European Commission
Information Society and Media

SEVENTH FRAMEWORK PROGRAMME

Specific Targeted Research Projects

SOLDER

Spectrum OverLay through aggregation of heterogeneous DispERsed Bands

FP7 Contract Number: 619687

WP3 – Aggregation of Heterogeneous dispersed spectrum bands in HetNet and h-RATs

D3.1
Initial report of heterogeneous Carrier Aggregation in LTE-A and Beyond

Contractual Date of Delivery:	31 October 2014
Actual Date of Delivery:	31 October 2014
Responsible Beneficiary:	SEQ
Contributing Beneficiaries:	ISI/ATHENA RC, EURECOM, IS-WIRELESS, KCL, SEQ, TCS
Security:	Public
Nature	Report
Version:	1.0

Document Information

Document ID: D3.1.doc
Version Date: 31 October 2014
Total Number of Pages: 55

Abstract This reports is the first report of the WP3. It captures the initial outcomes of the technical activities, related to carrier aggregation. Several use cases are considered, aggregation of LTE carriers in homogeneous or heterogeneous environment, aggregation of LTE and WiFi, consideration of TV white space spectrum. As multiple scenarios could be imagined, the WP3 has distributed activities to provide a good coverage of these various scenarios. Initial outcome are provided, both in terms of simulation and with respect to foreseen implementation, anticipating WP4 activity.

Keywords Carrier aggregation, Link adaptation, Radio resource management, system capacity, TVWS, WiFi, LTE.

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Document History

Revision	Date	Modification	Authors
V0.1	May 2014	Table of Content generated	G. Vivier
V0.4	July 2014	Initial contributions	ALL
V0.12	Oct 2014	Final round of contributions received	ALL
V1.0	Oct 2014	Clean-up for release	ALL

Executive Summary

D3.1 is the initial report of WP3, about Carrier aggregation for LTE-A and beyond. It captures the initial outcomes of task 3.1, 3.2 and 3.3. It covers the usage of carrier aggregation in various scenarios, from "classical LTE" deployment, either homogeneous or heterogeneous, to more advanced scenario such as aggregation with WiFi or consideration of TV White Space.

Since carrier aggregation could be addressed from many standpoints, several aspects are covered in this report:

The report starts by paving the way to the UE prototype that will be elaborated in WP4. Various design choices are discussed, especially with respect to board design to have an integrated prototype with good flexibility in terms of RF carriers to be aggregated.

Then, we investigate the implementation of LTE-Advanced (LTE-A) evolving physical layer technologies in heterogeneous networks (HetNets). The considered HetNet involves macro and pico eNode base stations, which implement multiple input multiple output (MIMO), link adaptation (LA) with the appropriate feedback and carrier aggregation (CA) technologies for the communication with a single user equipment. We present an improved LA algorithm, which facilitates the enhancement of the total throughput.

Radio resource management is addressed: a pertinent description of what will be evaluated in both Homogeneous and Heterogeneous network deployment is proposed. In particular we are eager to develop a holistic scheduling approach which should be in charge of CC assignment, CC revision and PRB allocation. This algorithm will be adapted to efficiently serve also in HetNets environment where both centralized and distributed management will be studied. Eventually we will focus on the impact of SCC activation/deactivation on the overall network performance indicators.

We further study the problem of radio resource management in heterogeneous networks with two radio access technologies: LTE and WiFi. We show that the introduction of aggregation of LTE and WiFi at both the user and the access point side can significantly improve both user and network throughput compared to the baseline scenario where the macro cells use LTE and the pico cells use WiFi and users can only connect to one of the two.

The use of TV White Space (TVWS), as well as some conceptually similar concepts such as LSA spectrum opportunities, are investigated through the consideration of direct mode communication between devices. This type of scheme is assessed in a way that is largely agnostic of the considered wireless communication systems, with parameter changes being able to reflect the different systems. It is evaluated in context of various aggregation scenarios, involving LTE in TVWS and WiFi in unlicensed spectrum, and LTE in licensed or LSA spectrum.

At last, issues that arise considering FBMC PHY layer CA in front of realistic transmitter front-end are addressed: rationale and description of what will be proposed in order to digitally compensated analog impairments at the transmitter side are described. The potential of the proposed approach is evaluated based on a simple model of a candidate 5G air interface based on FMBC.

Table of Content

1. Introduction

SOLDER project addresses carrier aggregation in many forms. As introduced in [1], multiple relevant scenarios could be considered. In WP3, we started to develop enabling technologies and solutions for such scenarios. Unfortunately, a given technical solution may not be applicable to all scenarios, and we had to address particular use case to progress on the technical activity. Definitely, one can find similarities between scenarios and we tried first to classify them in order to be sure to have a proper coverage of all scenarios identified in [1] within SOLDER activity.

We then distributed among the partner the technical activity as described in the Figure 1. In context of tasks 3.1, 3.2 and 3.3 we investigated carrier aggregation scenarios through different facets, addressing PHY/MAC and RRM aspects as well simulation and implementation aspects.

This report captures the initial outcome of tasks 3.1, 3.2, 3.3.

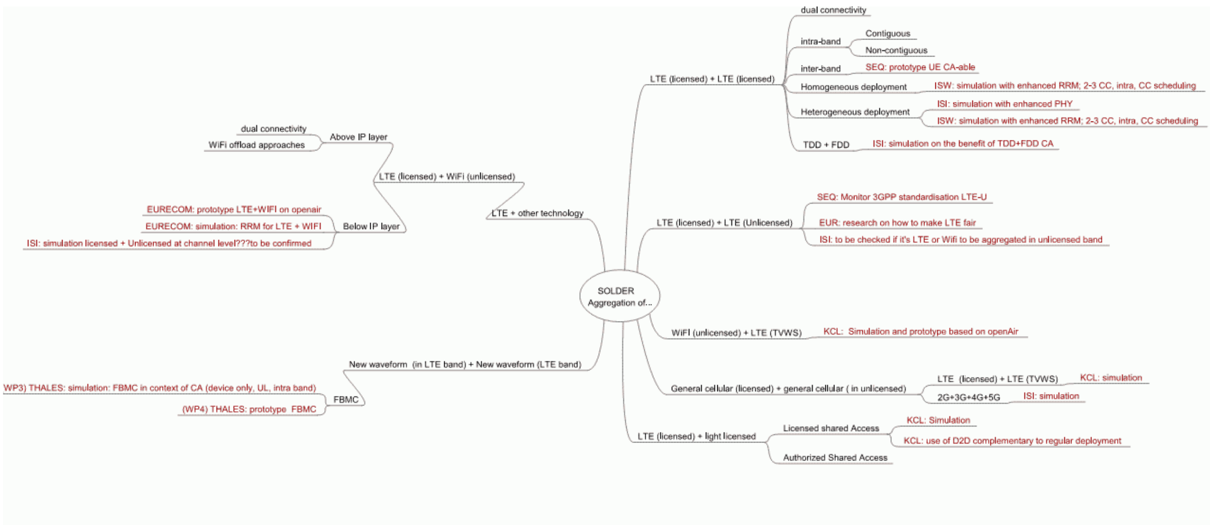


Figure 1: Various flavors of carrier aggregation and Solder scenarios

The document is structured as follows. Section 2 recalls briefly some definition related to carrier aggregation; Section 3 addresses the common case of LTE carrier aggregation, using licensed spectrum; in context of homogeneous deployment. Sections 4 and 5 discuss the heterogeneous case (aggregation of carrier from a small cell and a larger cell, in an overlay deployment), from MIMO/link adaptation and radio resource management standpoint. Section 6 is a placeholder for future activities related to LTE-U (the use of LTE in unlicensed spectrum, relying on carrier aggregation). Then Section 7 leverages direct communication to aggregate LTE channels in TV white space spectrum. Such approach is also analysed for the case of WiFi and TVWS in section 9, while section 8 discusses the aggregation of WiFi and LTE in their respective spectrum. Finally, section 10 introduces SOLDER activities about FBMC as a candidate of 5G waveform that could be aggregated too.

2. Definitions

When a wireless transmission uses several bunch of spectrum, one usually refers to Carrier Aggregation or Spectrum Aggregation. However, several alternate denominations could exist. In SOLDER project, we usually consider the definition as used in 3GPP standardisation body. The main definitions, extracted from [4] are given below.

- **Aggregated Channel Bandwidth:** The RF bandwidth in which a UE transmits and receives multiple contiguously aggregated carriers.
- **Carrier aggregation:** Aggregation of two or more component carriers in order to support wider transmission bandwidths.
- **Contiguous carriers:** A set of two or more carriers configured in a spectrum block where there are no RF requirements based on co-existence for un-coordinated operation within the spectrum block.
- **Contiguous spectrum:** Spectrum consisting of a contiguous block of spectrum with no sub-block gaps.
- **Inter-band carrier aggregation:** Carrier aggregation of component carriers in different operating bands.
    - NOTE: Carriers aggregated in each band can be contiguous or non-contiguous.
- **Intra-band contiguous carrier aggregation:** Contiguous carriers aggregated in the same operating band.
- **Intra-band non-contiguous carrier aggregation:** Non-contiguous carriers aggregated in the same operating band.
- **Non-contiguous spectrum:** Spectrum consisting of two or more sub-blocks separated by sub-block gap(s).
- **Sub-block:** This is one contiguous allocated block of spectrum for transmission and reception by the same UE. There may be multiple instances of sub-blocks within an RF bandwidth.
- **Sub-block bandwidth:** The bandwidth of one sub-block.
- **Sub-block gap:** A frequency gap between two consecutive sub-blocks within an RF bandwidth, where the RF requirements in the gap are based on co-existence for un-coordinated operation.
- **Synchronized operation:** Operation of TDD in two different systems, where no simultaneous uplink and downlink occur.
- **Unsynchronized operation:** Operation of TDD in two different systems, where the conditions for synchronized operation are not met.

Moreover, other bodies may use their own definitions. It is for instance the case the community of dynamic spectrum access, as for instance within IEEE P1900.1 for which the project has submitted the following definitions as initial inputs (to be expanded upon) on definitions related to aggregation within the scope of dynamic spectrum access [5]:

- **Spectrum Aggregation**, In the context of dynamic spectrum access, the concurrent access of spectrum opportunities by a radio or a set of radios on a device, that are in totality or in part realized by dynamic spectrum access technology.
    - NOTE 1—This is typically done to achieve a given purpose such as to obtain capacity that matches to the user's traffic requirement.
- **Carrier Aggregation**, In the context of dynamic spectrum access, the combining of carriers into a single link, that are in totality or in part realized by dynamic spectrum access technology.

  - NOTE 1—This is typically done to achieve a given purpose, such as to obtain capacity that matches to the user's traffic requirements.
  - NOTE 2—A good example of such aggregation might be the aggregation of LTE-U carriers operating in white space with licensed LTE carriers.

- **Channel Aggregation,** In the context of dynamic spectrum access, the concurrent access of different channels by a radio or a set of radios on a device, that are that are in totality or in part realized by dynamic spectrum access technology.
  - NOTE 1—This is typically done to achieve a given purpose, such as to obtain capacity that matches to the user's traffic requirements.
  - NOTE 2—A good example of this is the aggregation of white space TV channels."
- **Link Aggregation,** In the context of dynamic spectrum access, the combining of links that are that are in totality or in part realized by dynamic spectrum access technologies, in order to provide a higher or more stable capacity to a higher ISO layer.
  - NOTE 1—A good example of this is the combining at the link level of TV white space links with links on licensed spectrum.

Regulators have also their own wording. For instance the FCC has defined in [22]:

- **Unlicensed Spectrum**, In spectrum that is designated as "**unlicensed**" or "**licensed-exempt**," users can operate without an FCC license but must use certified radio equipment and must comply with the technical requirements, including power limits, of the FCC's Part 15 Rules. Users of the license-exempt bands do not have exclusive use of the spectrum and are subject to interference.
- **Licensed spectrum** allows for exclusive, and in some cases non-exclusive, use of particular frequencies or channels in particular locations. Some licensed frequency bands were made available on a site-by-site basis, meaning that licensees have exclusive use of the specified spectrum bands in a particular point location with a radius around that location. Since 1994, the rights to use commercial spectrum have generally been auctioned and licensed by particular geographic areas, such as Economic Areas (EAs) or Cellular Market Areas (CMAs). Some bands include a hybrid of these two models, in which the spectrum was initially licensed on a site-by-site basis, and then the "**white space**" around those licenses was auctioned and licensed on a geographic area basis.

In the classification of the various scenarios of spectrum aggregation, as depicted in Figure 1, we usually use Licensed and Unlicensed spectrum to respectively refer to systems where an operator has an exclusive use of the spectrum (Licensed) and a share spectrum access (Unlicensed). The wireless technology used in the spectrum is indicated too. For instance, section 3 "LTE (Licensed) + LTE (Licensed)" is referring to the carrier aggregation in LTE systems, as introduced by the 3GPP standardization.

3. LTE (Licensed) + LTE (Licensed) – Homogeneous deployment

The LTE+LTE in Licensed spectrum scenario is the most common one as it directly corresponds to the scheme as defined in the standardisation. Early deployments by operator are on-going although there are still room for innovation, would it be in the implementation of CA in practice (see section 3.1) or in the combination of CA and other communication techniques as the direct mode (D2D) (see section 3.5).

3.1 Practical consideration of LTE + LTE in Licensed band: the B13+B4 example

As justified in D2.2 [1] the primary scenario to be investigated for this scenario of LTE (Licensed) aggregated with LTE (Licensed) is to consider inter-band aggregation of a low and a high band, with 2 DL carriers and 1 UL carrier. The proposed bands are band 4 and band 13 corresponding to the practical case of one of the most advanced LTE operator. Another candidate could be the use of band 4 and band 17. However, in the following paragraph we will show that this latter case is a little trickier from a deployment standpoint.

3.2 Standard update

Although being not the first case considered in 3GPP, the B4+B13 is one getting much attention to be completed, in order to enable commercial deployment. As a result, specifications are almost complete up to RAN5 (certification).

It should be noticed that every quarter, novel aggregation cases are brought into the standardisation mostly by operators. Since band allocation is specific per region and per operator there is a multiplicity of scenarios that have to be addressed which raise the definition of a single solution that could operate in all operators in all regions of the world.

The Figure 2 illustrates the complexity of defining a global solution that could accommodate all the possible aggregation cases as defined by the standardisation. It should be noted that beyond the RF, additional complexity enters the base band because for instance of the additional peak data rate that may have to be supported, as well as all the process to support the mechanisms of CA.

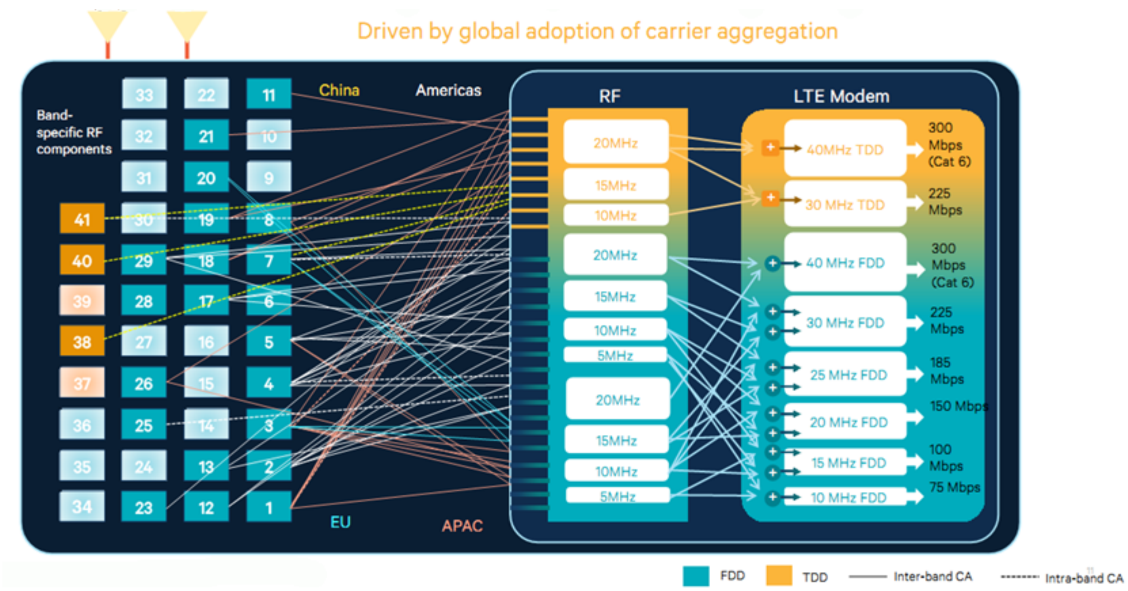


Figure 2: illustration of the RF complexity driven by CA [source Qualcomm]

The complete list of CA cases considered by the standard as of October 2014 is available at http://www.3gpp.org/ftp/Information/WORK_PLAN/Description_Releases/3GPP_Carrier%20 Aggregation%20for%20LTE_20140924.zip

3.3 Implementation aspects

We consider here the case of inter-band carrier aggregation, since we believe that intra-band (and moreover contiguous case) are particular cases of this general former case. Indeed, for particular cases, specific radio architecture could be envisaged. Typically, for contiguous aggregation of two channels of 20MHz, a single RF path, 40MHz wide, followed by a 4096 points FTT could be a smart solution. Such architectures were already investigated. In SOLDER, we prefer to focus to a more generic architecture that could be used to prototype various aggregation cases (and therefore, intra or inter-band).

Depending on the aggregated bands, there could be issue at the RF level due to intermodulation products of one band falling into the other band. This obviously also depends on the duplex mode considered, TDD or FDD.

For instance, the B13+B4 scenario does not present any intermodulation issue. The B13 is a low band (DL from 746MHz to 756MHz; UL from 777MHz to 787MHz) while B4 is a high band (DL from 2110MHz to 2155MHz, UL from 1710MHz to 1755MHz). None of the intermodulation products of B4 (or B13) falls into B13 (or B4) receive band.

However, considering the case of B4+B17 (B17 is a low band, DL from 734MHz to 746MHz and UL from 704 to 716 MHz), it can be seen that the 3rd harmonic of a B17 transmission falls into the receive band of B4 (3x704 = 2112. So, from the UE perspective, a B4+B17 CA UE may generate self-interference because its B17 transmission is likely to interfere with its B4 reception.

It should be note that from the UE side, assuming a CA scenario with a single UL, the intermodulation problem is a bit simpler compared to the similar issue at the base station side, because, at the base station, both carriers have to be transmitted anyway. There are more intermodulation products to be considered.

So, in order to design the prototype of a UE able to aggregate two inter-band DL channels (and 1 UL), we should consider these possible intermodulation issues, if we like to have a design as flexible as possible.

In the following section, other requirements for the UE prototype design are listed.

3.3.1 Requirements

RF agility

In a deployment, nothing prevents one carrier or the other to be the primary carrier. Although it seems logical that the low band carrier should be the primary one (in order to limit the burden of handover due to mobility), the operator may like to switch dynamically primary and secondary carriers for network optimisation. Moreover, a given carrier could be PCC for one UE and SCC for another one.

The design should be thus able to easily support various band (and bandwidth) combinations. Moreover, the Primary cell is not necessarily tied to a given band. As a result, the design should be able to support Pcell on the two paths, and be able to smartly handle mobility management.

Time and Frequency synchronisation

In carrier aggregation context, there are at least two carrier to be demodulated, with their own frequency and timing errors. It is indeed, required to be able to correct frequency and timing drift from local oscillators compared to base station one. In addition, in case of hetnet deployment, the primary and secondary cells may not be collocated, generating additional burden in the time and frequency management (e.g. beyond the frequency difference, the Doppler to be mitigated may not be the same due to geometry).

The standard gives some details: [6] "A UE should cope with a relative propagation delay difference up to 30 ms among the component carriers to be aggregated in inter-band non-contiguous CA. This implies that a UE should cope with a delay spread of up to 31.3 µs among the component carriers monitored at the receiver, since the BS time alignment is specified to be up to 1.3 µs.

The design should be able to support various time and frequency errors, possibly independent from one carrier to the other.

Automatic Gain Control (AGC)
The AGC controls the RF and the digital gains in order to maintain the received signal to the desired level. In context of CA, it may be possible that the power level of the two carriers is different. In that case, two commands should be issued to control separately the two Rx paths.

The design should be able to control the gain of the two Rx chain independently

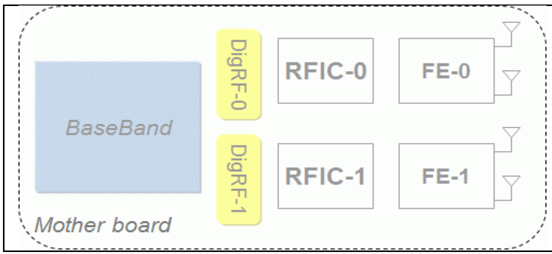
Timing advance and UL power control
Since the prototype is defined to support 2 DL CC and 1 UL CC, there is no specific development related to power control and timing advanced compared to a non-CA UE: they are driven by the primary cell.

PHY layer procedure and protocol stack
The prototype should support Rel.10 features in order to support CA operation. For instance, the modification of the UL to support PUCCH format 3 should be supported, as well as the management of all ACK/NACK and SRS exception cases. Actually, when 2DL CC are used in conjunction of 1 UL CC, all the measurements, reporting, feedback related to the secondary CC are feedback on the primary one following priority rules.
A SCell could be configured but not activated. Activation/Deactivation of SCell is done dynamically at MAC level. A UE should process all activated SCell(s) (decoding of control channel, measurement, CQI estimation)

The design should support the procedure and protocols stacks features as per standard in order to operate in a CA mode

3.3.2 *Early design choices*

Based on the requirements listed in the previous section, we analyzed various high level architectures for the prototype UE, as depicted in the Figure 3 (RFIC being the transceiver and FE the front-end, respectively for one carrier and for the other).

<table>
<tr>
<td>
</td>
<td>All integrated on a single board.
Pros: less connectors, more integrated board
Cons: no flexibility to change frequency</td>
</tr>
</table>

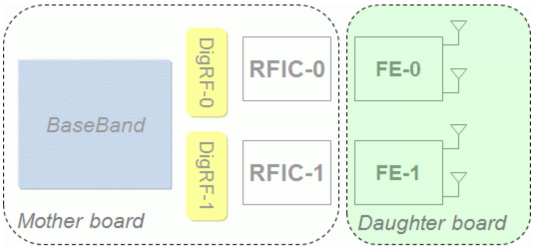
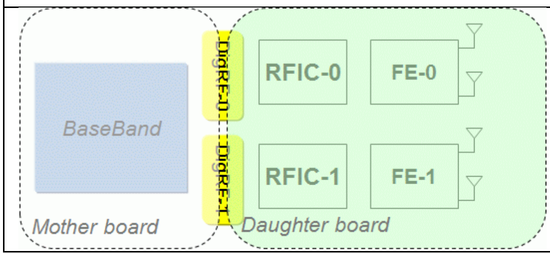
<table>
<tr><td>
</td><td>RFIC with the baseband; separated front-end
• Pros: assuming that RFIC are multiband, such approach is able to support multi RF scenarios cases, assuming change of the front-end. No need to cable the DigRf interface
• Cons: Requires RF connectors between RFIC and FE, not so easy to integrate, and likely poor performance</td></tr>
<tr><td>
</td><td>Digital on the mother band; RF on daughter board
• Pros: Very flexible band support
• Cons: need to implement DigRF interface on connector</td></tr>
</table>

Figure 3: High level architectural options for the CA UE prototype

Have comparing the Pros and Cons of these possible approaches for the board design, we have selected the last one, in which all the RF is deported on daughter boards. The design will have a high modularity and will be able to support any bands and band combinations. To change band, it will be "only needed to change the RF daughter board. Similarly, it could support both inter or intra-band combination.

Then, going further in the analysis, because of the requirement that the primary carrier could be on any band, each RF daughter board should be able to "host" the primary cell, and thus should include a Tx path. Similarly, because of mobility management (and associated capability to make measurement), we open the question to build multi-band RF daughter board, as illustrated by the Figure 4.

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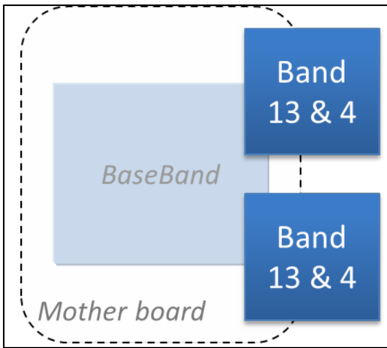
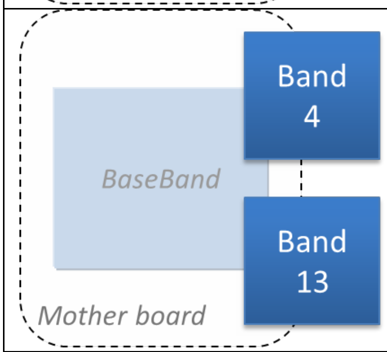
<tr><td>
</td><td>Both RF daughter board are multi-band. In that case, it facilitates legacy operation (single carrier), still able to handle measurements and mobility operation (inter-band handover). In addition it doubles the measurement capability of the receiver although at a higher complexity for gap management. Primary carrier could be hard coded on a given RF board
However, this approach is more expensive, larger (duplicate multi-band front-end) and would require complex design in case of change of RF to support</td></tr>
<tr><td>
</td><td>This approach is lighter and much more cost effective. RF daughter board has to be designed for a given frequency, and is easy to swap frequency.
It put some complexity increases on the management of primary/secondary carrier.</td></tr>
</table>

Figure 4: single or multi-band RF daughter board options

We are in the process to further conduct analysis for our design choices.

Building a UE able to support carrier aggregation is one aspect of the work undergone in SOLDER. The next section introduces activities related to radio resource management (RRM).

3.4 RRM aspects

The simplest case of Carrier Aggregation (CA) in Homogeneous environment is a combination of just two Downlink carriers which originate from the same frequency band and are mutually adjacent. Such approach significantly facilitates the process of aggregation as it can be assumed contiguous carriers encounter similar propagation conditions. If the transmission in Band 4 (AWS band, widespread in North America) is considered then in downlink there is an opportunity to utilize the spectrum ranging from 2110 MHz to 2155 MHz. CA mechanism for LTE entails the possibility to bind carriers of different widths. As an example 20 MHz (i.e. 100 Physical Resource Blocks, PRB) can be linked with adjacent 10 MHz of spectrum (i.e. 50 PRBs). It provides more flexibility for allocation procedure and can result in increased throughput per user as well as overall cell throughput. New transmission opportunities require dedicated solutions to fully exploit extended bandwidth. Thus, a new approach to resource assignment is necessary. It embraces both legacy users (i.e. 3GPP Release 8, CA non-capable) as well as CA-enabled UEs (i.e. from 3GPP Release 10 onwards). In our research we ponder the area where half of the UEs support Carrier Aggregation whereas the remainder is confined to just a single carrier. Definitely the actual ratio of CA-capable UEs in initial phase of commercial CA availability would be lower. Users with a mono carrier are distributed evenly between the two involved frequencies. Furthermore, scheduling algorithm must face the challenge of allocating resources in at least two separate cells which brings additional complexity. A Joint Scheduler will be implemented in a way the following requirements are fulfilled:

- Past allocations on each of the Component Carriers (CC) assigned to the certain UE are taken into account. Such approach is compliant with Proportional Fair mechanism.
- Considering the absolute number of PRBs assigned on all (both) Component Carriers to a certain UE as a basic scheduling metric could lead to the situation when CC-enabled UEs would not be scheduled at all due to excessive past allocations. Thus, in case of CA-enabled UEs we propose to estimate the average throughput per CC and treat this value as a metric for comparison with non-CA users
- Scheduling decision is also determined by the SNIR values reported by each UE on considered PRBs. If n-th UE ($1 \le n \le N$, N – number of the UEs handled by the eNB) reports the highest SNIR on i-th PRB ($1 \le i \le M$, M – number of PRBs available on certain CC) then past allocations (described above) play decisive role whether to assign i-th PRB to n-th UE
- Further enhancements of this algorithm would take into account also QoS (Quality of Service) parameters. Certain carriers can be dedicated or prioritised for the users having high service demands. Moreover, delay constraints can be also considered.

In addition to scheduling decisions (i.e. PRB assignment executed each TTI), also Component Carrier allocation is a significant issue to be evaluated. We propose a dynamic approach in Component Carrier selection. Basic idea is that assigned CCs are not given once per RRC Connection. On the contrary, every k TTI (k >> 1) the allocation of Component Carriers is revised. The parameter k should be neatly chosen in order to ensure optimal carrier allocation while maintaining moderate signalling overhead. It should be noted that Secondary Component Carrier allocation and activation can take 8 subframes (i.e. 8

ms). Thus, CC reassignment might be disadvantageous in certain cases. A bitmap will be sent in MAC control message where “1” would indicate certain Component Carrier remains active or should be activated whereas “0” implies CC should be kept inactive or deactivated from now onwards. This basic concept is shown below.

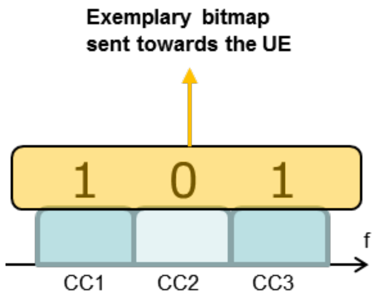


Figure 5: Bitmap with indication which CCs should be activated

During the revision it will be also checked whether certain UE has more favourable radio conditions on a different carrier. Moreover, load on each CC will be evaluated and balanced in order to keep approximately the same amount of UEs on each Component Carrier. Such approach guarantees fairness and optimizes system performance without neglecting particular users or Component Carriers.

Besides mitigating the excessive load on Component Carriers it is also vital to reduce interferences by avoiding unnecessary transmissions. A basic solution which will be implemented is Cross Carrier Scheduling depicted below (Figure 6). Downlink Control Information (DCI) is transmitted on PDCCH within PCC for all Component Carriers. As a result control region is protected and interferences are mitigated. Obviously the gain is larger with the increasing number of Component Carriers.

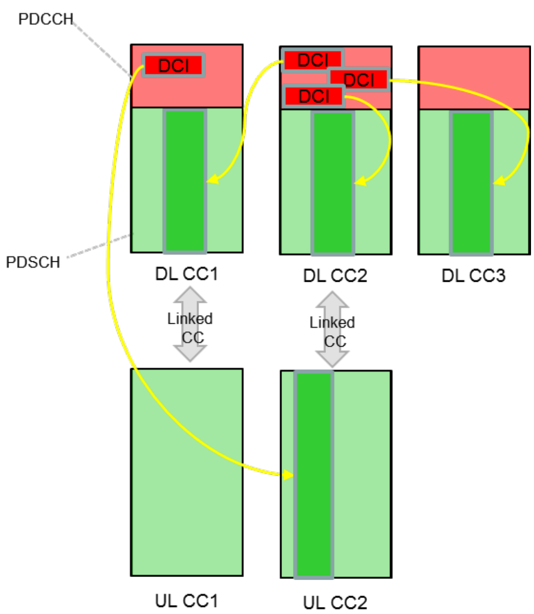


Figure 6: The idea of Cross Carrier Scheduling

The extension of the environment proposed above is to analyse Component Carriers originating from separate frequency bands. Band 4 and Band 13 will be taken into account and those have clearly distinctive radio conditions. Thus, Radio Resource Management module in eNB has additional tasks to execute such as pathloss or channel impulse response calculation and comparison in order to take the optimal scheduling decision. Nevertheless, at the end of the day, this increased complexity might be beneficial due to improved system performance by taking advantage of utilizing diverse transmission frequencies. RSRP level measured by the UE will be a basis for decision which band should be predominantly used for a certain user. If the UE will encounter relatively low RSRP then Band 13 (i.e. 746 – 756 MHz in Downlink) will be prioritized owing to more favourable propagation characteristics as it can be assumed the user is not in the vicinity of the eNB.

Delving deeper into signalling details associated with Carrier Aggregation, we will estimate the impact of "*sCellDeactivationTimer-r10*" which is used to deactivate Secondary Component Carriers (SCCs). The value assigned to this counter has to be sufficiently large in order to avoid unjustified SCC deactivation. At the same time too long waiting period could lead to resource wastage and increase of cell interferences. We will try to emphasize and depict the benefits of proper "*sCellDeactivationTimer-r10*" configuration. Eventually, the outcomes of a study on "shortening SCC activation procedure" will be presented. 3GPP Release 10 describes the sequence of SCC configuration (via RRC Connection Reconfiguration) and then activation (via MAC control messaging). The idea is to verify whether in certain cases it is feasible to simplify this procedure by simultaneous configuration and activation of SCCs if certain transmission is highly prioritized.

In order to evaluate the performance of SCC allocation and more generally RRM strategies related to CA, we are in the process of upgrading our system simulation tool. We expect the result to be available for next deliverable, D3.2.

3.5 Carrier Aggregation in Device-to-Device (D2D) Communications Scenarios

D2D communications offers a number of benefits. Depending on the proximity and channel quality between the two devices that are communicating directly, D2D might reduce the necessary transmission power to achieve a given quality communication link as compared with communication though a base station. D2D also halves the number of transmissions that are necessary, as only a single transmission is required to send a message between the two communicating devices in D2D, as compared with a transmission up to the base station then another transmission back down from the base station to the device in conventional infrastructure-based communications. Moreover, in many scenarios, e.g., if the devices are in the same building, D2D communication might take place with a natural shadowing from the outside world hence achieving a convenient form of frequency reuse. Given all of these characteristics, if D2D communication is used carefully it can greatly improve resource usage efficiency of wireless communications, and for such reasons, D2D is considered within the scope of the SOLDER aggregation solutions that are investigated. D2D aggregation will be combined with other aggregation scenarios as further work, for example, the aggregation of D2D transmission with infrastructure-based communications. However, such work will be provided in later Deliverables of SOLDER.

3.5.1 Simulation Platform and Multi-hop D2D Aggregation Implementation

The aggregation that we investigate in D2D communication scenarios is implemented at the MAC layer as a joint scheduling solution among the frequency bands/channels. Under this scenario, the frequency bands that are being aggregated need not be contiguous, and the aggregation can be implemented in a way that it is *for the most part* agnostic to the types of systems operating in those frequency bands. Hence, a similar simulation platform is developed to investigate each of the D2D aggregation scenarios covered in this deliverable, with various parameterisation differences being present to represent the different systems/bands that are being aggregated on a per-case basis. It is also noted that this that the D2D aggregation simulations and associated platform present a very early view on this aspect of work as part of the SOLDER project; the associated simulations will be enhanced and refined as the project progresses.

To investigate the performance of the D2D aggregation scenarios, we have developed a multi-hop D2D simulation platform using a Monte-Carlo approach. As depicted in Figure 7, a square region of 1,200m*1,200m is assumed, where for the LTE-LTE aggregation case each of the devices has access to up to five 20MHz channels, at the frequency of 1,800MHz. It is assumed that the device always uses one channel as the primary user, and other LTE channels that are aggregated are accessed in an opportunistic manner from other systems.

D2D devices are randomly located with a Poisson distribution in the square region. The D2D devices are assumed to be influenced by the environment at their location, which means different D2D devices observe different spectrum utilization/availability information for the LTE channels. The choice of source and destination node for the multi-hop D2D scenario are randomly chosen at each iteration from any of the set of D2D devices, and results are averaged over all iterations. Each hop in the end-to-end link is able to aggregate a given number of channels, as specified in the chosen scenario. The “primary” LTE services using the channels which the D2D links attempt to use opportunistically use an ON/OFF traffic model for which the ON/OFF times are randomly set in the interval [0, 1]. Furthermore, our simulations use the Okumura path loss model and Rayleigh fading. The conventional LTE service is assumed to be in the field of the simulation as reflected in Figure 7, whereby each D2D hop transmits only according to a maximum allowed power for each given channel and location such that no higher than a threshold of allowed interference to other conventional LTE service is caused. Moreover, each D2D device also has a total power constraint which limits its total transmission power for all aggregated channels combined. Each D2D device implements an adaptive transmission power technique which allows the transmission power to be adjusted hop-by-hop based on each channel’s condition at each hop; if the total power limit it violated for a D2D device, then the transmission power in all is aggregated channels is scaled back equally until to the total transmission power limit is met. For D2D communication, the D2D devices either use individual spectrum bands (e.g., for the LTE scenario in this section), or for opportunistic spectrum access scenarios use the adaptive power technique to share spectrum with conventional users based on the current traffic load and channel quality.

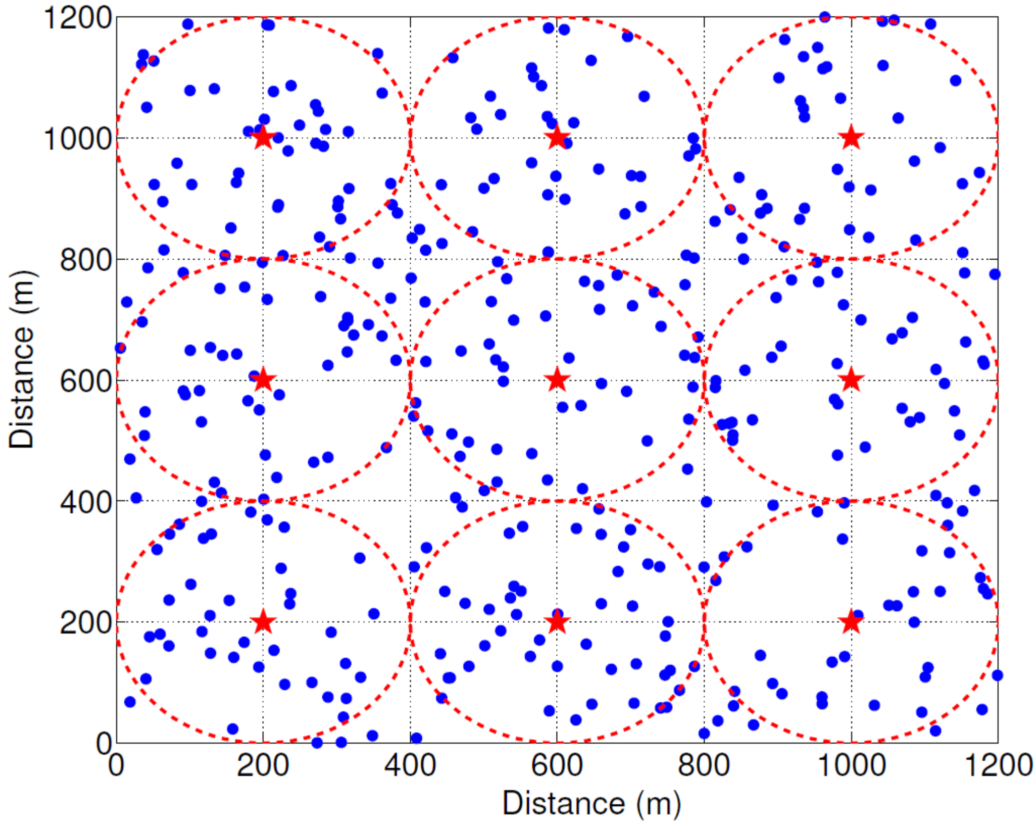


Figure 7: Simulated region. Blue dots are mobile terminals that communicate in a D2D fashion. Red stars are the primary base stations or other fixed transmitters (TV transmitters in the TVWS cases), and dashed red lines indicate the primary transmitter coverage areas

In the context of the LTE-LTE aggregation covered in this section, it is noted that the opportunistically accessed aggregated carriers could be obtained, for example, using Licensed Shared Access (LSA) or a variant thereof. Cases where users are able to access and aggregate another operator's channels opportunistically with a good guarantee of service quality.

The simulation parameters used for the D2D aggregation cases are given in Table 1. These parameters, and the wider simulation platform/methodology, apply for all investigated D2D cases, with parameterisation differences discussed on a case-by-case basis. It is noted that in setting the maximum transmit power for a device to 30 dBm, we are relaxing the default assumption of 23 dBm for mobile devices more towards such D2D communication being performed by laptops or dedicated access points that are likely more distanced from the user. We hope that such a higher transmission power might eventually be allowed for these types of devices.

Table 1: Simulation parameters for D2D aggregation cases

Parameter	Value
Frequency	1,800 MHz, unless otherwise stated
Channel bandwidth	20MHz, unless otherwise stated
Transmission time of a data packet	60 ms
Maximum device transmit power	30 dBm

Maximum allowed transmit power per aggregated channel	Varied
Primary user transmission range	200 m
D2D user transmission range	150 m
Antenna height	15 m
Transmission rate demand	512 kbps, unless otherwise stated
Data packet size	1,000 B
Path loss model	Okumura [X], applicable for 150-3,000 MHz
Fading	Rayleigh

The simulated algorithm is as follows. When D2D Communication starts, the source device initially selects the best route to the destination through shortest path selection function (Dijkstra or Bellman-Ford algorithm). A given number of spectrum bands are aggregated at each hop in the whole route. The spectrum aggregation algorithm can be summarized as follows:

1. Initially, both LTE systems operate centralized spectrum allocation for D2D devices. Every pair of D2D devices is allocated an individual LTE spectrum band for communication by the LTE base station (eNodeB).
2. If the D2D devices operate with spectrum aggregation, the transmitting device sends a spectrum aggregation request to the eNodeB. There is a spectrum aggregation controller (SAC) in each eNodeB, which determines whether the spectrum aggregation request can be granted. If the request is granted, the SAC sends the grant with spectrum information to the eNodeB, and the eNodeB allocates the spectrum bands for D2D devices.
3. The device will always prioritise the aggregation of those LTE spectrum bands which have the low traffic load and good channel quality (e.g., low fading, and larger allowed transmission power for the channel), in order to optimize the Metric (e.g., minimum transmission power, or maximum capacity).
4. After all channels to be aggregated are selected, the transmitter sends packets to the next hop. At the MAC layer, the packets are divided into parts which are equal in number to the number of the aggregated channels. Each part of the packets will be coded and modulated individually, and transmitted simultaneously by relevant carriers on the PHY layer, as shown in Figure 1.
5. The receiver device receives the packets simultaneously on all carriers, and recombined the packets to reconstruct them.
6. If an error occurs on one carrier during the transmission, the source device would only need to re-transmit the relevant packet on the relevant carrier.
7. In the next transmission time, if the spectrum information for the current channel is changed, the eNodeB which has all the spectrum information allocates other spectrum bands for the D2D devices in order to avoid interference to other conventional LTE users, as well as to achieve the best D2D communication performance.

In case of multiple hops, the same operation continues at each hop until the packet is received by the destination device.

Figure 8 depicts the layered simulated aggregation scenario, the key element being multiplexing at the MAC layer, which makes the scheduling decisions among the aggregated channels.

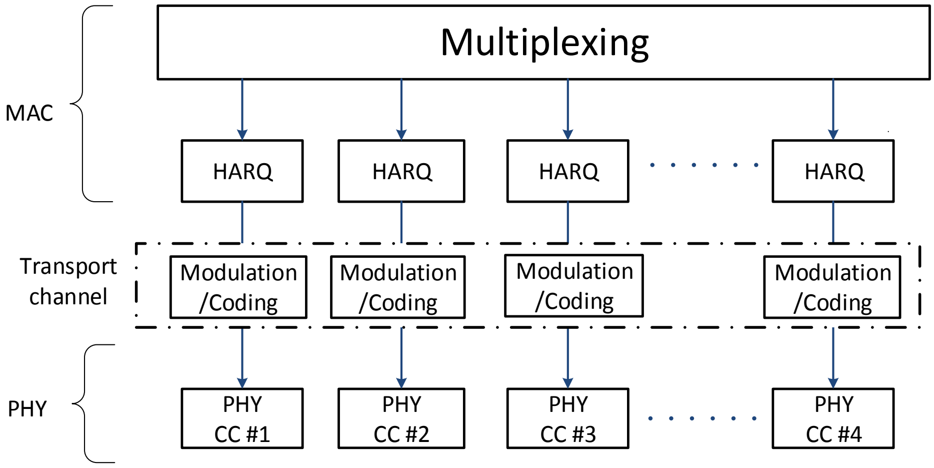


Figure 8: MAC and PHY layer architecture for spectrum aggregation among in two licensed LTEs bands

3.5.2 *Initial results*

Figure 9 plots the average achieved end-to-end capacity under this scenario where multi-hop D2D aggregation is performed with the purpose of increasing capacity. Figure 10 plots the average necessary transmission power over each hop, for the case where aggregation is used with the objective of minimising necessary transmission power to achieve a given rate demand. Both cases are implemented as the previously described form of aggregation at the MAC layer through jointly scheduling among the spectrum opportunities in the different channels, whereby the channel quality varies independently among the given channels. Furthermore, the traffic load of each channel changes with time, and should be different among the hops.

Figure 9 yields a capacity performance increase that is approximately equal for each additional opportunistic LTE carrier that is added (carriers 2-5 being added), and a larger capacity gain for the base licensed LTE carrier, as would be expected. The capacity increase reaches a saturation point as soon as the total transmission power reaches the constraint of the maximum total allowed power transmitted by a device. In Figure 10, where the system attempts to opportunistically schedule among the channels being aggregated to minimise transmission power, it is clear that the availability of a range of channel options to schedule among through aggregation can significantly reduce the required transmission power for a given fixed rate demand. This is due to there being a higher probability of better channels being made available among the scheduling options if there are more channels being aggregated.

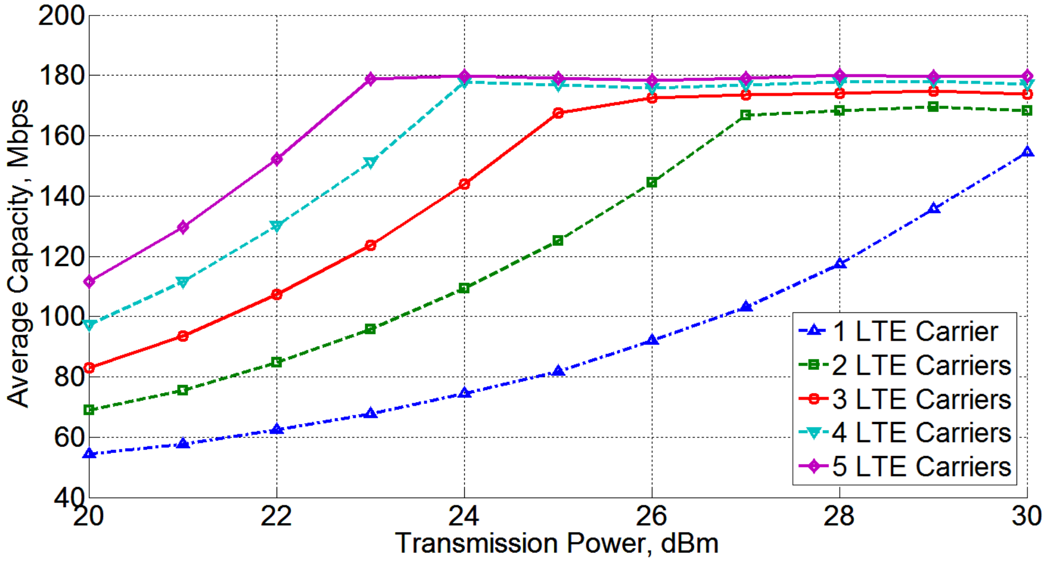


Figure 9: Example of throughput enhancement through aggregation of resources in LTE.

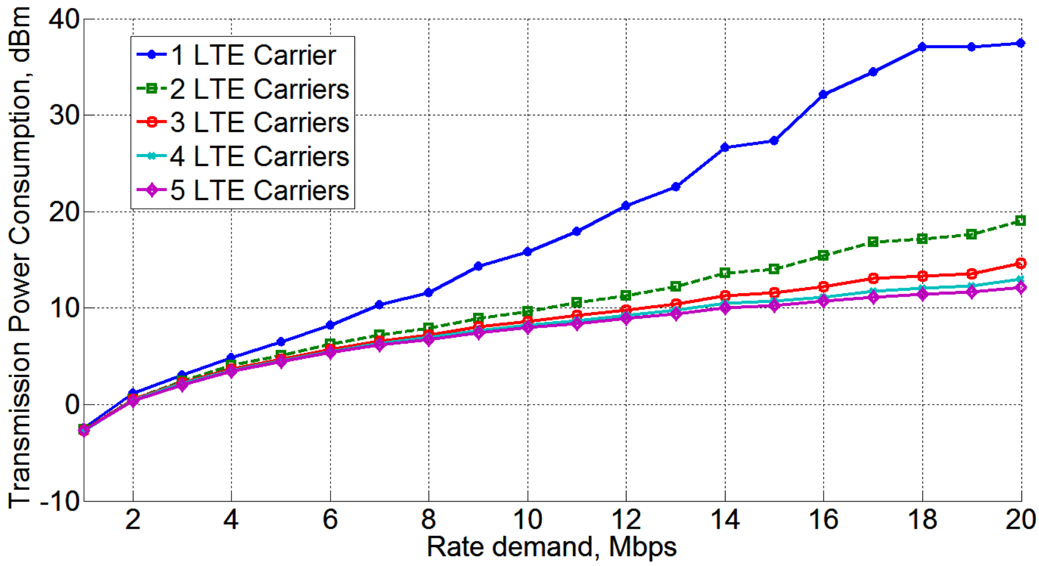


Figure 10: Example transmission power reduction through aggregation of resources in LTE.

4. LTE (Licensed) + LTE (Licensed) – HetNet deployment (PHY layer)

This section addresses the scenario of aggregation of two or three (tri-band) LTE carriers with or without feedback delay, in licensed spectrum, although one carrier is transmitted by a macro cell and the other by small cells in a layered deployment. The scenario was initially introduced in [1] section 4 and enhanced in the current deliverable.

4.1 High level architecture of what will be simulated / prototyped

A practical LTE-A scenario with non-contiguous (NC) carrier aggregation (CA) in a HetNet considering closed-loop spatial multiplexing (CLSM) multiple-in multiple-out (MIMO) link adaptation (LA) is considered. Specifically, the HetNet deployment is composed of a macro eNode base station (eNodeB), two pico eNodeBs and the user equipment (UE), all working under 3GPP LTE standards (tri-band CA scenario). The number of HetBands is available from the macro- and pico- cell eNodeBs as shown in Figure 11.

In CLSM, the UE analyzes the current channel conditions and provides a set of rank indicators (RIs) and precoding matrix indicators (PMIs) for each eNodeB. The PMI determines and applies the optimum spatial domain precoding matrix on the transmitted signal, while the RI indicates the number of spatial layers that can be supported by the current channel experienced at the UE. Each eNodeB may decide its transmission rank, L_j, $j \in \{1,2,3\}$, taking into account the RI reported by the UE, as well as other factors, such as the traffic pattern, the available transmission power, etc. It is also assumed that at the CLSM used by macro eNodeB consists of L_1 layers and $N_T^{(1)}$ transmit antennas ($N_T^{(1)} \geq L_1$), while the one used by each pico eNodeBs consists of L_2 layers and $N_T^{(2)}$ transmit antennas ($N_T^{(2)} \geq L_2$). To support adaptive modulation and coding (AMC) in the downlink, the UE needs to feed back a set of channel quality indicator (CQI) values at each eNodeB. The CQI feedback indicates a combination of modulation scheme and channel coding rate that the eNodeB should use, in order to ensure that the block error rate (BLER) experienced at the UE will not exceed a target (equals to 10%).

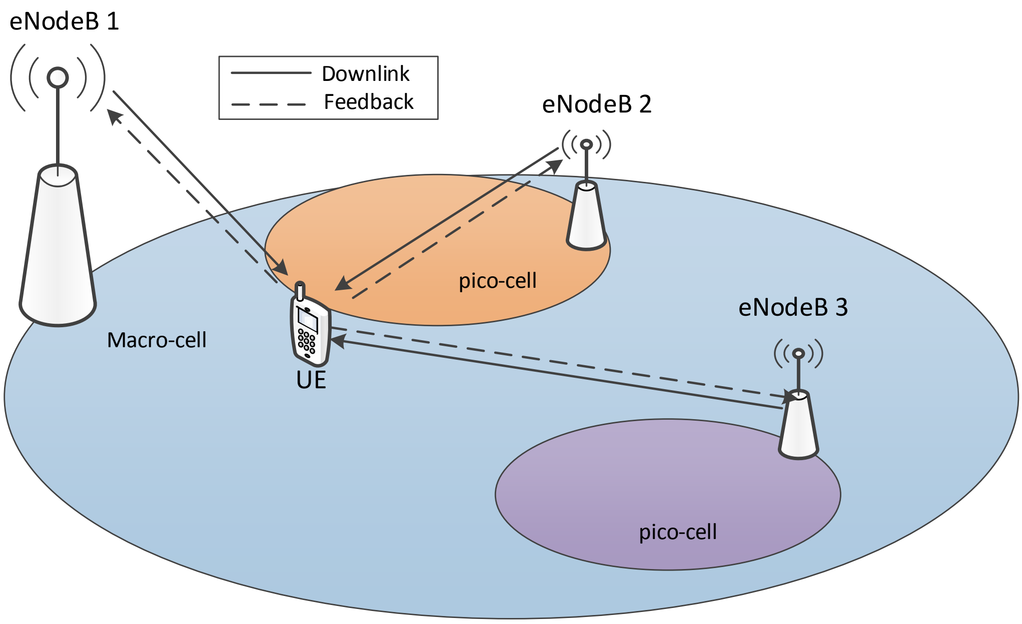


Figure 11: System model of a tri-band CA scenario.

Feedback and Link Adaptation Algorithm

In MIMO LA CA systems multiple parallel data streams (layers) can be transmitted. In general, each layer has different channel quality. Because the transmitter does not have the necessary channel knowledge, feedback from the receiver is required. For this purpose three sets of indicators (CQI, RI, PMI) for each eNodeB are used.

A. Quality Metrics and Feedback Parameters

1) CQI feedback: The CQI value is employed to signal the supported AMC scheme in order to achieve a BLER target (BLER≤ 0.1), which is a typical operating point for mobile communication systems), given the current channel conditions. LTE uses the same modulation order and coding rate, corresponding to a CQI value given in given in [6] (Table 7.2.3-1), for all the resources allocated to a CC. The feedback strategy is based on averaging the postequalization SNR of each CC over all resources of interest. This includes SNRs corresponding to single or multiple RBs per layer but also to RBs of different layers. Effective SNR mapping (ESM) method maps several SNR values to an effective SNR value of an equivalent SISO additive white Gaussian noise (AWGN) channel. This equivalent AWGN channel has similar BLER performance as the original OFDM system.

2) PMI and RI Feedback: The RIs and PMIs are employed for MIMO pre-processing to achieve high spectral efficiency by choosing the appropriate transmission and precoder's rank. Therefore, PMI and RI values indicate the precoder that maximizes the mutual information for a specific subcarrier of CC and temporal-range of interest.

B. Proposed LA Algorithm

The basic idea of the proposed LA algorithm is to maximize the throughput of each CC, so that the system will be able to achieve the maximum possible data rate. The complete LA per CC algorithm is presented below and comprises the following steps:

1) The post-equalization signal-to-noise ratios (SNRs) and mutual informations for all rank and precoding matrix combinations and all resource block (RBs) of each CC are computed using [3] (eqs.(9) and eqs.(8)), respectively.
2) The rank and precoding matrix combination that maximizes the total mutual information over all RBs for each CC are selected, as described in. Note, that the RI is given by this layer number and the PMIs by the codebook indices of the precoders. Furthermore, a layer number L can only be combined with the corresponding precoders given by [7] (Table 6.3.4.2.3-1) for transmission of 2 antennas, and by Table 6.3.4.2.3-2 for transmission on 4 antennas.
3) The effective SNRs, using effective SNR mapping (ESM) [3] (eq.(6)), are calculated for each CC and are mapped to the corresponding CQI values.

Next, each CQI, PMI and RI sequences are fed back to the corresponding eNodeB by error free feedback channels.

4.2 Initial results

This section presents simulation results obtained with a standard compliant LTE-A physical layer simulator [8]. A block fading channel model is assumed; that is, the channel is constant during one subframe duration and fades independently between subframes. The current analysis has been carried out using normalized matrices and hence the path loss of the channel has been removed from the measurements. This is analogous to assuming a perfect

power control in the MIMO system. Additionally, we consider that the UE's receiver has perfect knowledge of the channel state information (CSI) and also a zero-forcing (ZF) equalizer is used to remove all intersymbol interference (ISI). The feedback is sent to the corresponding eNodeB without delay or with outdated feedback (imperfect feedback channel) 1 or 2 transmission time intervals (TTIs). Furthermore, antennas are assumed to be spatially uncorrelated. The exponential effective SNR mapping (EESM) method has been used to map several SNR values to an equivalent SNR value of a SISO AWGN channel. Additionally, the ETU LTE channel model is selected for the following reasons: a) It models typical urban areas; b) it is strongly frequency-selective; c) it represents a high Doppler spread environment. The CC's central frequencies bands were selected as follows: 900MHz (Band # 8) for macro-cell; 1800MHz (Band #3) and 2500MHz (Band #7) for pico-cells, respectively. The selection of CCs central frequencies was made according to band combinations expected in LTE- Rel. 12 where CA from different sites will be allowed, including the aggregation of macro-cell layer carriers with carriers from the small-cell layer (inter-site CA) [9].
The main simulation parameters are summarized in Table 2 .

Table 2: Simulation parameters

Simulation Parameters	Macro	Pico 1	Pico 2
Number of simulated subframes	30	30	30
Fading Type	Block Fading	Block Fading	Block Fading
Channel	ETU	ETU	ETU
Bandwidth (MHz)	5	10	15
CC's Central frequency (MHz)	900	1800	2500
Number of BS antennas	4	4	4
Number of UE antennas	4	4	4
MIMO technique	CLSM	CLSM	CLSM
MIMO decoder	ZF	ZF	ZF
PMI feedback granularity	50	75	75
CQI feedback granularity	50	75	75
Subcarrier spacing (kHz)	15	15	15
CFO normalized to the subcarrier spacing	π	π	π
Feedback delay in TTIs	0, 1, 2	0, 1, 2	0, 1, 2

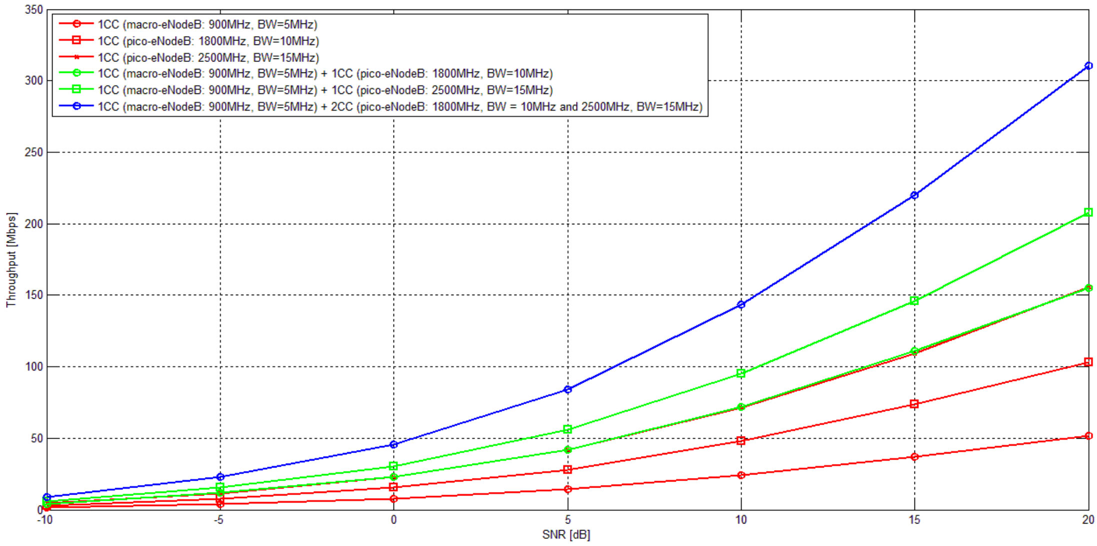


Figure 12: Throughput vs SNR considering ETU channels without TTI feedback delay.

Figure 12 illustrates how the throughput changes with the SNR considering a 4x4 MIMO scenario, and schemes with or without CA. The feedback delay is equal to 0 and ETU block fading channel model is assumed in each of the three scenarios, respectively. The simulation results clearly show the significant increase in the system's throughput, when multiple antennas are employed both at the transmitter and the receiver. Specifically, the throughput for 4×4 scenario with CA is the sum of data rates of each CC. Note that by using the same equipment at the eNodeBs and UE, CA technique seems to be an exceptional tool to increase the overall capacity in heterogeneous environments.

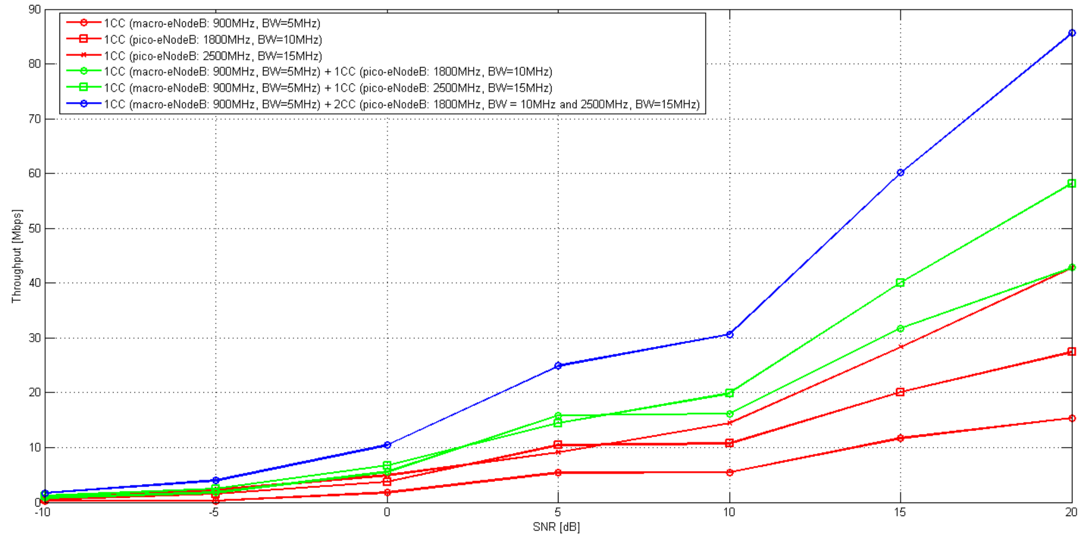


Figure 13: Throughput vs SNR considering ETU channels with 1 TTI delay feedback.

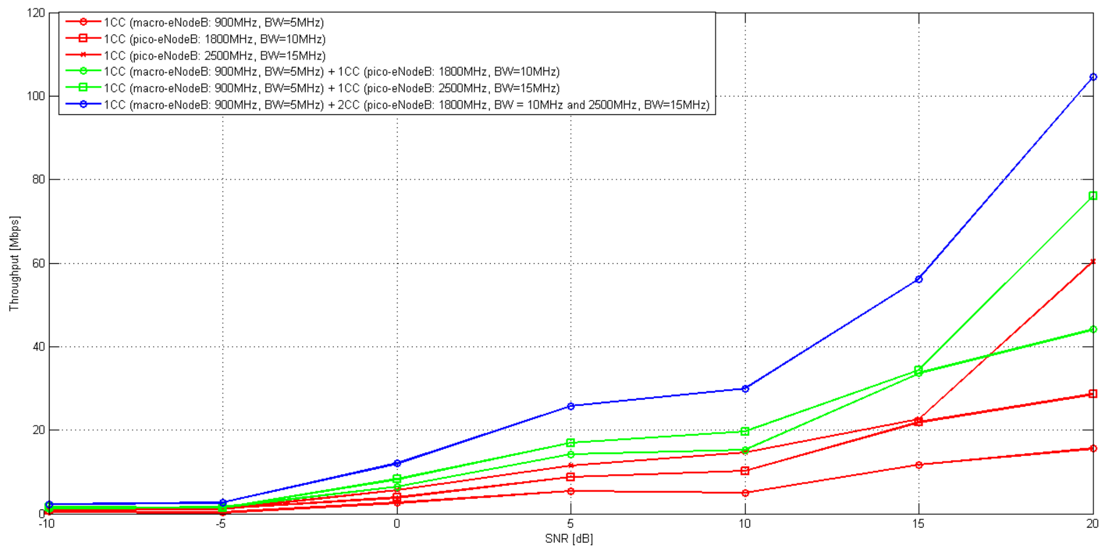


Figure 14: Throughput vs SNR considering ETU channels with 2 TTI delay feedback.

In Figure 13 and Figure 14 system throughput is plotted against the SNR obtained for this setup, assuming an ETU block fading channel model and feedback delay equal to 1 or 2 TTI, respectively. As expected a throughput degradation occurs due to the non-zero feedback delay, which is worse in lower SNR values. Moreover, it should be noted that the degradation is significantly lower when CA is considered.

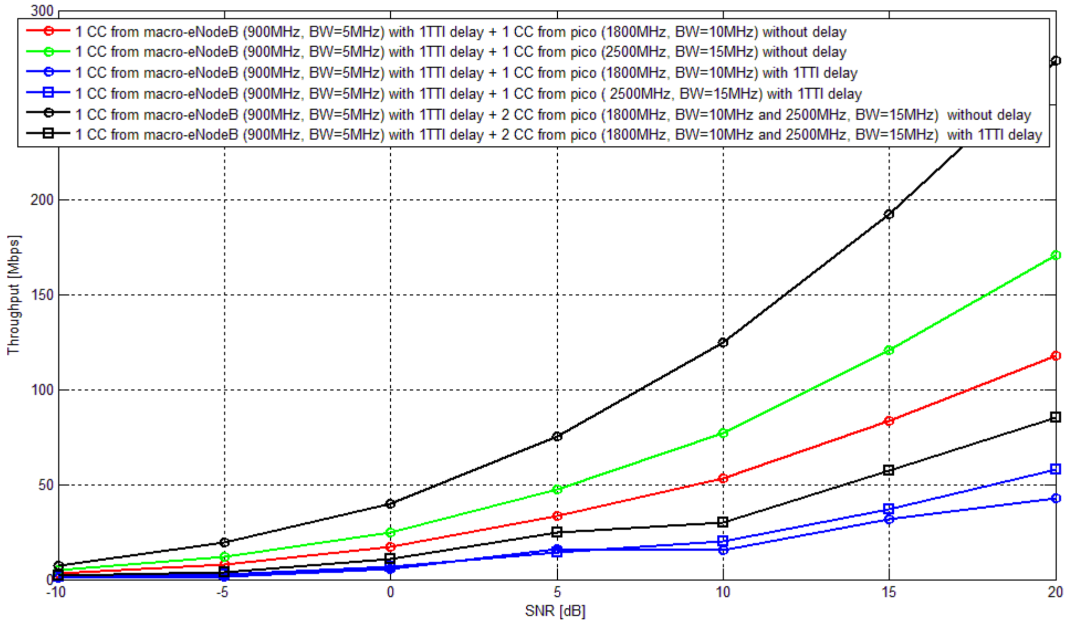


Figure 15: Throughput vs SNR considering ETU channels with 1 TTI delay feedback in macro-eNodeB CC and 0 or 1 TTI delay feedback in pico-eNodeB CCs.

In Figure 15 system throughput is plotted against the SNR obtained for this setup, assuming an ETU block fading channel model, respectively, and feedback delay equal to 1 TTI in the macro eNodeB CC. The outcomes are similar to those above, however in this case the considered scenario assumes heavy heterogeneous fading channels.

5. LTE (Licensed) + LTE (Licensed) – HetNet deployment (RRM)

This section addresses similar scenario as previous section, but focuses on radio resource management.

5.1 High level architecture of what will be simulated / prototyped

The environment used for Radio Resource Management study in case of Heterogeneous deployment will comprise one macro base station (mBS) and two pico base stations (pBS1, pBS2). Macro BS will be capable of transmitting with 43 dBm power level (i.e. 20 W) whereas pico BS will have no more than 30 dBm of output power available. In compliance with a traditional approach – mBS will be connected via X2 interface with pico base stations. This is a key solution to facilitate resource coordination and avoid excessive interferences.

First technique which will be exploited thanks to X2 interface is Cell Range Extension (CRE). An inherent trait of such Heterogeneous deployment is a significant output power imbalance between engaged base stations. In order to mitigate its negative impact and maximize the number of UEs served by small cells, RSRP measured by the UE will not be the ultimate metric to decide which carriers to allocate to a certain user. A positive bias (expressed in dBm) will be added to pico cell RSRP measured by the UE. As a result – UEs which normally would not be considered as potential small cell members, can be scheduled within such cell and this enables Multi-site Carrier Aggregation. The relative proximity of pico BS to the end-user can be in parallel exploited in a different way. As it is shown in Figure 16, the presence of Line of Sight and low user mobility may allow to utilize 256 QAM for a Downlink transmission. It is anticipated it will boost the achievable peak data rates by one-third (compared to 64 QAM) due to increased spectral efficiency. However, this comes at a price of more stringent requirements concerning Signal to Noise Ratio (SNR). Such high order modulation is already involved in 802.11ac WLAN standard and will be a part of 3GPP Release 12. Thus, its applicability to HetNets environment in case of Multi-site Carrier Aggregation will be carefully evaluated..

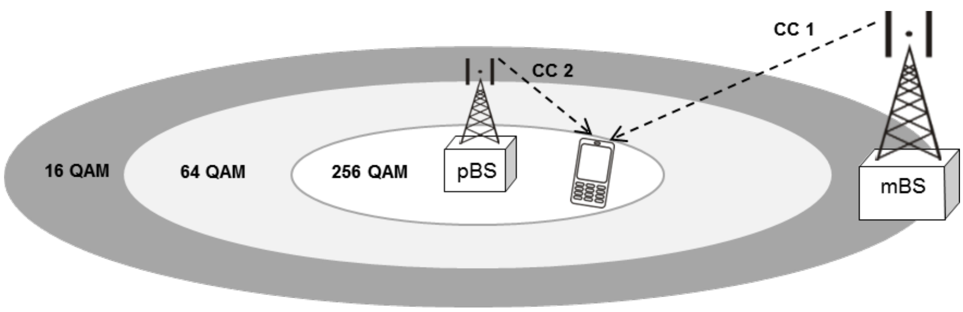


Figure 16: Limited area of 256 QAM applicability

We will assess the effective cooperation of mBS and pBS where CC 1 from macro BS will serve as a Primary Component Carrier responsible for RRC signalling. CC 2 from pico BS will be mainly intended for user data transmission (a concept conformable to Lean Carrier [37]). It is envisaged such approach will provide multiple gains such as increased peak user throughput, more balanced resource distribution or better interference management. Nevertheless, robust and reliable X2 interface is a prerequisite to achieve abovementioned goals. Furthermore, a precise lookup table associated with 256 QAM usage must be defined. An alternative to the ordinary (i.e. centralized) resource assignment scheme can be achieved by introducing additional intelligence to pico base stations. We propose to equip each pBS with the capability of “neighbourhood sensing”. This procedure will enable autonomous carrier selection – without the participation of central managing entity (e.g. macro base station). Pico base stations will communicate directly with each other and exchange the information about the interference levels on candidate Component Carriers. Such approach is shown in Figure 17 and was presented in [38].

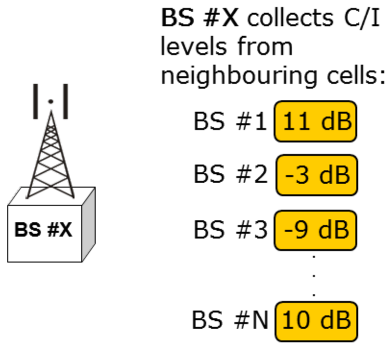


Figure 17: C/I matrix stored and updated by BS #X

i-th CC is chosen as a SCC only if the following condition is fulfilled: *current_int* + *own_int* ≤ *THRESHOLD*. “current_int” denotes the interference level before allocating i-th CC as a SCC, “own_int” reflects the additional interferences such allocation would cause. Threshold must be set adequately in order to ensure no allocation would have detrimental influence on surrounding cells. A simplified system working in compliance with the rules described above will be simulated.

6. LTE (Licensed) + LTE (Unlicensed) – LTE-U

This aggregation case will be addressed in the next report of WP3: D3.2. Technical activities are just starting within the project. With the newly created study item in 3GPP (starting in October 2014) LAA, Licensed Assisted Access, this scenario is of particular interest.

7. LTE (Licensed) + LTE (TVWS)

White spaces inherit the same uncertainties in the quality of the accessed spectrum as spectrum opportunities based on unlicensed spectrum. Indeed, the TV White Space (TVWS) rules in the US [2], UK [10], and under some other national administrations, as well as across the EU through the definition of an ETSI 301 598 Harmonised European Standard [11], in effect make TVWS devices "license-exempt". This is as long as they are certified as communicating directly with a geolocation database, implementing the channel/power usage instructions sent from the geolocation database, take into account security considerations, and comply with requirements such as achieving their stated spectrum mask, among others. It is noted that there are currently 5 options for spectrum mask classes in the UK/EU [11].

There might be, in many locations, vast opportunity for usage of additional spectrum yielded in TVWS (see, e.g., [12]). However, the aforementioned uncertainty implies that there will likely be a very high variance in the interference hence overall SINR that is achieved by devices that are using white spaces in such locations. For this reason, such spectrum opportunities will likely often need to be classified as "best-effort", and the matching of these spectrum opportunities to the underlying requirements of the traffic that wireless links are aiming to carry is therefore extremely important. Moreover, it is noted that in many locations, such spectrum opportunities may be limited in terms of transmission power that can be used in order to avoid interference with primary systems, and there may be a mismatch in allowed transmission power between downlink and uplink directions especially in the case were two separate white space TV channels are being used for downlink and uplink in an FDD case, and also somewhat even in the case that TDD is being used. This means that in order to achieve a more viable communication channel or range of communication options, the combination of such opportunities should be employed, also in some cases comprising the combination of these opportunities with other forms of spectrum opportunities.

This leads on to the benefits of spectrum aggregation. First, the aggregation of conventional spectrum usage (e.g., in licensed bands) with TVWS can yield a given baseline certainty or aggregate confidence increase in the quality of provision that will be achieved, in addition to the often significant albeit highly variable spectrum capacity that might be achieved through TVWS or other unlicensed opportunities. This might be treated as a statistical means of improving the reliability of a given link for the devices as a single communication trunk, or might assist the higher-layer applications in better matching their requirements to the lower-layer communication opportunities, e.g., through selectively mapping flows to the different forms of spectrum opportunities that are being aggregated. For example, applications such as video-conferencing, might combine aspects that require a relatively high rate and high certainty on that rate (hence lower uncertainty in traffic delay), such as a bidirectional video link with a high rate and low delay requirement, with other best-effort aspects such as file transfers and other interactions in a chat window. In such cases, mapping of the bidirectional video link to the reliable, licensed spectrum and the best-effort chat aspects to the more variable, best-effort opportunities such as TVWS will lead to a higher satisfaction for the end-user than would an uncoordinated use of simple TVWS or a less reliable mapping to the entire summation of the spectrum as a single trunk. Moreover, under the application of a layer video codec [13], the mapping of the base layer plus optionally more of the layers to the licensed spectrum, and the augmenting of that with additional codec layers as provided by white spaces access, will also lead to an increase in user satisfaction or the video stream as compared with the case where the layers are randomly mapped to the spectrum opportunities. In the latter case, the uncertainty in spectrum quality through the use of TVWS might lead to complete drop-outs of the video stream through the base layer of the stream being lost, whereas in the former case more graduated variations in quality (e.g., the compression rate with associated artefacts), with the base layer being maintained and no drop-outs, will likely be achievable. This observation underlines the fact that not only are cross-layer considerations essential in the use of TVWS and especially in the aggregation of such spectrum opportunities with other types of spectrum opportunities, the cross-layer considerations in the optimal use and aggregation of such spectrum opportunities involving TVWS can easily become very complicated.

It is noted that there are numerous facets of aggregation and levels at which aggregation could be performed involving TVWS. As is the case for many spectrum aggregation scenarios, it may often be necessary that aggregation is performed only at a relatively high layer, e.g., through the combination of links at IP/network-layer or higher, each of which links are served by a different radio interface on a different spectrum band. There are numerous capabilities that already exist within operating systems to allow the aggregation of such links (see, e.g., [14], [15]). It is noted that such forms of aggregation may often be the case when the spectrum aggregation opportunities are spaced significantly apart in spectrum, thereby not allowing them to be covered concurrently under the footprint one radio chain, or the regulatory rules of the associated spectrum bands under aggregation (which, it is noted will in many cases might be significantly different) may disallow such aggregation. Alternatively, the rules for the bands in between the two aggregated bands that a radio interface may also be overlapping but not intentionally transmitting in, may not allow the radio interface to perform such aggregations. Also covering such cases, it is noted that aggregation may still be performed at a relatively low layer, e.g., by jointly scheduling among the developed links. This could be seen as pushing towards a loose form of aggregation at the MAC layer.

There is, however, hope for aggregation involving TVWS spectrum opportunities to operate at lower layers, progressing to true aggregation at the MAC or even at the PHY layer. To such ends, it is noted that TVWS rules, as well as some fortunate coincidences and developments in radio regulation, potentially lead to scenarios where multiple channels can be aggregated—even by the same radio chain and even perhaps involving other forms of licensed spectrum access outside of TVWS. First, rules for access to TVWS in the UK and EU already envisage scenarios where multiple channels can be accessed concurrently by a TVWS device, with different access patterns (groupings of channels) being able to be specified by TVWS device manufacturers for a device as part of certification [11]. This readily presents scope of the device to aggregate the TV channels according to the given patterns that the equipment is capable of. Second, TVWS, almost internationally, is currently situated directly below prime IMT-Advanced (LTE) spectrum (see, e.g., [16][17]). This presents opportunity for the aggregation of that LTE spectrum with LTE unlicensed accesses in TVWS, where it is noted that 5, 3 and 1.4 MHz LTE bandwidths might access TVWS opportunities for aggregation with the spectrum above. In saying this, it is noted that although the OFDM waveform of LTE presents a challenging scenario for transmission in TVWS due to out-of-band emissions, reduction of the utilised bandwidth to 3 or even 1.4 MHz does gives opportunity to rectify this issue by distancing intended transmission further away from the adjacent channel, and the more lenient spectrum mask classes of Ofcom/ETSI further alleviate the situation. Moreover, it is noted that there is a very strong interest in LTE-Unlicensed (LTE-U), the application of LTE to unlicensed bands, often taken in conjunction with aggregation of licensed and other spectrum with spectrum opportunities that LTE-U access will produce (see, e.g., [18]). Although initial applications of this seem to be aimed at higher frequencies (e.g., 5GHz UNII) and are often linked with assisting small-cell deployments, such "license-exempt" access for LTE might also consider the license-exempt case of TVWS.

7.1 Simulation Platform and Multi-hop D2D Aggregation Implementation

Concerning D2D aggregation, the simulation platform and scenario is broadly as described already for the LTE-LTE case in 3.5.1, with the layered simulated model being depicted in

Figure 18. However, in this case the scheduling decision is made in consideration of the differing characteristics of the systems being aggregated in licensed LTE spectrum and in TVWS, and with one LTE carrier at 1,800 MHz always being used and varying numbers of TVWS channels being aggregated on top of that. The TVWS transmission is assumed to occur in a given number of aggregated 8MHz channels at the upper end of the current ITU Region 1 TV spectrum (790 MHz). The entire bandwidth of each 8MHz channel is assumed to be used, as an idealistic case where it is possible to aggregate, for example, one 5MHz and one 3MHz LTE carrier in 8 MHz, without an unacceptable level of power leakage into adjacent channels.

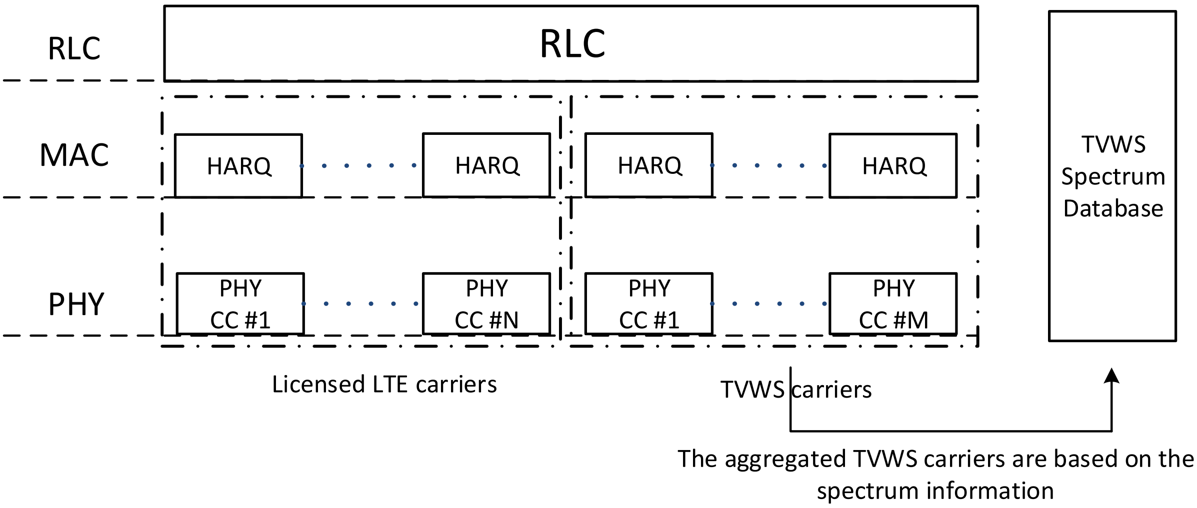


Figure 18: MAC and PHY layer architecture for spectrum aggregation in licensed LTE and LTE (TVWS).

7.2 Initial results if any

Figure 17 plots the average achieved end-to-end capacity for the case where aggregation is performed to increase capacity, and Figure 18 plots the average necessary transmission power over each hop for the case where aggregation is performed with the objective function of minimising necessary transmission power to achieve a given rate demand.

Figure 17 yields a capacity performance increase as the number of channels aggregated is increased. As expected, the performance increase through use of the licensed LTE channel is higher than the additional performance increase achieved with each TVWS LTE channel being aggregated, due to the greater bandwidth of the licensed LTE channel and the “cleaner” spectrum in licensed LTE. Again, the performance plateaus out as the total power limit of devices is reached.

In Figure 18, where it is attempted to opportunistically schedule among the channels being aggregated to save power, the availability of a range of channel options to schedule among can significantly reduce the required transmission power for a given rate demand. Comparing this with the licensed LTE – licensed LTE case in Figure 10, the results for the single LTE carrier are broadly similar aside from some statistical differences, however, the addition of TVWS carriers to save power achieves nearly as much power saving as for the addition of further licensed LTE carriers in Figure 10. This reflects a complex inter-play between a number of factors when comparing the performance of TVWS LTE carriers with licensed LTE carriers. On one hand, the TVWS LTE carriers are at lower frequency and require far less transmission power due to improved propagation. One the other hand, the bandwidth of the TVWS LTE carriers is less, and the interference among carriers is greater due to transmission in the "uncontrolled" TVWS environment as well as interference from the primary TV system to the TVWS D2D devices. On balance, the latter negative aspects slightly outweigh the positive aspects when comparing in TVWS LTE against licensed TVWS in the 1,800 spectrum example.

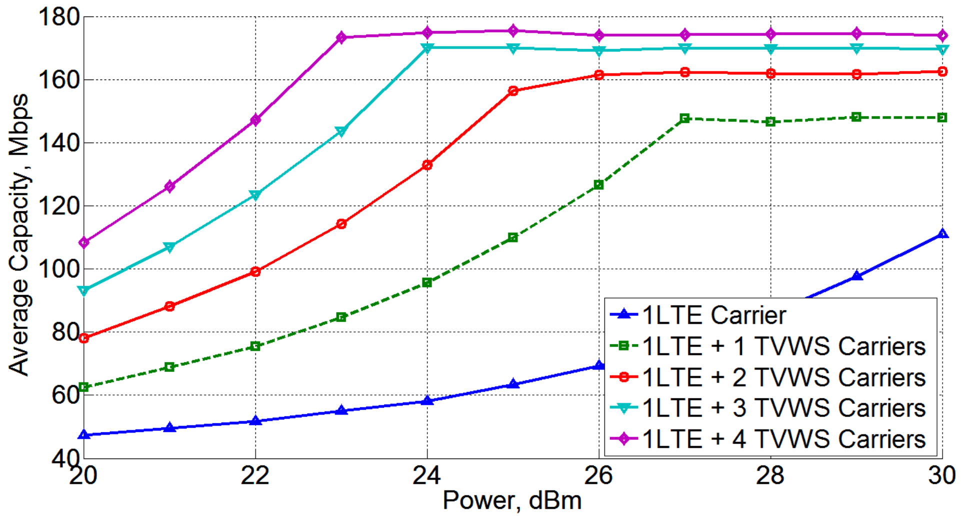


Figure 19: Example of throughput enhancement through aggregation of resources in TVWS.

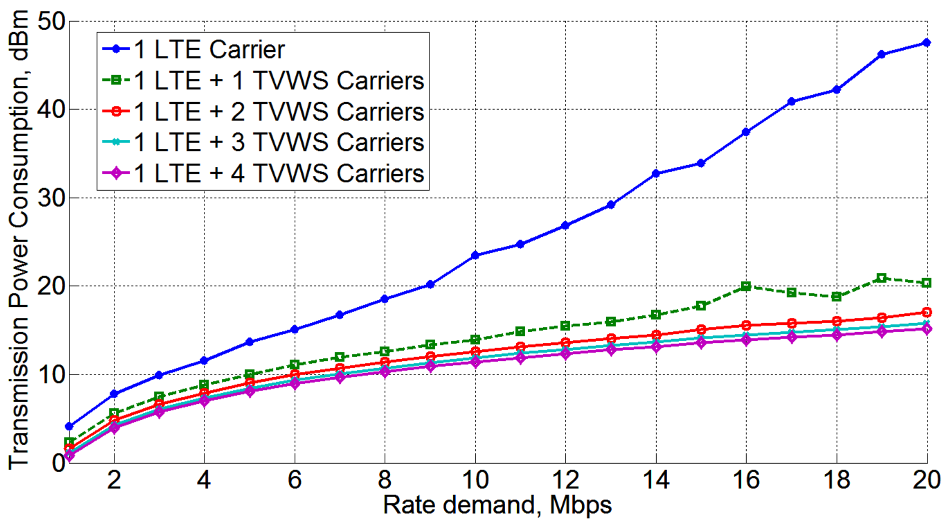


Figure 20: Example transmission power reduction through aggregation of resources in TVWS.

8. LTE (Licensed) + WiFi (Unlicensed)

8.1 High level architecture of what will be simulated / prototyped

We have to model a typical HetNet consisting of 2 tiers (LTE and Wifi BSs) and different kind of users. Our goal is to simulate the Radio Recourse management part and to take some first conclusions about the gain of different Carrier Aggregation techniques (Single-tier, Multi-tier)

8.1.1 Scenarios

An initial set of scenarios has been outlined in D2.2, but they are repeated here including small updates.

The application scenario for the aggregation of WiFi and LTE are heterogeneous networks consisting of macro and pico cells. The pico cells have a high number of users and limited spectrum availability in the licensed band. In scenario 1 the macro cells use LTE in licensed bands and the pico use WiFi in unlicensed bands. In scenario 2, the pico cells support both LTE and WiFi (these cells are also called integrate LTE – WiFi (ILW)).

We will further consider 6 types of users:

- users that support LTE only;
- users supporting WiFi only;
- users supporting WiFi or LTE but not both at the same time (single-connectivity, single-RAT)
- users supporting LTE aggregation from different tiers (multi-connectivity, single-RAT)
- users supporting LTE+WiFi aggregation from the same tier (single-connectivity, multi-RAT)
- users supporting LTE+WiFi aggregation from different tiers (multi-connectivity, multi-RAT)

Figure 21 shows the two scenarios as well as the reference scenario (Scenario 0), where users can connect to either LTE or WiFi, but not to both.

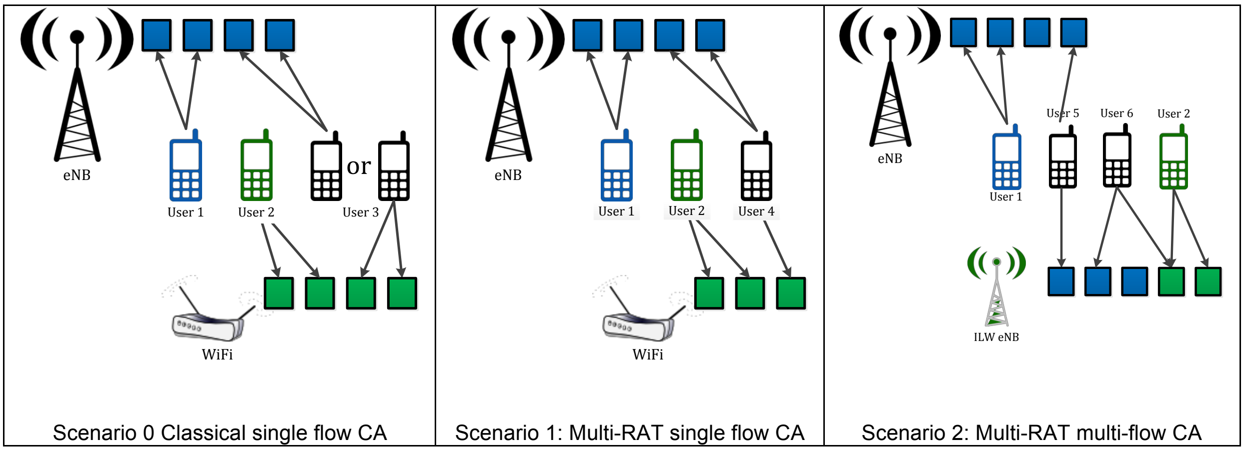


Figure 21: LTE + WiFi aggregation scenarios

8.1.2 Topology of the Network

The placement of the BSs and the UE will be Poisson Point Process (PPP). As it showed at [19] and [20] instead of assuming BSs are placed deterministically on a regular grid, we can model their location as a PPP of a density λ. This approach is accurate, realistic and it gives the opportunity of analytical, theoretical calculations with stochastic geometry based to the independence of the BS position.

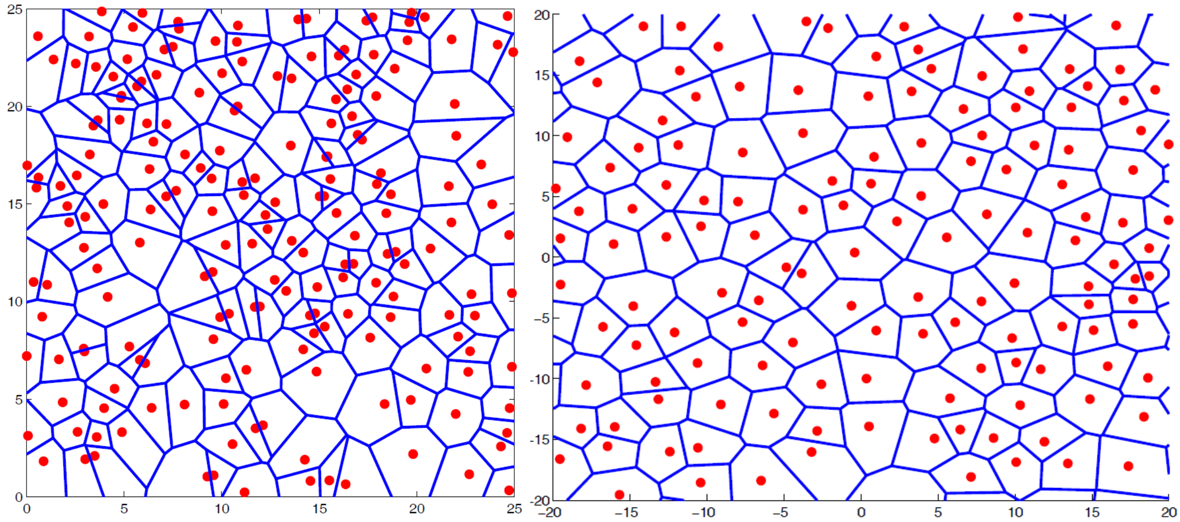


Figure 22: Left, Poisson distributed base stations. Right, A 40 × 40 km view of a current base station deployment by a major service provider in a relatively flat urban area. The cell boundaries correspond to a Voronoi tessellation.

As we see at the Figure 22 the disadvantage of this process is that there is a possibility two BSs be placed very closed to each other, something uncommon for the topology of macro cells. From the simulation point of view, we overcame this problem by model the macro users as Hardcore Process (Hardcore processes are point processes, with exact point density λ, where the points are forbidden to be closer than a certain minimum distance).

8.1.3 Channel Model

We assume that, each of k-tier BS transmits at constant power P_k. Then the received power $\bar{P}_i$ at the typical UE i, which located at Euclidian distance $d_{i,j}$ from the j BS is modeled as

$$\bar{P}_i = P_k H_{k,d} C_k \left\| d_{i,j} \right\|^{-a_k}$$

C_k is the constant loss when the link length is 1. $H_{k,d}$ is a random variable capturing the fading value of the link between the US and the BS. To be accurate $H_{k,d}$, C_k and a_k are not depend from the tier k, but are depend from the carrier frequency e.g. $C_k \cong (\mu_k/4\pi)^2$ where μ_k denotes the wavelength, in our case each tier has one main frequency so we use the same notation for simplicity.

8.1.4 Load Modeling

We Assume that all the UE are have unlimited demands so they want as higher rate is possible. Additionally, there is a minimum fractal where bandwidth can be segmented. So b is the quantum of the bandwidth (may represent the basic frequency resource allocation unit in LTE). If we represent as N_j the number of UE attempting to connect to the BS j (which is at tier k) and $bN_j > B_k$ where B_k is the total bandwidth of the BS of tier k, then the BS is fully loaded, in this case some of the UE which are at the coverage of BS j have to be blocked.

8.1.5 Association Criterion

Each UE has to decide in which tier (or in which BS) will be connected, the criterion at this choice will be the maximum SINR criterion. So each UE will receiving the SINR from all the BS and it will be connected to the strongest one. Different criterion which will take into account the Load of the BS and provides better load balance such as the sum of $\log(SINR)$ [20] or taking into account the Load of each BS at the .
At the other hand, the criterion how a BS will allocate the Resources to the connected users will be the Round Robin (RR). Round Robin scheduler allocates the resources fairly between the UE without taking into account the SINR of each user. So is fair and low complexity solution but not necessary the optimal.

8.2 Initial results

We suppose that we have an area A of size $1\,km^2$ and a 2-tiers HetNet, each tier has different frequency so we have 2 bands, 800MHz (LTE) and 2.4 GHz (Wifi). The Table 3 summarize the specific system parameters.

Table 3: System Parameters

Density of LTE BSs λ_1	$10^{-5}m^{-2}$
Density of LTE BSs λ_2	$\lambda_2 = 3\times\lambda_1$
Density of UEs λ_u	$2\times\lambda_1\ to\ 20\times\lambda_1$
Max T_x power of LTE BSs	$43dBm$
Max T_x power of Wifi BSs	$23dBm$
Noise PSD	$-175dBm$
Noise figure	$6dB$
$800MHz$ wavelength μ_1	$0.375m$
$800MHz$ path loss constant a_1	3
$800MHz$ bandwidth B_1	$40MHz$
$2.4GHz$ wavelength μ_2	$0.125m$
$2.4GHz$ path loss constant a_2	4
$2.4GHz$ bandwidth B_2	$20MHz$
quantum frequency b	$1.8MHz$

We consider six different kind of users as outlined above. At these initial results we have implement scheduler which sorts the users with respect to $SINR$ and after cyclically allocates the resource blocks. The user with the best $SINR$ desides first where he will connect his first carrier and he allocates a quantum b of the whole bandwidth, after decides the user with the second best $SINR$ users, ech. When the last user connects his carrier we repeat the same procedure for the second carrier and after with third.

The Figure 23 shows that the average rate per user is decreasing as the number of users is rising. At the light load the multi-tier user has not significant gain than the single tier one. This is because the load is not enough to full any BS (wifi or LTE) so at both cases the users connects all of their carriers to the preferable BS. When the load raise up, some BS running out of resources so the users should find another BS to connect their next carriers, and then the Multi-tier user has advantage because he does not have any constrains about the tier of the BS which will serve him. Additional is obvious if we look the Multi and the Single tier users from one hand and Wifi and Cellular at the other, that the gain of choosing the tier of your preference is significant.

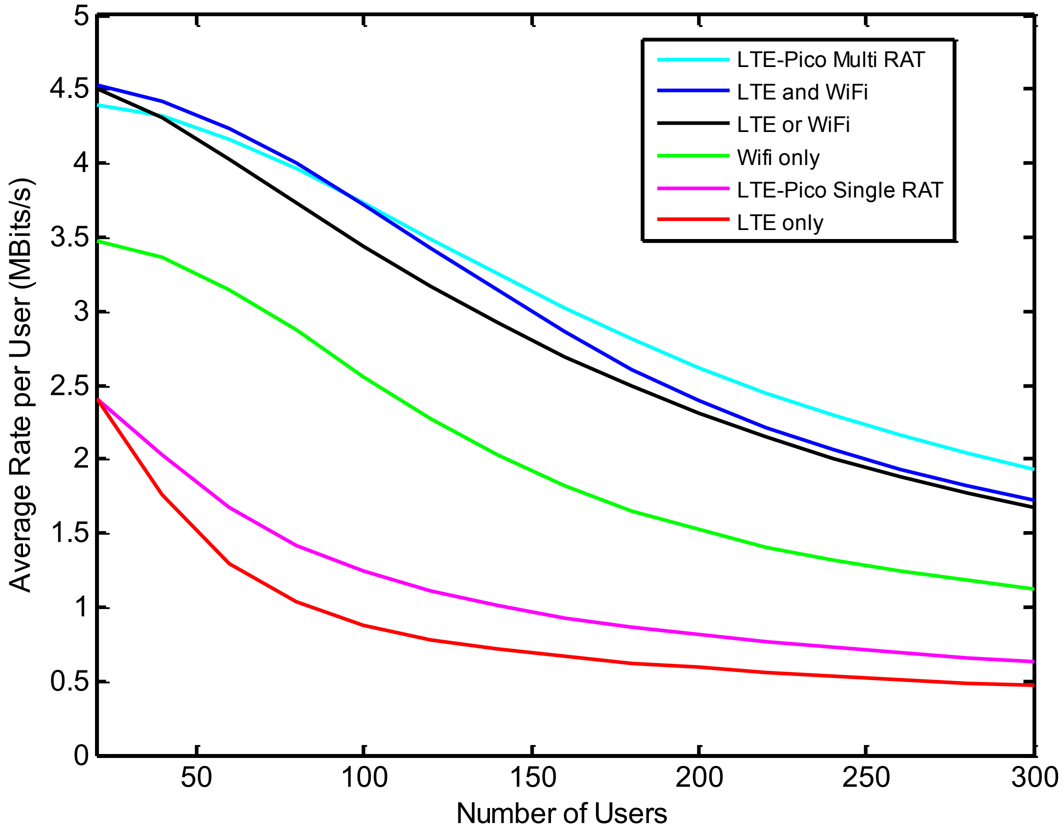


Figure 23: Average Rate per User

At Figure 24 we see the Total Rate of the network. Again we observe that the Multi-tier and the Single-tier are almost equal at light load scenario.

At both Figure 23 and Figure 24 we see that the WiFi Network has better rate than the Cellular. The reason is the difference densities and the low noise spectral density of our scenario.

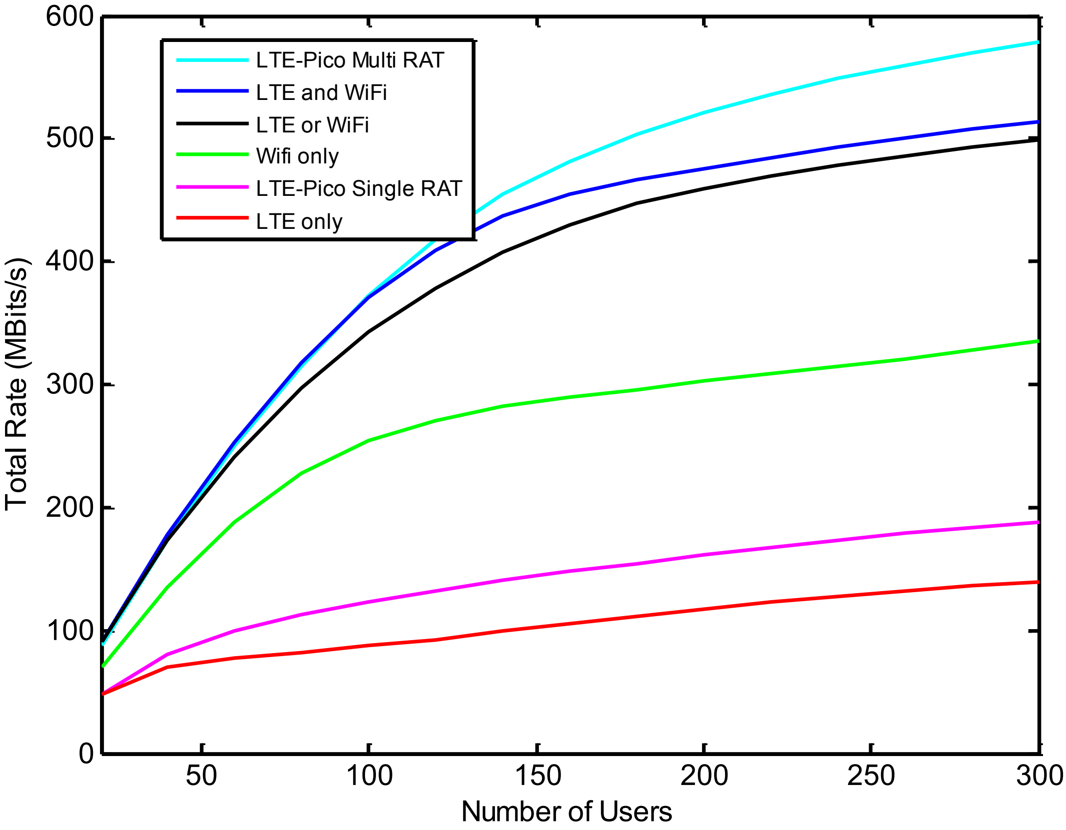


Figure 24: Total Rate

9. Wifi (UnLicensed) + LTE (TVWS)

9.1 Simulation Platform and Multi-hop D2D Aggregation Implementation

“Conventional” unlicensed spectrum and TVWS spectrum have very similar characteristics, although with some differences. One key difference is that TVWS channels might have a different maximum allowable power in different locations under the UK/EU rules for TVWS, as opposed to the fixed maximum allowed power for all locations that is the assumption in unlicensed spectrum. Moreover, TVWS is of lower frequency hence has far better propagation characteristics than most unlicensed frequency bands, especially the most commonly-used 2.4GHz and 5GHz ISM and UNII unlicensed bands. This has the positive implication that greater coverage can be achieved or less power need be used to achieve a given link, but the negative implication that interference among the TVWS devices is far more of a problem.

Our simulations are built in the same broad model as in the prior Section 3.5.1 and Section 6.2. The layered simulated model is as in Figure 25. The key differences in this case are that a WiFi connection of 40MHz bandwidth is used all the time over each D2D link, and a given number of TVWS LTE carriers are aggregated on top of that. The WiFi connections in the simulation system have a choice of two 40MHz channels to use, based on the interference observed in the channels.

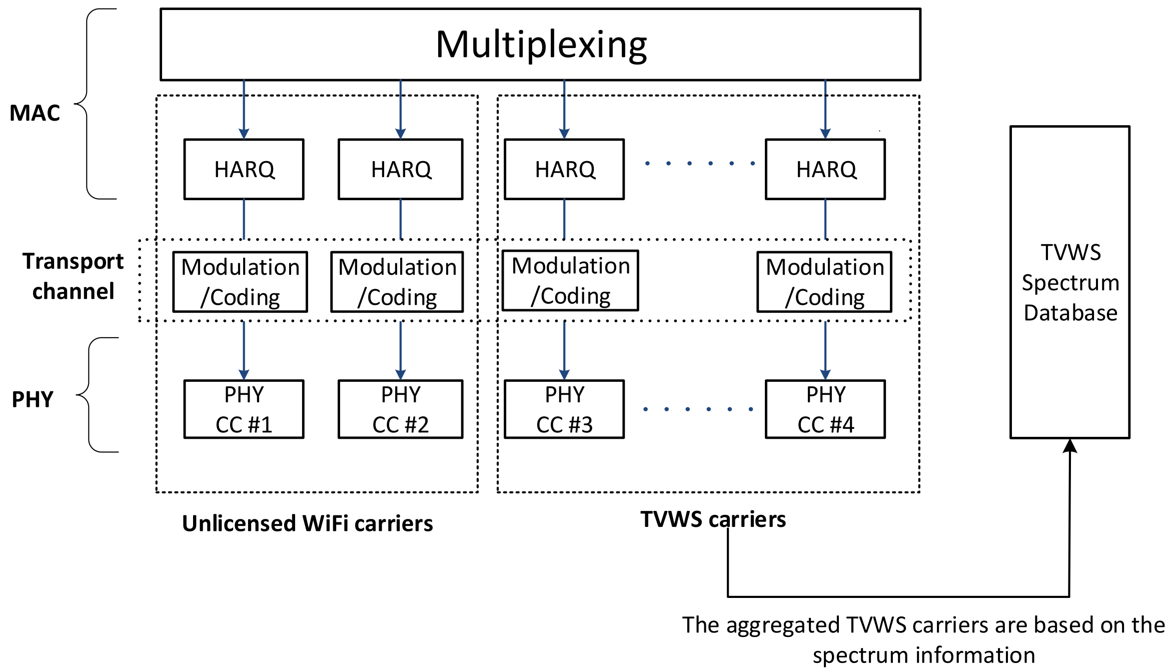


Figure 25: MAC and PHY layer architecture for spectrum aggregation in licensed LTE and LTE (TVWS)

9.2 Initial results

Figure 26 plots the average achieved end-to-end capacity for Multi-hop D2D connections where aggregation is performed to increase capacity, and Figure 27 plots the average necessary transmission power over each hop, for the case where aggregation is performed with the objective function of minimising necessary transmission power to achieve a given rate demand.

Figure 26 yields a small capacity increase with each TVWS carrier that is aggregated on top of the WiFi channel. This is because the bandwidth and capacity of the WiFi channel far outweighs each of the 8MHz LTE TVWS channels. The capacity performance again plateaus as expected once the transmission power limit for each device is reached. Figure 27 shows a modest power saving achieved by intelligently scheduling with the LTE TVWS channels added and aggregated. This saving is modest because the 40MHz WiFi is already relatively power-efficient due to its large bandwidth hence good diversity.

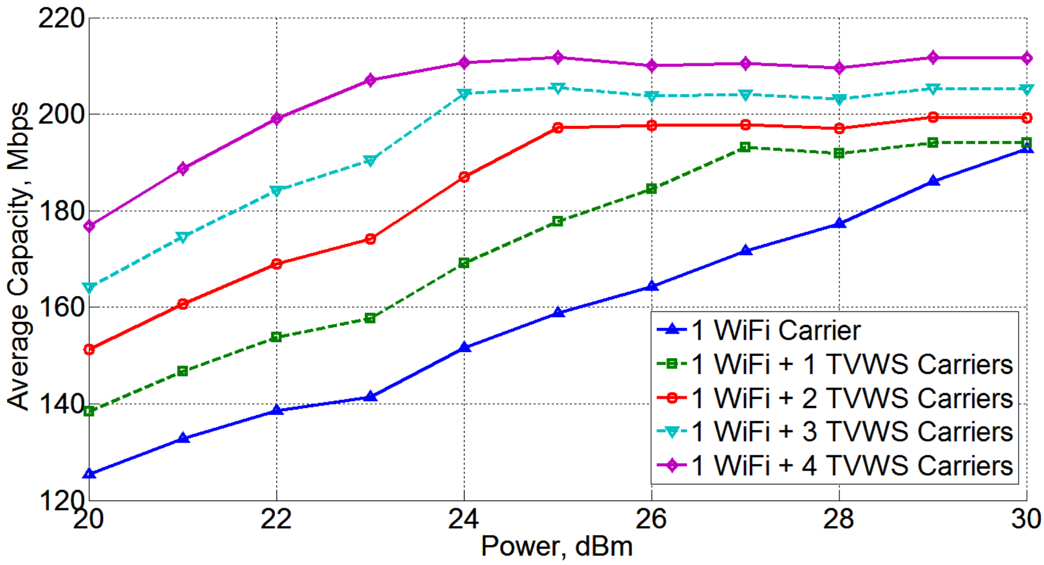


Figure 26: Example of throughput enhancement through aggregation of resources in WiFi and TVWS.

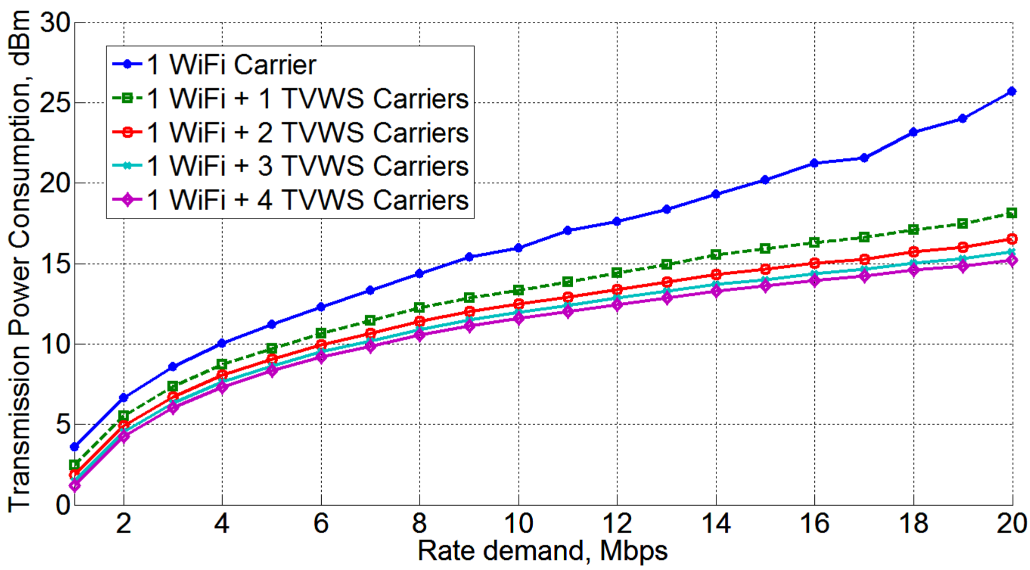


Figure 27: Example transmission power reduction through aggregation of resources in WiFi and TVWS.

10. 5G waveform (Licensed) + 5G waveform (Licensed)

The physical layer selection of the future generation of civil radio system (beyond 2020) is an open topic. Today's mobile communication systems (LTE and WiFi standards for instance) massively use multicarrier schemes with prefix cyclic (namely OFDM(A)). This scheme is particularly attractive but has some drawbacks for future potential 5G services such as extensive crowd communication and network heterogeneity:

- Spectral efficiency: The use of a cyclic prefix implies that OFDM(A) cannot achieve full spectral efficiency. The demand in terms of data rate exponentially increases and it could be useful to reallocate the time devoted to the cyclic prefix for data transmission.
- Doubly selective channels: OFDM is particularly attractive for frequency selective channels and relatively time invariant channels. Nevertheless, the increase of data rate, and in consequence the bandwidth, and the higher demand in terms of QoS for high mobility scenarios modify the channel to be considered. The receiver shall be capable to provide excellent performance in front of time and frequency selective channels, the so-called doubly selective channels. OFDM is known to be extremely sensitive to this type of channels due to the poor sinc shaped subcarrier frequency localization.
- Spectral containment and out of band radiation: For similar reasons, the spectral containment of OFDM is poor and is not compliant with waveform co-existence in crowd communication scenarios where the spectrum could be extremely fragmented.
- Strict synchronization: OFDM requires very strict time and frequency synchronization in order to keep orthogonality between the different users.

The above mentioned drawbacks have encouraged the study of an alternative multicarrier waveform such as Filter Bank MultiCarrier (FBMC). The major difference between OFDM and FBMC lies in the subcarrier shaping and the time-frequency use. In OFDM, the subcarrier frequency response is a wide sinc shape, whereas FBMC can be tuned in order to have any type of subcarrier frequency response. It is the role of the so-called FBMC prototype filter. In general, the time frequency localization of the FBMC prototype filter is excellent, avoiding the use of a cyclic prefix.

Nevertheless, the excellent spectral containment and out of band radiation of FBMC can vanish when realistic radiofrequency front-ends are considered for the transmission of the signal in space. In SOLDER, we aim at providing solutions in order to keep excellent spectral containment properties of FBMC in front of realistic RF front-end. For this purpose, we will develop PAPR reduction algorithm for FBMC, a linearization technique and possibly some specific RF impairments digital compensation techniques.

10.1 High level architecture of what will be simulated / prototyped

The high level architecture of what we intend to simulate and prototype is presented in Figure 28. Sections 10.1.1, 10.1.2, 10.1.3 and 10.1.4 briefly describe each functionality.

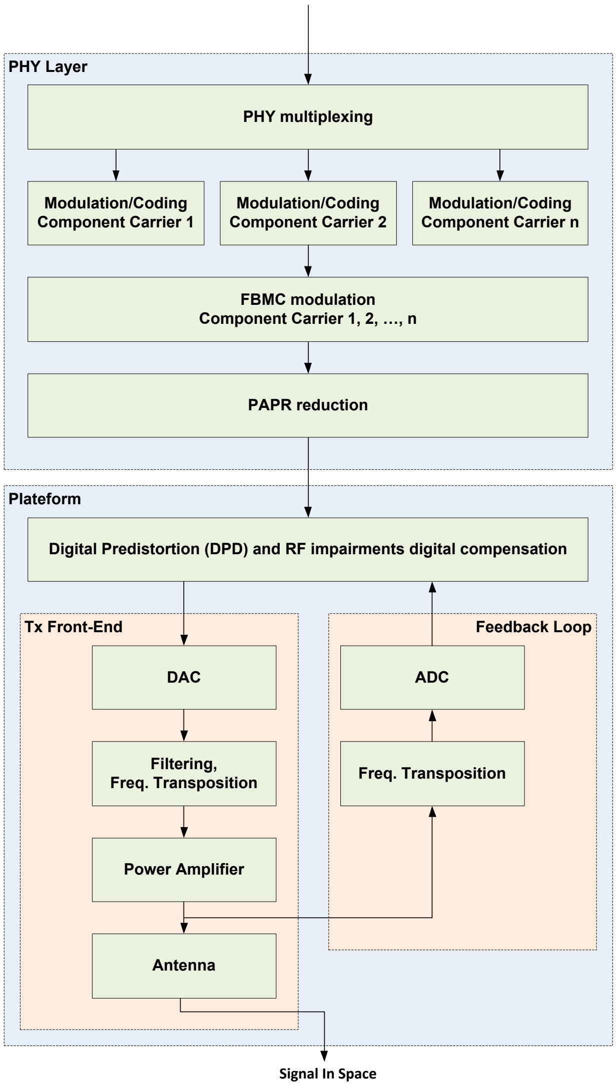


Figure 28: High level block diagram of 5G waveform

10.1.1 FBMC

There exist a lot of FBMC schemes, but it is possible distinguish three different types [23]

- Filtered MultiTone (FMT): Each FMT symbol is transmitted every T and is composed of several complex symbols (X_1, X_2, …) carried on different subcarriers equally spaced every F=(1+α)/T, where α refers to the roll off factor (see Figure 29). We can observe a bandwidth loss due to the use of this roll off factor. Usually, the frequency containment is good and depends on the prototype filter that shapes each carrier.

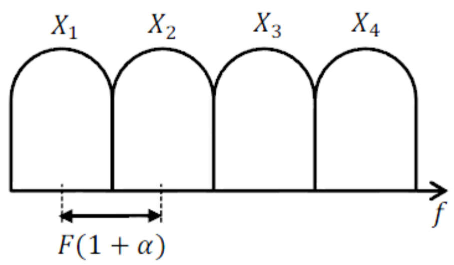


Figure 29: Frequency representation of a Filtered MultiTone scheme

- Cosine modulated Multitone (CMT): Each CMT symbol transmitted every T is alternately composed of pure real and imaginary symbols (X_1, X_2, …) carried on different subcarriers equally space every F = 1/(2xT), where F is the bandwidth of each carrier (see Figure 30). The order of the pure real imaginary symbols is modified each CMT symbol: for even CMT symbols, pure real symbols are transmitted on even subcarriers and pure imaginary symbols are transmitted on odd subcarriers ; for odd CMT symbols, pure imaginary symbols are transmitted on even subcarriers and pure real symbols are transmitted on odd subcarriers.

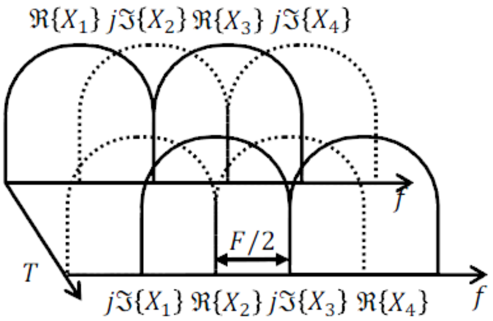


Figure 30: Time-Frequency representation of a Cosine modulated Multitone scheme

- Staggered MultiTone (SMT): each SMT symbol transmitted every T/2 is alternately composed of pure real and imaginary symbols (X_1, X_2, …) carried on different subcarriers equally space every F = 1/T, where 2xF is the bandwidth of each carrier (see Figure 31). The order of the pure real imaginary symbols is modified each SMT symbol: for even SMT symbols, pure real symbols are transmitted on even subcarriers and pure imaginary symbols are transmitted on odd subcarriers ; for odd SMT symbols, pure imaginary symbols are transmitted on even subcarriers and pure real symbols are transmitted on odd subcarriers. Note that OFDM-OQAM [11] is another name for FBMC SMT scheme.

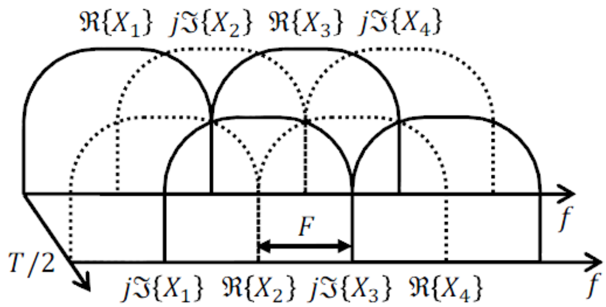


Figure 31: Time-Frequency representation of a Staggered MultiTone scheme

It is important to note that both CMT and SMT reach full spectral efficiency, which is not the case for FMT due to the bandwidth loss imposed by the roll off factor. Furthermore, results presented in [24] show that there is a simple relationship between CMT and SMT. Finally, many projects that consider FBMC as a next generation PHY layer are focused on SMT (or similarly OFDM-OQAM [33]) instead of CMT [25][26][27].

For these reasons, and in order to ensure that the work provided in SOLDER is complementary to what is proposed in the others FP7 project [25][26][27], we choose to consider SMT as the FBMC scheme for SOLDER.

10.1.2 PAPR reduction for FBMC

FBMC is by definition a multicarrier modulation and, according to the central limit theorem, its instantaneous amplitude fluctuation follows a Gaussian process. Thus, the instantaneous power fluctuation defined as the PAPR (Peak to Average Power Ratio) is known to be similar to OFDM, i.e. around 10-12 dB. Such high PAPR is especially problematic with nonlinearities, as the nonlinear effect is more pronounced for signals of high dynamic range, but it is also problematic from the power amplifier efficiency point of view. To minimize the effects of nonlinearities while maintaining the efficiency of the PA, we have to reduce the PAPR with a method causing no significant performance loss in spectral efficiency, link budget and in our case no regrowth of out-of-band radiation and spectrum notch. The solutions proposed in SOLDER to reduce the PAPR of an FBMC scheme will be presented in D3.2 and potentially D3.3.

Nevertheless, as mentioned in [28], the reduction of the PAPR is not a sufficient condition in order to ensure limited spectral regrowth due to transmitter non linearity: in most of the cases, it is necessary to add a linearization technique to fulfill a predefined spectrum mask.

10.1.3 Digital predistortion

Power amplifier hardware non linearities is a well-known problem in all transmitter systems. They cause in-band, out-of-band and notch degradations, which respectively result in received bit error, adjacent channel pollution, and notch pollution. Besides, there always exists a complex tradeoff between the linearity and the efficiency of the PA: the less linear the PA is, the higher efficient the PA is. The purpose of our study is to improve the linearity performance of a real power amplifier for the transmission of FBMC signals.

To avoid PA non linearity, many linearization techniques have been proposed like feedback [29], feedforward [30] and baseband digital predistortion [31]. Performance, complexity and adaptation capability criterions indicate to use the Digital PreDistortion (DPD) approach. Moreover in order to decrease FBMC linearity sensitivity and to improve PA efficiency, PAPR reduction technique will be used with DPD.

DPD algorithms can be classified into two main categories:

- Direct Learning (see Figure 32, left): The direct learning method requires an estimation of the PA behavior based on the input and output PA signals (“power amplifier estimation” block). Once the model has been estimated, the inverse model shall be computed (“adaptive inverse model” and “predistortion computation” block), and finally applied to the signal to be transmitted (“pre distorter” blocks).
- Indirect Learning (see Figure 32, right): The indirect learning computes directly the inverse of the power amplifier behavior based on the input and output PA signals (“Post Distorter” Block). Once the post distorter has been computed, the predistortion is applied to the signal to be transmitted (“Pre distortion” block).

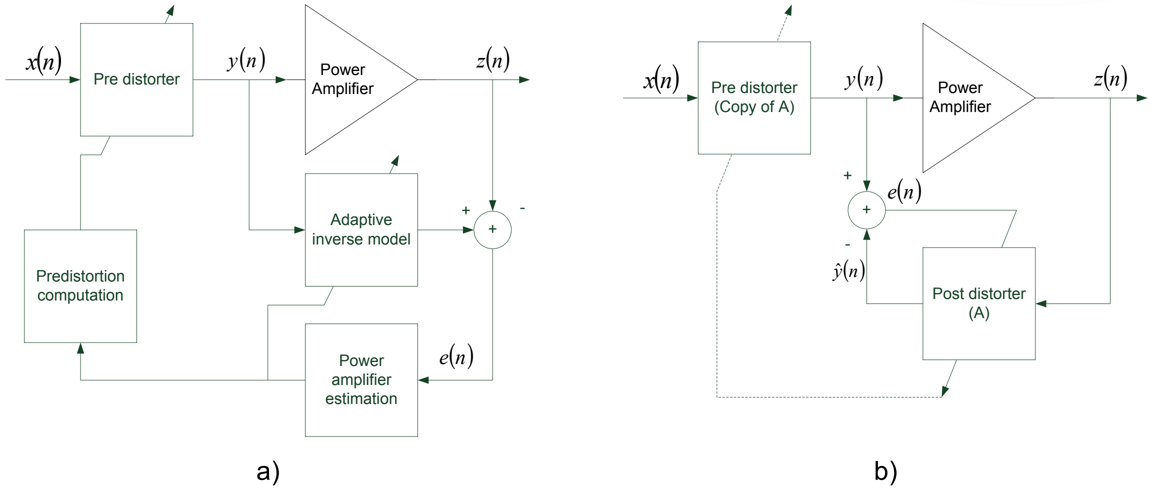


Figure 32: a) Direct learning, b) Indirect learning

It has been shown that the performances of the direct and indirect learning are almost similar [32]. For this reason and due to the fact that Direct Learning approach requires a complex computation step ("power amplifier estimation"), we will develop in SOLDER an Indirect learning DPD.

According to the complexity of the power amplifier behavior and also to the bandwidth of the signal to be transmitted, complex memory effects could have to be considered and corrected by the DPD in order to ensure very small spectral regrowth. Obviously, the more complex the PA behavior is, the more complex the DPD is. In the coming deliverables, D3.2 and D3.3, we will define the exact DPD to be developed in WP4 according to the platform assumptions.

10.1.4 Radiofrequency impairments compensation

There exist different architectures in order to transpose the baseband signal to the frequency carrier (and respectively to transpose the signal on a carrier to the baseband): some are fully analog (homodyne, heterodyne, super-heterodyne) and some are mixed analog-digital (low-IF). The analog part is in general subject to non idealities, whereas the digital part is usually considered as perfect. According to the type of architecture defined for the transmitter part of the radiofrequency front-end, and also to the feedback loop required for DPD, some radiofrequency impairments could modify the integrity of the signal. For DPD learning purpose, it is of high importance that the digitalized signal coming from the feedback is impaired only by non linearity mainly due to the power amplifier. Among the impairments that could destroy the DPD capabilities, we can cite the IQ imbalance, the DC-offset and the carrier frequency offset caused by the IQ modulator and/or demodulator.

In SOLDER, we will consider a fully digital solution and, according to the platform architecture, we will develop dedicated or joint algorithms (with regards to DPD technique) in order to limit the impact of such impairments.

10.2 Initial results

In this section, we present rough simulation results that show efficiency of the proposed joint use of PAPR reduction and DPD for the transmission of an FBMC signal.

We have tested several signals that present a spectral notch and we have analyzed the spectral regrowth inside this spectral notch at the output of a very simple power amplifier model. The common parameters setting of the three tested signals are:

- A first band occupied by 70 subcarriers

- A frequency notch created switching off 20 subcarriers
- A second band occupied by 50 subcarriers

The tested signals are regular OFDM, time domain windowing OFDM, and FBMC. As previously mentioned, OFDM suffers from poor out of band rejection due to the sinc shape subcarrier frequency response. Sometime domain windowing techniques exist for OFDM in order to have better subcarrier frequency localization. Among all the existing technique, we have chosen the raised cosine time domain windowing [34] for comparison. The prototype filter used for FBMC is the one defined in [35] with an overlap factor of 4 (K=4). Note that this filter has been chosen because it seems to be a good tradeoff between spectral containment capabilities and complexity, but it is not necessarily the one that will be designed or selected for SOLDER. The impulse response and the subcarrier frequency response of each candidate are respectively presented in Figure 33 a) and b). The cyclic prefix overhead used for both OFDM schemes has been set to 20% with regards to the OFDM symbol duration, which is a common value. The time domain windowing is half the duration of the CP. It is important to note that the duration used for time windowing decreases by the same amount of time the frequency domain equalization capability.

As expected, we can observe that regular OFDM has poor spectral containment. Time domain windowing OFDM has good spectral containment only outside a bandwidth of +/- 7 subcarriers. Finally, the out of band radiation of an FBMC scheme is lower than 40 dB on the adjacent subcarrier and is quickly negligible outside.

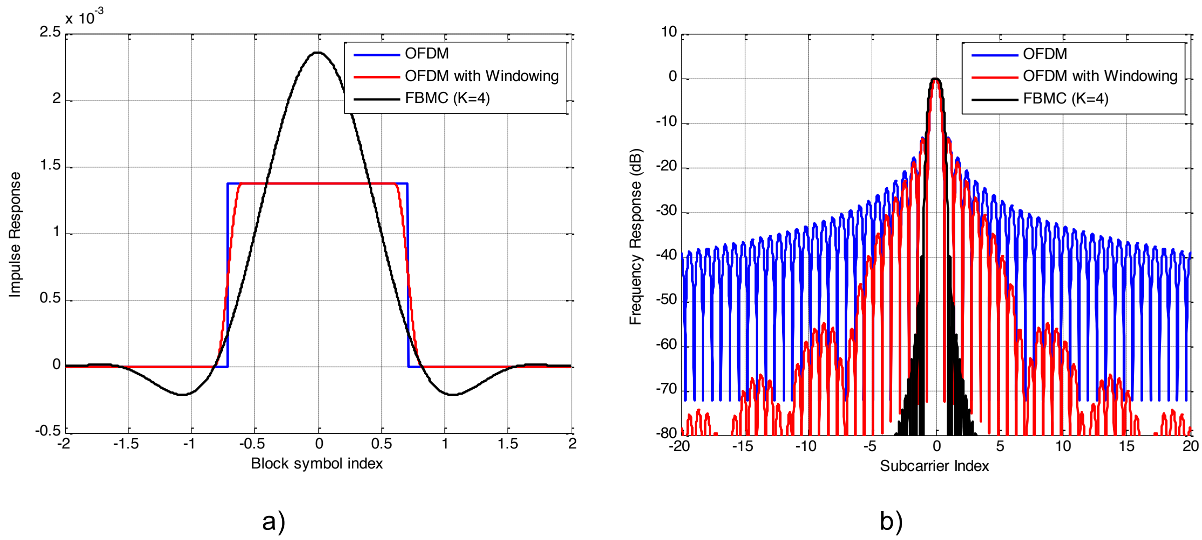


Figure 33: a) Impulse response and b) Frequency response of the prototype filters for OFDM, OFDM with raised cosine time windowing, and FBMC.

Figure 34 presents the power spectral density of the tested signals to be transmitted. We can observe the efficiency of the use of FBMC schemes for creating deep frequency notch.

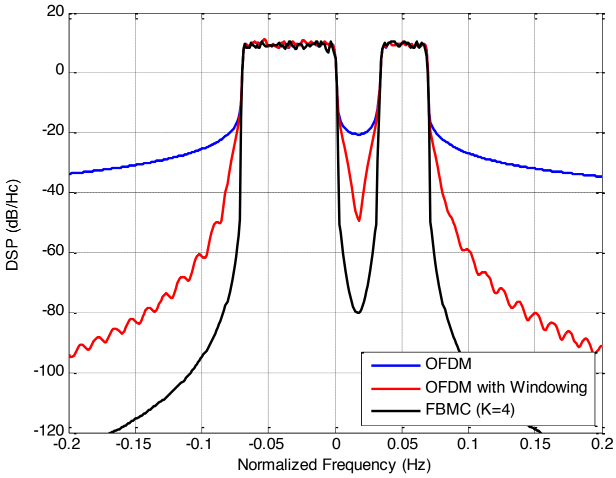


Figure 34: Power spectral density of OFDM, OFDM with time domain windowing, and FBMC

In the following, we propose to measure the notch power ratio at the output of a simple power amplifier model. The notch power ratio is the power spectral density difference between the useful transmitted signal on band 1 or band 2, and the power spectral density inside the created notch. The power amplifier model is the Rapp model that can be considered as very simple since it does not model the phase non linearity (AM-PM curve) and does not take into account any memory effects. The relationship between its input/output is [36]:

$$out_{PA}(n) = Gain \frac{in_{PA}(n)}{\left[1 + \left(Gain \frac{|in_{PA}(n)|}{out_{SAT}}\right)^{2p}\right]^{\frac{1}{2p}}}$$

Where

$in_{PA}(n)$ refers to the power amplifier input signal,

$out_{PA}(n)$ refers to the power amplifier output signal,

$Gain$ refers to the gain (set to 1) of the power amplifier,

out_{SAT} refers to the saturation level (set to 1),

p refers to the “knee factor” that controls the smoothness of the transition from the linear region to the saturation region of characteristic curve.

We consider two cases, according to the fact that the power amplifier has been linearized or not. “p” is set to 2.5 for the case where DPD is not activated, and set to infinite for the case of an ideally linearized power amplifier. Figure 35 presents the input/output amplitude relationship for both cases.

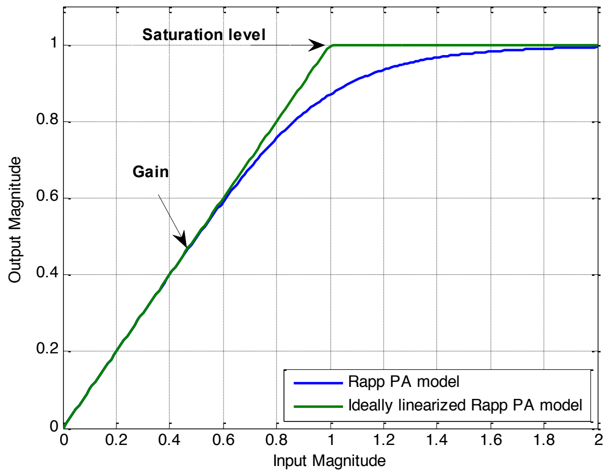


Figure 35: Power amplifier behavior for a Rapp model and for a perfectly linearized Rapp model (AM/AM curve)

Figure 36 presents the notch power ratio according to the power amplifier back off, the modulation schemes, and also according to the fact that the power amplifier has been ideally linearized or not. The "Back Off" is the ratio between the power at the power amplifier input, and its saturation level. This figure is supposed to give an upper and lower bounds of what can be achieved with a DPD linearization technique. It is important to note that the given values (notch power ratios and back off) depend on the power amplifier behavior and is highly subjected to change according to the considered platform.

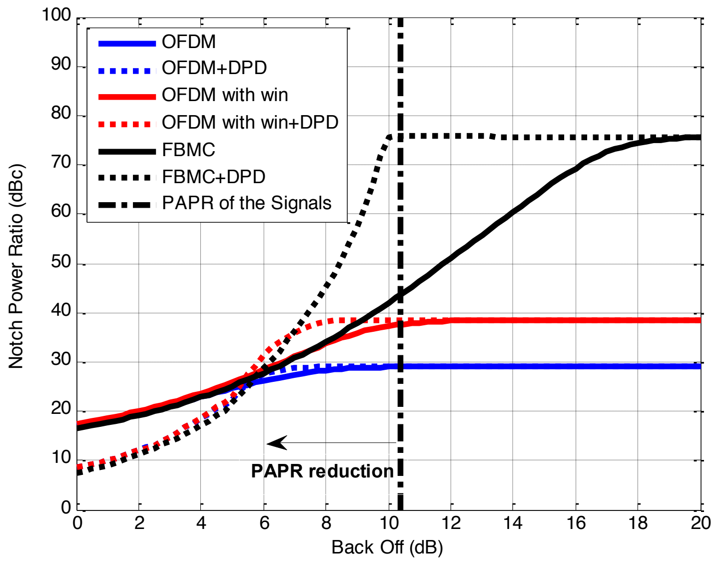


Figure 36: Notch power ration according to the power amplifier back off

The PAPR of the three tested signals is about 10.2 dB. We can observe that the DPD allows to reach a plateau given by the maximal possible notch power ratio for back off values comprise between the PAPR value and infinite. As expected, the FBMC plateau is much greater than both OFDM plateaus due to its excellent prototype filter frequency containment.
For a back Off lower than the PAPR, the notch power ratio drops quickly. This shows that the PAPR reduction helps in maintaining the plateau for lower Back Off. The advantage of low

back off is twofold: i) it maximizes the link budget since more power is transmitted for a given power amplifier, ii) it maximizes the power amplifier consumption and efficiency.

11. Conclusions

This report is the initial report of WP3. Since carrier aggregation could be addressed from many standpoints, several aspects are covered in this report:

We started the design of a UE able to aggregate 2 DL carrier (with 1 UL CC) that will conduct to a prototype, embracing some RF coexistence issues, depending on the carrier to aggregate, that may present intermodulation issues.

We studied the use of LTE-A physical layer technologies in HetNets context, which involve pico and macro eNodeB. We consider a practical LTE-A scenario under non-continuous CA with closed-loop spatial multiplexing (CLSM) MIMO LA. A performance analysis of how the current and a proposed improved MIMO LA techniques affect the behavior of CA per CC has been provided, taking into account the possibility of outdated feedback.

The report has also provided a pertinent description of what will be evaluated in relation to Radio Resource Management in both Homogeneous and Heterogeneous network deployment. In particular we are eager to develop a holistic scheduling approach which should be in charge of CC assignment, CC revision and PRB allocation. This algorithm will be adapted to efficiently serve also in HetNets environments where both centralized and distributed management will be studied. Eventually we will focus on the impact of SCC activation/deactivation on the overall network performance indicators

We have further studied the problem of radio resource management in heterogeneous networks with two radio access technologies: LTE and WiFi. We showed that the introduction of aggregation of LTE and WiFi at both the user and the access point side can significantly improve both user and network throughput compared to the baseline scenario where the macro cells use LTE and the pico cells use WiFi and users can only connect to one of the two.

We have assessed a number of novel spectrum opportunities and usages such as TV White Spaces (TVWS) and unlicensed spectrum usage, that might be aggregated with more conventional spectrum usages (e.g., licensed and unlicensed spectrum). We have shown, through some early-stage simulations particularly in the scope of direct communication between devices, the benefits of aggregation of such spectrum opportunities with conventional licensed and unlicensed spectrum usage, in terms of both significant capacity improvement and energy consumption reduction.

At last, the type of FBMC waveform that will be considered for PHY CA in SOLDER has been considered as a promising candidate for 5G waveform. We have demonstrated the issues that arise when considering CA at PHY layer level in front of realistic transmitter front-end. More specifically, FBMC good spectral containment requires digital techniques and digital estimation/compensation that we will propose and develop respectively in WP3 and WP4:

- PAPR reduction of the FBMC signal
- Power amplifier linearization
- Radio-frequency impairments minimization

Finally, we have shown the potential of the proposed approach considering a simple power amplifier model and an ideal predistortion.

Although most of the information captured in this report will be further enriched in the following deliverable, they show the promises of carrier aggregation considered in its various forms, e.g. not only aggregating LTE and LTE carriers as originally defined by the standardisation but extending the concept to other spectrum and other technologies.

List of Acronyms

Acronym	Meaning
3GPP	3rd Generation Partnership Project
ACK/NACK	Acknowledgement / Negative Aknowledgement
AWS	Advanced Wireless Services
BS	Base Station
CA	Carrier Aggregation
CC	Component Carrier
CQI	Channel Quality Indicator
CSI	Channel State Information
D2D	Device-to-Device
DCI	Downlink Control Information
DL	DownLink
eNB	Evolved node B
E-UTRA	Evolved UMTS Terrestrial Radio Access
FBMC	Filter Bank MultiCarrier
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FE	Front End
HARQ	Hybrid Automatic Repeat Request
HetNet	Heterogeneous Network
IP	Internet Protocol
LA	Link Adaptation
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MAC	Media Access Control
MIMO	Multiple Input Multiple Output
NAS	Non-Access Stratum
Ofcom	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
PCC	Primary Component Carrier
PCell	Primary Cell
PDCCH	Physical Downlink Control CHannel
PHY	Physical Layer
PRB	Physical Resource Block
RB	Resource Block
RF	Radio Frequency
RFIC	RF Integrated Circuit
RRC	Radio Resource Control
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
SCC	Secondary Component Carrier
SCell	Secondary Cell
SINR	Signal-to-Interference-Plus-Noise Ratio (SINR)
TDD	Time Division Duplex

TTI	Transmission Time Interval
TVWS	TV White Space
UE	User Equipment
UL	UpLink
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network

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