tool developed for aggregation decision making involving TVWS.

### 3.4.4 System-Level QoS Requirements and KPI Expectations

This scenario and resulting aggregation solution is highly independent of the systems that are being aggregated, meaning that a range of QoS requirements and KPI expectations might apply. The following QoS requirements and KPI expectations are assessed:

1. In terms of QoS requirements on the individual systems being aggregated, it is expected that end-to-end delays similar to current wireless systems will be sufficient, as an absolute maximum, a good example could be the ITU recommendation ITU-T G.114 [8], 200 ms for voice communications. In terms of packet loss, the effect on TCP can be severe even for a packet loss of 1% [9], and such a characteristic is seen to persist in future TCP to the present even though various efforts have been undertaken to improve TCP performance over wireless links (i.e., with packet loss). It is clear from such research that a good level for acceptable packet loss would be 0.1%.

2. Regarding KPIs it is anticipated that at least a doubling of throughput will be achieved by aggregation (i.e., at least two or more channels will be aggregated). E.g., for a system with a 5 MHz bandwidth (again matching LTE case in TVWS) and a 10 dB SINR, the Shannon rate is 17.3 Mbps. If the system achieves half of that (8.65 Mbps, again approximately equivalent to our LTE example in terms of theoretical maximum performance), then a doubling to 17.3 Mbps through aggregation, or better, can be expected. In terms of typical LTE deployments, this represents more like a tripling of throughput achieved by aggregation.

## 3.5 LTE Licensed with Wi-Fi Unlicensed Aggregation

The scenario for aggregation of LTE in licensed bands with Wi-Fi in "conventional" unlicensed spectrum (typically 2.4GHz) has been introduced in Section 3.2.2.2 of D2.1. WiFi is a very popular technology and it is often deployed in hot-spots on top of existing broadband wireless networks. 3GPP allows the integration of such networks as so called "non-trused access networks" into their core network. This allows for easier authentication, handover, and roaming. Some devices even support dual connectivity, but based on different IP flows. A true aggregation of resources is not possible and will be studied in the SOLDER project.

### 3.5.1 System-Level Assumptions

System-level assumptions are as follows:

1. We assume a heterogeneous network consisting of macro and small cells. Macro cells support LTE only while small cells are able to aggregate both Wi-Fi and LTE. Users also can aggregate Wi-Fi and LTE.
2. We further assume that the bands available for aggregation have been selected by the responsible entities in the system level architecture. The methodology for selecting these bands in this scenario is out of the scope of the SOLDER project.
3. We further assume that Macro, small cell, as well as users are distributed according to a homogeneous Poisson point process to facilitate the theoretical analysis.

Details about the scenario can be found in scenarios and use cases [1]. Details about the aggregation mechanism itself can be found in the component level requirements [12].

### 3.5.2 System-Level Architectural Requirements

The system level architecture shall follow the general system level architecture described in Figure 3 of Section 2, where RAN 1 is LTE and RAN 2 is Wi-Fi.

### 3.5.3 System-Level Functional Requirements

1. Integrated LTE + Wi-Fi (ILW) eNB capable of aggregating LTE over licensed bands and Wi-Fi over ISM bands.
2. Integrated LTE + Wi-Fi (ILW) UE capable of aggregating LTE over licensed bands and Wi-Fi over ISM bands.

### 3.5.4  System-Level QoS Requirements and KPI Expectations

Using tools from stochastic geometry we expect to be able to study the trade-off between the rate and the coverage based on the density of the base stations and the users. This further allows to quantify the ratio between WiFi and LTE Base Stations densities with the aim of achieving the same user performance and the aggregation gain if the LTE network supported by WiFi.

## 3.6  LTE TVWS with Wi-Fi Unlicensed Aggregation

The scenario for aggregation of LTE in TVWS with Wi-Fi in "conventional" unlicensed spectrum (typically 2.4GHz) has been introduced in Section 3.2.3.1 of D2.1. The primary case being considered here is aggregation of broadcast LTE (eMBMS), i.e., unidirectional downlink only, with locally-available Wi-Fi in order to augment that broadcast, although TD-LTE in TVWS might also be considered at a later date. The core application for this scenario is the provision of augmented broadcast such as extra layers of layered video, and speeding up of large-scale application-layer coded software downloads, through aggregation with locally-available Wi-Fi when available. There are also other conceivable purposes, especially if TD-LTE in TVWS is considered.

### 3.6.1  System-Level Assumptions

The following system-level assumptions are derived in this case:

1. Given that the LTE system is operating in TVWS in this case, at the system-level it is assumed that the LTE BS has Internet connectivity to be able to the geolocation database. Such connectivity is of course standard for LTE. The query of the geolocation database would be done via the NAM or CSAC in Section 2, in order case implemented in the same physical computer that achieves the base station functionality.
2. At the system level, the Wi-Fi access point should have Internet connectivity. However, in some far-fetched applications of this scenario, this is not necessarily a requirement. For example, coded packets for such an information transfer might be provided by a memory stick or through another pre-installed functionality to the Wi-Fi access point. It is possible to achieve this through various packet-level coding schemes.
3. Regarding coverage on the system level and aspects such as frequency reuse and network planning, it is assumed that the LTE broadcast covers a wide area and is fixed, and the Wi-Fi is fixed and sporadic, covering relatively small areas within the wide-area coverage of the LTE broadcast. It is anticipated that the LTE system might

### 3.6.2  System-Level Architectural Requirements

The following system-level architectural requirements are derived:

1. There must be a geolocation database that assesses TVWS availability dependent on location.
   a. According to the current TVWS rules, it is the LTE BS that must directly access this through the Internet, and not a network management entity within the LTE standard. This may not be fully in line with LTE architecture, depending on the level to which the TVWS support is integrated within LTE. However, it is anticipated that there will be flexibility in white space rules if a degree of system reliability/security in the implementation is demonstrated, such as through a standard (e.g., LTE/LTE-A). In this case, it may be possible for the system to query the database on behalf of the LTE base station itself.

### 3.6.3 System-Level Functional Requirements

The following system-level functional requirements are assessed:

1. The application will be aware of the deployment scenario and coordinated at each end of the link. Particularly, at each end of the link (i.e., the receiver of the content, and the server from which the content originates), coding/decoding at the application layer (e.g., layered video, or application-level coding of a software-download) must be undertaken in order to allow the combining of the streams. It is noted that future transport layer protocols are also possible that might handle such coding. This coding is particularly necessary given that, as the core initial solution at least, it is anticipated that the aggregation will occur at the IP layer or higher, with coded packets being combined that are transported over the different systems (LTE and Wi-Fi) in different streams. MAC-level aggregation solutions are alternatively being considered for this scenario, however, they require clear adaptations to the LTE and Wi-Fi systems that are being aggregated, thereby making it such that they can no longer be referred to as 3GPP or 802.11 compliant if such adaptations are made. Further, MAC-level aggregation requires the Wi-Fi and LTE transmitter/receiver in this case to be co-located at each end of the aggregated link, which is clearly not possible in this case. However, such a scenario might still be workable in the context of a distributed RAN or cloud RAN implementation serving this scenario.
   a. It is possible for such coding to be implemented at an intermediary in the network. The two options for this scenario are illustrated in Figure 9.
   b. As in Section 3.4.3, such coding would be implemented in the CSAC/NAM and TAM, respectively using Spectrum Aggregation, Decision and Control, and Terminal Aggregation, Decision and Control functions in Section 2.
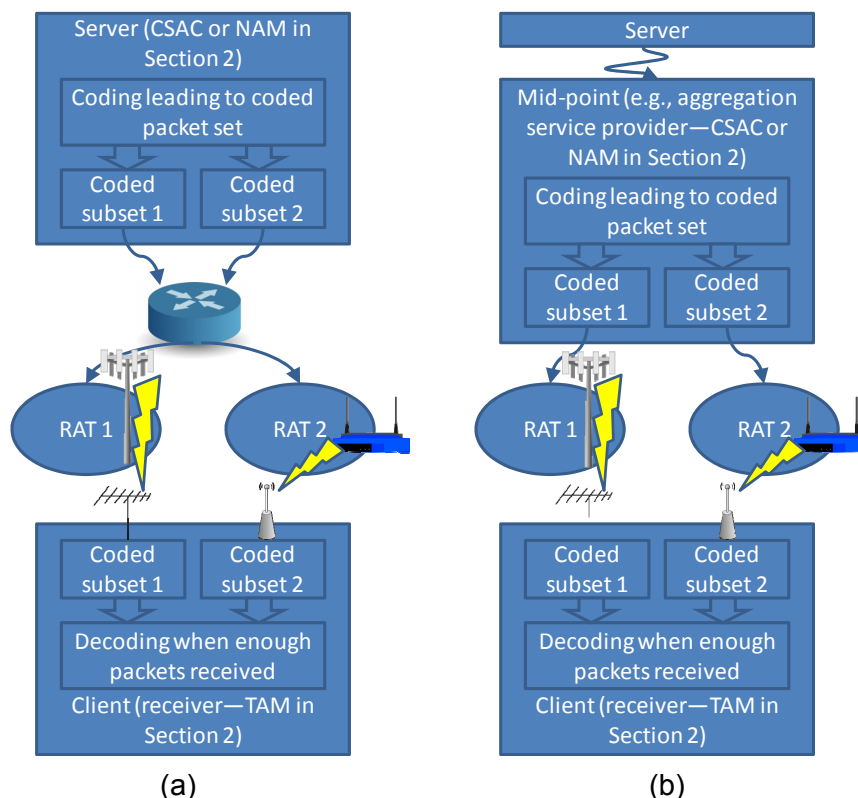


Figure 9: Options for multi-stream aggregation and coding as seen from a system-level viewpoint.

2. There must be a multi-stream functionality. There are a number of transport layer implementations that could support this. Moreover, this might be implemented again at an intermediary (at a common point on the route) in the network. Further, the end-points of these streams, and indeed the coding mentioned above could likely be seen as at the CSAC/NAM and TAM as in Section 2. Such multi-stream operations are also illustrated in Figure 9. Moreover, such capability might again be implemented at MAC level, although significant adaptations to LTE and Wi-Fi would be required to achieve this (likely through integration).

### 3.6.4 System-Level QoS Requirements and KPI Expectations

The following QoS requirements are assessed for this context:

1. First, in terms of the requirements of the separate systems that are being combined, delay requirements are highly flexible, although must typically be able to satisfy a given bound. Coded packets can be buffered in almost all conceivable application scenarios in order to cope with aspects such a delay variability. In order to achieve sufficient end-user satisfaction, the maximum delay bound in this variability (hence, the duration of buffering before video playback, in the case of layered video application) could range from one to a small number of seconds. Regarding other QoS requirements, such as the rates of the separate systems, it is noted that the rate of the LTE system must be sufficient to provide the base layer of the layered video, and the rate of the Wi-Fi system being aggregated should ideally be sufficient to provide one of more of the additional layers. In the case of background software downloads, such constraints need not apply. Finally, requirements such as packet loss of course depend on aspects such as the coding rate that is applied to the base video layer. For the software download case, as the separate packet are coded, there is no particular requirement on packet loss rate. In the Wi-Fi case, of course, packet loss is automatically addressed by the system.
    a. The QoS requirements of the aggregated traffic are already implied by the requirements on the separate LTE and Wi-Fi provisioning described above.
2. Concerning KPI expectations, a key expectation is that the aggregation will be able to support at least one additional layer of video. This is very much open to interpretation, however, it is anticipated that an additional 2-3 Mbps throughput through aggregating with Wi-Fi should be sufficient to achieve this purpose, noting that HD video typically only requires 5Mbps (e.g., Netflix streaming [10]). This can be considered as the absolute baseline requirement. It is further noted that the 5MHz LTE bandwidth, which we are currently using to best match to the 8 MHz TV channel width, will likely easily achieve even a 5Mbps requirement. We may investigate higher bandwidth video, or smaller LTE bandwidths, to address this issue. If we choose a higher bandwidth 4k video, this represents a throughput of around 15-16 Mbps (or a most-challenging case of 25 Mbps, using Netflix as an example [10]). The 15-16 Mbps case almost a doubling of the absolute maximum that 5MHz LTE can achieve [11] in lowest modulation rate with no coding (QPSK, achieving 8.4 Mbps). The choice of KPI expectation for the software download case is again somewhat arbitrary, however, it is expected that through at least a doubling of the theoretical maximum of 5MHz LTE is a good aim, to around 16 Mbps.

### 3.7 5G Waveforms Supporting Aggregation

This scenario is quite different from the others in the sense that a new waveform is being developed that aims to achieve aggregation by combining distributed spectrum opportunities. It is not necessary applicable only to a particularly spectrum type (licensed, unlicensed, etc.),

and could be applicable to many different possible RATs going in to the future. Hence, requirements from a system-level have to be assess from a different perspective than those for the other scenarios.

### 3.7.1 System-Level Assumptions

We assume any type of network (macro, small cells, licensed, unlicensed, etc) and we consider that contiguous or non-contiguous intra-band component carriers (CC) available for aggregation have been selected by the responsible entities in the system level architecture. The methodology for selecting these band/carriers in this scenario might be addressed by the NAM as depicted in Figure 2 of Section 2, based on spectrum feedback information from the NAIC, and TAIC via the TAM.

Details about the scenario can be found in scenarios and use cases [1]. Details about the aggregation mechanism itself can be found in the component level requirements [12].

### 3.7.2 System-Level Architectural Requirements

The following architectural requirements are ascertained:

1. The higher layers must be fed real-time information on the capabilities of the dynamically-adjusted alternative PHY layer, i.e. FBMC. In terms of this architecture in Section 2, this information would originate from the NAIC and be controlled by the NRM. The way the channel availability detection is performed (spectrum sensing, spectrum databases, etc) is out of the scope of the 5G scenario considered in SOLDER.
2. For the optimal combination of users of the new waveform, a coordination mechanism is set up with parameters such as channel quality indicator or effective signal to noise ratio in order to share and coordinate information on utilised resources.

### 3.7.3 System-Level Functional Requirements

The following functional requirements are ascertained:

1. The eNB shall be capable of aggregating at least two contiguous or non-contiguous intra-band component carriers at the PHY layer.
2. The UE shall be capable of aggregating at least two contiguous or non-contiguous intra-band component carriers at the PHY layer.

### 3.7.4 System-Level QoS Requirements and KPI Expectations

It is expected that the carrier aggregation through a 5G waveform will mainly result in improving the usage of the available spectrum, which is considered to be a more and more scarce resource. More specifically, we expect that the side-emissions (considered as interferences) are much lower than in the 4G scenarios. It is also expected that the stringent time and frequency synchronizations in the neighboring cells are much more relaxed since there is no need for time synchronicity between cells.

In a nutshell, one KPI expectation is to improve the area power-spectral-efficiency (Watt/bit/s/Hz/km²) by causing less interference in a usage of resource through the usage of FBMC as an alternative PHY layer. Another KPI expectation is to enhance the cell-edge throughput thanks to the relaxed synchronicity constraints between cells. A further KPI is the power amplifier efficiency which should be improved through such an FBMC concept.

### 3.8 Multi-RAT Aggregation

This scenario is related to the h-RATs aspect of SOLDER. The aim of this approach is to provide a spectrum overlay system that can accommodate multiple heterogeneous RATs managed by an eNodeB offering CA to the UEs among those RATs.

#### *3.8.1 System-Level Assumptions*

We assume a spectrum overlay system that relies on the primary LTE-A system, in which 2G and 3G bands can be embedded therein.  The following assumptions are considered for the proposed spectrum overlay:

1. Time and frequency synchronization is assumed among the heterogeneous physical resource blocks (PRBs).
2. The channel gain at each subcarrier of each RAT varies during the time of interest; hence, the spectrum organization is accomplished in a sub-carrier basis.
3. Inter-technology interference is provided through transmit power control on the PRBs that are adjacent to the primary RAT, e.g. HSPA (3G) or GSM (2G). The TPC will provide more power to the non-adjacent PRBs.
4. A centralized radio resource management (RRM) entity is considered for parallel transmission among the multi-RATs. This might be seen as achieved by the NAM in Section 2 in the context of the RATs being under the control of a single owner and decision making entity, or otherwise might be seen as achieved by the CSAC.

#### *3.8.2 System-Level Architectural Requirements*

The following requirements are defined at network side for this scenario, involving NAM and NAC entities as defined in Section 2:

PRBs Organization – Refarming (NAM/NAC)

1. PRBs are organized based on **long-term statistics** per h-RAT and in a sub-carrier basis.
2. *RAT selection* is also carried out based on a large time-scale, e.g. an average traffic load (on a different basis, e.g. hourly or daily) derived from long-term observations is obtained from the RRM entity.

PRBs Reservation (NAM/NAC)

1. To select the best possible positions for the PRBs within the spectrum overlay (Figure 10). Primary LTE-A system is considered with priority for service provision.
2. Minimization of any negative impact to the synchronization and control channels providing reservation using channel estimation with perfect or imperfect assumption.
3. The efficient PRBs utilization will be modelled using traffic demands and QoS metrics provision.

#### *3.8.3 System-Level Functional Requirements*

Figure 10 shows the concept of managing and controlling the multi-RAT CA efficiently relying on the UE assistance through feedback, synchronization and control channels activation. As mentioned above, we will tackle with the negative impact of the management procedures on the performance of the overall system. The CA in such an heterogeneous environment with different traffic demands, statistics and priorities for each technology must be controlled by the operation efficiently.
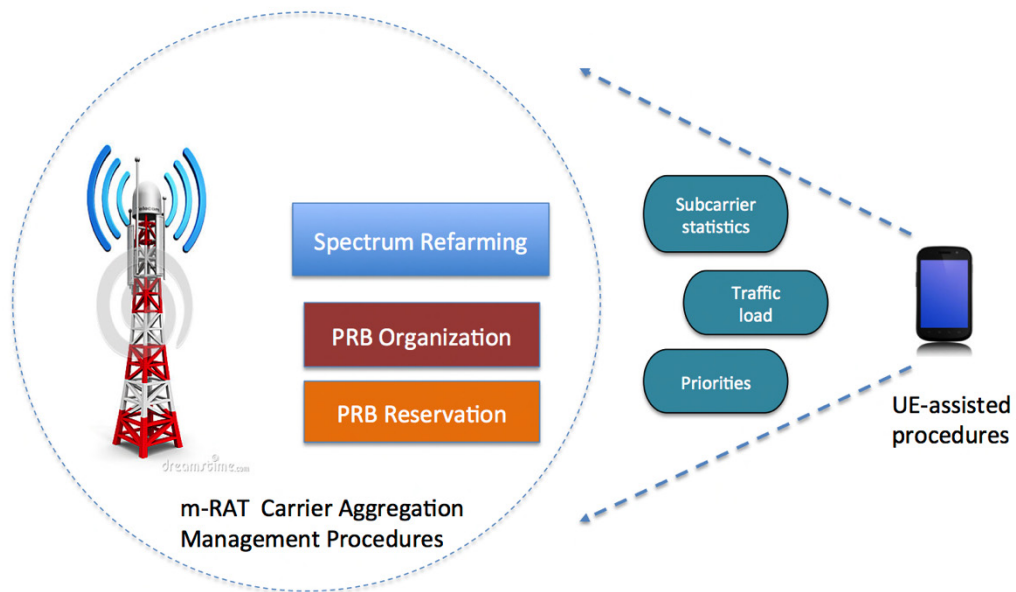
Figure 10: Multi-RAT carrier aggregation management procedures including the UE-assisted ones.

### 3.8.4  System-Level QoS Requirements and KPI Expectations

Our approach is considered to minimize the transmit power and maximize the aggregated throughput for each RAT transmission. The minimization of the amount of allocated spectrum and the switching among RATs is also provided with our approach.

Finally, energy efficiency maximization is provided by jointly optimizing the set of active RATs and the subcarrier assignment for the given RATs.

# 4. Conclusions

This Deliverable has discussed the system-level requirements for the SOLDER aggregation scenarios as summarised in Annex B of Deliverable 2.1. Moreover, is has outlined broad architectures as assumptions upon which the aggregation solutions are built and which the system-level requirements analyses refer to.

System-level aspects are important when it comes to aggregation, as many aspects that have to be addressed affect different components in different locations or apply in a cross-layer sense within a single device (such considerations can also be defined as system-level, from the commonly-used perspective of a radio device being a "system"). Moreover, analysis from a system-level viewpoint is extremely important to the success of aggregation solutions, as many such solutions will require involvement of the wider system (e.g., different network elements, different base stations, different RANs, etc.) or will impact on the wider system in an area-sense (e.g., aggregation decisions for one link affecting availability or potential to aggregate for another link). These realisations act as a motivator for the work that is done in this Deliverable.

It is noted that this document represents the final Deliverable within the planned duration of SOLDER work package 2. Nevertheless, continued and future SOLDER work will maintain the use of this Deliverable and other WP2 Deliverables as reference in the development of aggregation solutions, and in the implementation, proof of concept and prototyping of those solutions. The objective of this is to provide a good link between the different work packages of SOLDER and a smooth progression of the SOLDER work.

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# List of Acronyms and Abbreviations

| Acronym/Abbreviation | Expansion |
| --- | --- |
| 3G | Third Generation (Mobile Communications System) |
| 3GPP | Third Generation Partnership Project |
| 4G | Fourth Generation (Mobile Communications System) |
| 5G | Fifth Generation (Mobile Communications System) |
| ARQ | Automatic Repeat reQuest |
| BS | Base Station |
| CA | Carrier Aggregation |
| CC | Component Carrier |
| CCA | Clear-Channel Assessment |
| CLD | Cross-Layer Design |
| COT | Channel Occupancy Time |
| CQI | Channel Quality Indicator |
| CSAC | Centralized Spectrum Aggregation Controller |
| CSG | Closed Subscriber Group |
| DIFS | DCF Inter-Frame Space |
| DL | Downlink |
| DTX | Discontinuous Transmission |
| DwPTS | Downlink Pilot Time Slot |
| eNB | Evolved Node B |
| eNodeB | Evolved Node B |
| EPC | Evolved Packet Core |
| ETSI | European Telecommunications Standards Institute |
| FBE | Frame Based Equipment |
| FBMC | Filter-Bank Multi-Carrier |
| FDD | Frequency-Division Duplex |
| GSM | Global System for Mobile Communications |
| GTP | GPRS Tunneling Protocol |
| GW | Gateway |
| HARQ | Hierarchical Automatic Repeat reQuest |
| HetBands | Heterogeneous Bands |
| HetNet | Heterogeneous Network |
| h-RAT | Heterogeneous RATs |
| HSPA | High Speed Packet Access |
| HTTP | Hypertext Transfer Protocol |
| HTTPS | HTTP over TLS, HTTP over SSL or HTTP Secure |
| IEEE | Institute of Electrical and Electronics Engineers |
| ILW | Integrated LTE + Wi-Fi |
| IP | Internet Protocol |
| ISM | Industrial, Scientific and Medical (spectrum bands) |
| ITU | International Telecommunication Union |
| ITU-R | ITU Radiocommunication Sector |
| ITU-T | ITU Telecommunication Standardisation Sector |
| KPI | Key Performance Indicator |
| LAA | Licensed-Assisted Access or License-Assisted Access |
| LBT | Listen Before Talk |
| LSA | License-Shared Access |
| LTE | Long-Term Evolution |
| LTE-A | LTE-Advanced |
| LTE-U | LTE-Unlicensed |

| Acronym/Abbreviation | Meaning |
|---|---|
| MAC | Medium-Access Control |
| MME | Mobility Management Entity |
| NAC | Network Aggregation Controller |
| NACK | Negative ACKnowledgement |
| NAIC | Network Aggregation Information Collector |
| NAM | Network Aggregation Manager |
| NAS | Non-Access Stratum |
| Ofcom | Office of Communications (UK regulator) |
| ORM | Operator Resource Manager |
| OSI | Open Systems Interconnection |
| PCell | Primary Serving Cell |
| PDCP | Packet Data Convergence Protocol |
| PMI | Precoding Matrix Indicator |
| PRB | Physical Resource Block |
| QAM | Quadrature Amplitude Modulation |
| QoS | Quality of Service |
| QPSK | Quadrature Phase-Shift Keying |
| RAN | Radio Access Network |
| RAT | Radio Access Technology |
| RI | Rank Indicator |
| RLC | Radio-Link Control |
| ROHC | RObust Header Compression |
| RRC | Radio-Resource Control |
| RRS | Reconfigurable Radio Systems |
| S11 | S11 LTE Interface |
| S1-MME | S1 Mobility Management Entity |
| S1-U | S1-U LTE Interface |
| S6a | S6a LTE Interface |
| SCell | Secondary Serving Cell |
| SCTP | Stream Control Transmission Protocol |
| SGi | SGi LTE Interface |
| SS | Spectrum Selection |
| TAC | Terminal Aggregation Controller |
| TAIC | Terminal Aggregation Information Collector |
| TAM | Terminal Aggregation Manager |
| TCP | Transmission Control Protocol |
| TDD | Time-Division Duplex |
| TD-LTE | Time-Division LTE |
| TPC | Transmission Power Control |
| TTI | Transmission Time Interval |
| TV | Television |
| TVWS | TV White Space |
| UDP | User Datagram Protocol |
| UE | User Equipment |
| UL | Uplink |
| UMTS | Universal Mobile Telecommunications System |
| U-NII | Unlicensed National Information Infrastructure |
| UpPTS | Uplink Pilot Time Slot |
| WF | Water-Filling |
| Wi-Fi | Wireless Fidelity (common misconception, widely used) |
| X2 | X2 LTE Interface |
| X2AP | X2 Application Protocol |