



Advanced Dynamic spectrum
5G mobile networks Employing
Licensed shared access



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Abstract: This deliverable presents the ADEL Consortium’s review of the MAC and Control Plane protocols that allow the deployment of LSA under the defined reference scenarios. First, we consider the potential capacity gains arising from location-based LSA. We then investigate how the control plane of LTE and LTE-A can support LSA. Finally, we propose a novel MAC-layer protocol that allows two LSA operators to cooperate through the use of a shared database.

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Executive Summary

This is the deliverable *D5.4 – Medium Access and Control Plane Protocols*, FP7 project ADEL (ICT- 619647). This work was carried out as part of WP5: Dynamic Spectrum Access. This deliverable relies on the work defined within task T5.4 detailed in the Description of Work.

In this deliverable we investigate the Control Plane and the Medium Access Control (MAC) part of the ADEL LSA communication system architecture.

The aims of this deliverable are split in three categories. First we assume a system of two overlapping Incumbent and Licensee operators and identify the capacity gain bounds from deploying Location-based LSA, according to the ADEL paradigm. This analysis matches the Macro cellular scenario defined in deliverable D3.1 [1]. The incumbent operator can be a Radar, or a Media and Entertainment operator that holds a spectrum license, but has limited deployment of sites, or infrequent and highly localised use of its spectrum. This gives an LSA MNO the opportunity to use the Incumbent operator's spectrum to increase its capacity. Our analysis assumes different levels of cell density for the incumbent operator.

Then, we look into the Control Plane (signalling and radio network) delay aspects from LSA licensee's standpoint. In particular, we analyse the existing LTE/LTE-A signalling mechanisms that can be reused for the deployment of the ADEL LSA system. Two distinct baseband architectures are considered, centralised and distributed, by analysing heterogeneous network topologies with collocated tiers of macro-cells and Low Power nodes (LPNs). LPNs may be Remote Radio Heads (RRHs) or small cells, representing the two baseband architectures considered. Such a scenario addresses Scenario 3 from [1], as well as future deployments that will invariably include networks with multiple tiers and which will utilise different baseband architectures with dense deployments of LPNs. In addition, we review the ways in which two prominent technologies, Carrier Aggregation (CA) and Dual Connectivity (DC), introduced as part of LTE-A, can be utilised in employing the LSA spectrum. More specifically, Carrier Aggregation is applicable to the centralised baseband architecture, while Dual Connectivity maps to the distributed baseband architecture. Our results show that Carrier Aggregation outperforms Dual Connectivity, both in terms of the average achieved user throughput and the delay in setting up and releasing the LSA resources.

Finally, we build on the ADEL architecture [1] to propose a novel MAC layer protocol which allows an Incumbent operator to share information on the frequency selective characteristics of the interference channel with a Licensee operator using a shared database. This allows the Licensee Operator to transmit over those subcarriers that cause minimal levels of interference to the Incumbent Operator. Our simulations show that by using a shared database, it is possible for the Incumbent and the Licensee Operators to coordinate access to the shared spectrum in such way that the Incumbent operator is protected from excessive interference while allowing the Licensee operator to access the shared spectrum. The overall sum-rate throughput exceeds the throughput of the single user, even when tight transmission cooperation is not possible.

Purpose and Scope

The deliverable presented in this document forms part of the output from Work Package 5 – *Dynamic Spectrum Access*, and Task 5.4 - *Medium access and control plane protocols*, in particular.

While several MAC protocols have been proposed on the Cognitive Radio paradigm, the work carried out in this deliverable explores the opportunities arising from the novel architecture proposed within the ADEL project.

In addition, deliverable D5.4 investigates the readiness of current generation cellular systems to support Licensed Shared Access solutions and evaluates the different options that could be developed as part of the LTE-A standards, providing valuable input to standardisation bodies.

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Abbreviations and Acronyms

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLER	Block Error Rate
BMI	Bitwise Mutual Information
BS	Base Station
CA	Carrier Aggregation
CC	Carrier Component
CEPT	The European Conference of Postal and Telecommunications
CESM	Capacity Effective SINR Mapping
CIF	Carrier Indication Field
CR	Cognitive Radio
CSI	Channel State Information
DC	Dual Connectivity
DCI	Downlink Control Information
DL	Downlink
ECC	Electronic Communications Committee
EESM	Exponential Effective SINR Mapping
eNB	Evolved Node B
EPS	Evolved Packet Service
E-RAB	Evolved UTRAN Radio Access Bearer
ETSI	European Telecommunication Standardisation Institute
FDD	Frequency Division Duplex
HARQ	Hybrid Automatic Repeat reQuest
IO	Incumbent Operator
LAA	Licence-Assisted Access
LO	Licensee Operator
LPN	Low Power Node
LSA	Licensed Shared Access
LTE	Long Term Evolution
LTE-A	LTE – Advanced
MAC	Medium Access Control
MCS	Modulation Coding Scheme
MIB	Master Information Block
MICB	Mutual Information per Coded Bit
MIESM	Mutual Information Effective SINR Mapping
MIMO	Multiple Input Multiple Output

MME	Mobility Management Entity
MNO	Mobile Network Operator
NRA	National Regulatory Authority
O&M	Operation and Maintenance
OFDM	Orthogonal Frequency Division Multiplexing
PCell	Primary Serving Cell
PDCP	Packet Data Convergence Protocol
P-GW	Packet Gateway
PRB	Physical Resource Block
PU	Primary User
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
RLC	Radio Link Controller
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
SCell	Secondary Serving Cell
S-GW	Serving Gateway
SINR	Signal to Interference and Noise Ratio
SISO	Single Input – Single Output
SNR	Signal to Noise Ratio
SU	Secondary User
TDD	Time Division Duplex
Tx	Transmit
UE	User Equipment
UL	Uplink
xDSL	Any version of a Digital Subscriber Line protocol, such as ADSL

1 Introduction

In this deliverable we investigate the Control Plane and the Medium Access Control (MAC) part of the ADEL LSA communication system architecture.

The aims of this deliverable are split in three categories. First we assume a system of two partially overlapping Incumbent and Licensee operators and identify the capacity gain bounds from deploying Location-based LSA, according to the ADEL paradigm. This scenario fits the Macro cellular scenario (reference scenario 2) defined in Section 6.2 of deliverable D3.1 [1]. The incumbent operator can be a Radar, or a Media and Entertainment operator that holds a spectrum license, but has limited deployment of sites, or infrequent and highly localised use of its spectrum. This gives an LSA MNO the opportunity to use the Incumbent operator's spectrum, outside the Incumbent's exclusion zone, to increase its own capacity without causing harmful interference on the Incumbent operator. Our analysis assumes different levels of cell density for the incumbent operator.

Then, we look into the Control Plane (signalling and radio network) delay aspects from LSA licensee's standpoint. In particular, we analyse the existing LTE/LTE-A signalling mechanisms that can be reused for the deployment of the ADEL LSA system. Two distinct baseband architectures are considered, centralised and distributed, by analysing heterogeneous network topologies with collocated tiers of macro-cells and Low Power nodes (LPNs). LPNs may be Remote Radio Heads (RRHs) or small cells, representing the two baseband architectures considered. Such a scenario addresses reference scenario 3 from deliverable D3.1 [1] (Section 6.3), as well as future deployments that will invariably include networks with multiple tiers and which will utilise different baseband architectures with dense deployments of LPNs. In addition, we review the ways in which two prominent technologies, Carrier Aggregation (CA) and Dual Connectivity (DC), introduced as part of LTE-A, can be utilised in employing the LSA spectrum. More specifically, Carrier Aggregation is applicable to the centralised baseband architecture, while Dual Connectivity maps to the distributed baseband architecture. Our results show that Carrier Aggregation outperforms Dual Connectivity, both in terms of the average achieved user throughput and the delay in setting up and releasing the LSA resources.

Finally, we build on the ADEL architecture as defined in Section 8 of deliverable D3.1 [1], as well as on the ADEL solution that participated in the DySPAN 2015 Challenge ([2]) to propose a novel MAC layer protocol which allows an Incumbent operator to share information on the frequency selective characteristics of the interference channel with a Licensee operator using a shared database. This allows the Licensee Operator to transmit over those subcarriers that cause minimal levels of interference to the Incumbent Operator. Our simulations show that by using a shared database, it is possible for the Incumbent and the Licensee Operators to coordinate access to the shared spectrum in such way that the Incumbent operator is protected from excessive interference while allowing the Licensee operator to access the shared spectrum. The overall sum-rate throughput exceeds the throughput of the single user, even when tight transmission cooperation is not possible. Our proposed MAC protocol can be applied equally to any of the three scenarios.

2 Location-based LSA

2.1 Introduction

In this section we present a location-based LSA scheme for the macro-cell scenario. The objective is to measure the capacity gain when using LSA bands with the help of location information and the LSA architecture, but in the absence of any sophisticated signal processing techniques (i.e. from a MAC layer perspective).

We consider a scenario where macro cells are deployed by a MNO and are operating on a dedicated bandwidth of 5MHz in the 2GHz band. We consider the presence of an incumbent in the 2.3-2.4 GHz band, protected by a geographical exclusion rule on its own band, when it is operational. The information on the geographical exclusion zone along with the permitted transmission power on it, and the time duration of protection are filled, among other information (Cf. D3.1 Ch. 8.2.1 P. 95 [1]), dynamically in the LSA repository. The ADEL architecture (see Figure 1) defines the Radio Environment Map entity that holds information on the LSA spectrum availability in different areas.

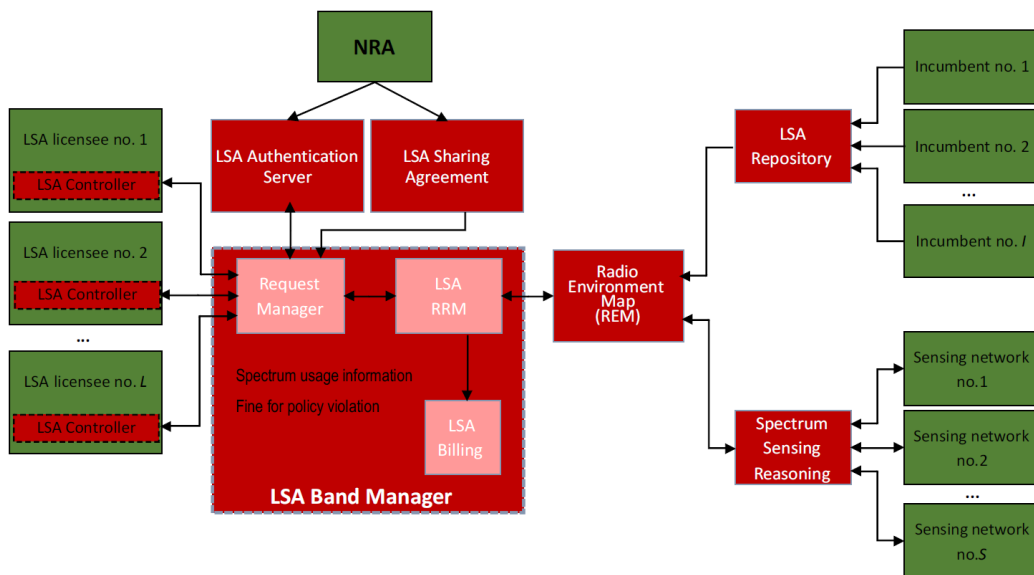


Figure 1: The ADEL proposed architecture

Location-based information can be provided by both the Incumbent operators, as well as the Sensing networks considered in the ADEL architecture. Deliverables D4.3 [2] and D5.2 [3] describe the centralised and distributed spectrum sensing algorithms that can be used by the sensing networks to identify areas where different LSA bands are being used. A modified version of the distributed spectrum sensing an ADEL sensing algorithm was also demonstrated during the 2016 EuCNC conference, receiving recognition.

For ease of implementation (Matlab) we assume that both the MNO cell areas, as well as the incumbent exclusion zone area are square. However, our approach can be applied to different topologies. The MNO employs a fixed reuse-4 frequency reuse scheme (Figure 2). Consequently, each cell has access to a dedicated bandwidth of 1.25MHz. 16 cells are considered in the scenario and the incumbent exclusion zone area excludes 4 cells from using the incumbent spectrum.

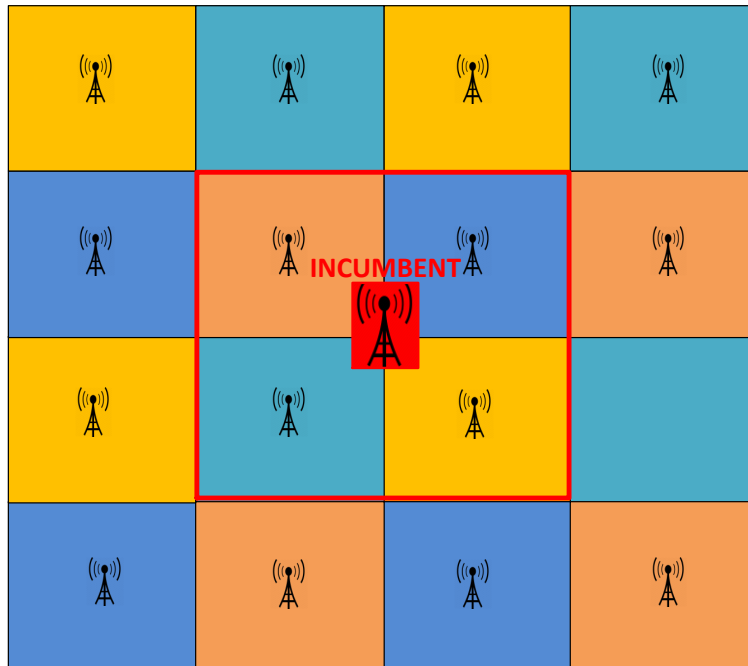


Figure 2: Illustration of the Location-based LSA scenario setup

The MNO’s eNBs decide to access the LSA spectrum according to their location information. They use a message exchange procedure to convey their respective requests to the LSA controller [1] as shown in Figure 3.

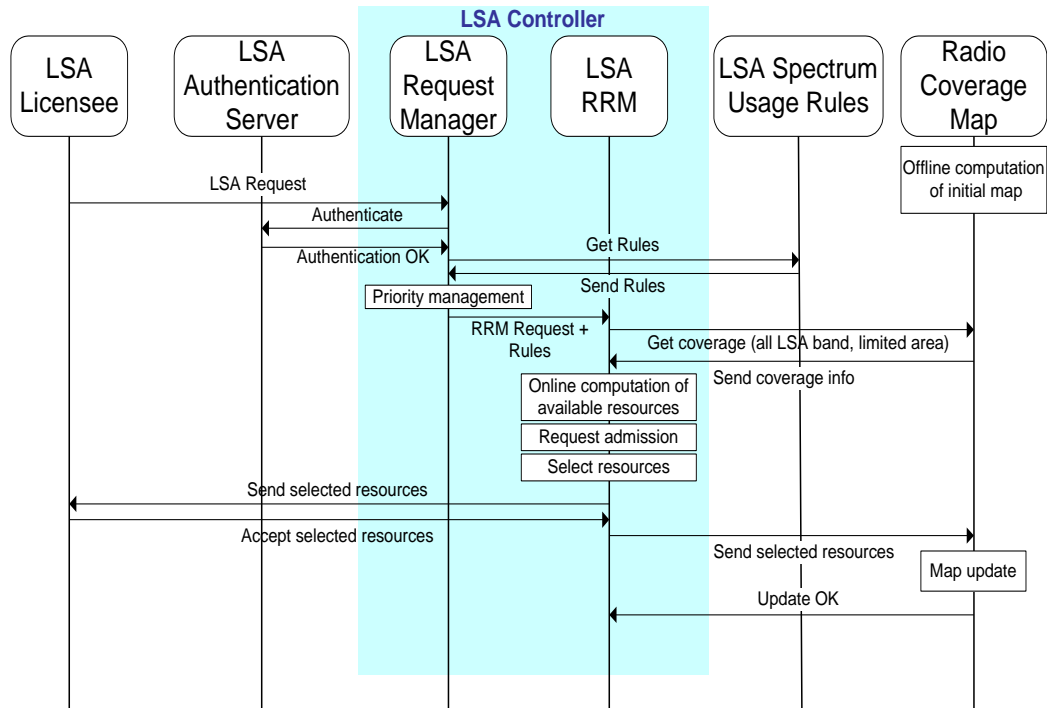


Figure 3: ADEL message exchange procedure for LSA requests

2.2 Simulation setup

We implemented a system level simulator to investigate the gains arising from the deployment of Location Based LSA. The simulation parameters are given in Table 1, below

Table 1: Simulation parameters

System type	LTE
Number of cells	16
Cell area	1km * 1km
Number of incumbents	1
Exclusion zone	2km * 2km
Number of UEs per cell	100
eNB power	40dBm

UE power	23dBm
Bandwidth	1,25MHz
Number of RBs	6
Antenna scheme	SISO
eNB height	20m
Path loss model	Erceg
Scheduling	MPFS

2.2.1.1 Path loss model

The Erceg model [6] for the path loss calculation is defined as

$$PL(d) = 20\log_{10}\left(\frac{4\pi d_0}{\alpha}\right) + 10\gamma\log_{10}\left(\frac{d}{d_0}\right) + S, \quad d \geq d_0$$

Where α is the wavelength in meters, and γ is the path-loss exponent with

$$\gamma = a - bh_b + \frac{c}{h_b}$$

h_b is the height of the base station in meters (between 10 m and 80 m), $d_0 = 100$ m, and a , b , c are constants dependent on the terrain category.

S represents the shadowing effect and follows a lognormal distribution with a typical standard deviation of 8.2 to 10.6dB.

We consider terrain of category A (where A corresponds to hilly terrain with moderate-to-heavy tree density and has a high path loss), the corresponding parameters values are: $a=4.6$, $b=0.0075$, and $c=12.6$ [6]

2.2.1.2 Physical layer abstraction model

We adopt the physical link abstraction model presented in [8] for its good balance between accuracy and complexity. Indeed, the proposed scheme in [8] allows for the arbitrary bandwidth assignments while at the same time reduces the storage requirements of complex operations of link abstraction. We apply the proposed methodology to take into account the wide variety of the modulation and coding schemes in LTE for a frequency selective channel as well as the variable bandwidth assignments.

The model requires only 3 AWGN mother code (1/3) reference curves corresponding to the maximum bandwidth assignment (5MHz) and a table of offset $\Delta(NB_RB)$ for different number of PRB (Physical Resource Block) assignments.

The offset Δ (in dB) is the gap at the 10% of the BLER for each type of bandwidth assignment with respect to the maximum bandwidth assignment. For the different possible combinations of code block size and coding rate Δ has to be calculated numerically from the link level simulator as there is no analytical expression available to calculate it. However, this approach benefits by the fact that Δ has to be calculated only once and only for the code rate 1/3.

The link abstraction is achieved then by the following steps:

1. Generate the frequency selective channel for assigned bandwidth (Rayleigh fading)
2. Determine the received SINR γ_i across each of the resource element
3. Calculate the effective SINR γ_{eff} using the received SINR (γ_i) as

$$\gamma_{eff} = \beta_1 I^{-1} \left[\frac{1}{N_{RB}} \sum_{i=1}^{N_{RB}} I \left(\frac{\gamma_i}{\beta_2} \right) \right]$$

Where $I(\cdot)$ is the information measure function.

information measure functions have been considered in the literature as listed in Table 2, below.

Table 2: Information measure functions

Effective SINR Mapping	Information measure
Capacity (CESM)	$I(x) = \log_2(1 + x)$
Exponential (EESM)	$I(x) = e^{-x}$
Mutual Information (MIESM)	$I(x) = MI(x)$

The results provided in [9] demonstrate that the MIESM (Mutual Information Effective SINR Mapping) method outperforms all the other mapping approaches in terms of approximation accuracy for the BLER curves. The calibration factors β_1 and β_2 are equal to unity for the MIESM.

As reported in [10], the Mutual Information per coded Bit (MICB) can be approximated through the following function:

$$J(x) = \begin{cases} a_1 x^3 + b_1 x^2 + c_1 x, & x < 1.6363 \\ 1 - \exp(a_2 x^3 + b_2 x^2 + c_2 x + d_2), & 1.6363 \leq x < \infty \end{cases}$$

Where the parameters have been obtained through numerical fitting and are reported in Table 3, below.

Table 3: Numerically estimated factors for MICB [5]

$0,001 \leq x < 1,6363$	$1,6363 \leq x \leq 1000$
$a_1 = -0,04210661$	$a_2 = 0,00181492$
$b_1 = 0,209252$	$b_2 = -0,142675$
$c_1 = -0,00640081$	$c_2 = -0,0822054$
	$d_2 = 0,0549608$

Specifically, it has been demonstrated in [10] that the MICB of any modulation M can be approximated as a mixture of $J(\cdot)$ functions as follows:

$$I_M(x) = \begin{cases} 0, & x < 0.001 \\ \sum_{k=1}^K \alpha_k J(\beta_k \sqrt{x}), & 0.001 \leq x \leq 1000 \\ 1, & x > 1000 \end{cases}$$

Where $\sum_{k=1}^K \beta_k = 1$ for some $K \geq 1$.

Numerical fittings have been carried out to obtain α_k and β_k for QPSK, 16-QAM and 64-QAM. The obtained approximations are reported in Table 4, below

Table 4: MICB function approximation for different modulation schemes

Modulation	MICB function, $0,001 \leq x \leq 1000$
QPSK	$J(2\sqrt{x})$ (exact)
16-QAM	$J(0,8\sqrt{x})/2 + J(2,17\sqrt{x})/4 + J(0,965\sqrt{x})/4$
64-QAM	$J(1,47\sqrt{x})/3 + J(0,529\sqrt{x})/3 + J(0,366\sqrt{x})/3$

4. Calculate the average bitwise mutual information over the different assigned resource elements as

$$BMI = \frac{I_M(Y_{eff})}{\log_2(M)}$$

- 5. If BMI is less than the rate r_q of the used MCS then the decoding fails
- 6. If $BMI \geq r_q$ then calculate the shift R in the reference BLER curve with the help of effective code rate r_q and the mother code rate r_m as

$$R[dB] = I_M^{-1}(r_m) - I_M^{-1}(r_q)$$

The argument behind the last equation is the fact that for the capacity achieving channel codes with long enough code block size, the normalized mutual information and channel code rate can be used interchangeably.

By using this difference one can be directly mapped onto another. In this approach, we calculate R and apply it to shift the reference curve corresponding to the mother code rate.

$$\gamma_m = \gamma_{\text{eff}} + R$$

So in this manner the number of required reference curves is reduced from 29 to 3 only for a fixed bandwidth assignment. For the variable bandwidth assignment, the slope of the reference curves is different. Ideally the BLER starts coming down at the same average SNR but then its' not an immediate waterfall for low bandwidth assignment. To account for this an offset Δ (in dB) is used at the 10% of the BLER for each type of bandwidth assignment with respect to the maximum bandwidth assignment. The Δ is obtained from 1 RB and the full RB BLER curves by linear interpolation.

$$\gamma_m = \gamma_m - \Delta(\text{NB_RB})$$

Table 5 shows modulation scheme, code rate along with the SNR threshold associated to each MCS.

Table 5: Modulation and coding schemes

MCS	Modulation	Code rate
0		
1	QPSK	0,08
2	QPSK	0,1
3	QPSK	0,11
4	QPSK	0,15
5	QPSK	0,19
6	QPSK	0,24
7	QPSK	0,3
8	QPSK	0,37
9	QPSK	0,44
10	QPSK	0,51

11	16QAM	0,3
12	16QAM	0,33
13	16QAM	0,37
14	16QAM	0,42
15	16QAM	0,48
16	16QAM	0,54
17	16QAM	0,6
18	64QAM	0,43
19	64QAM	0,45
20	64QAM	0,5
21	64QAM	0,55
22	64QAM	0,6
23	64QAM	0,65
24	64QAM	0,7
25	64QAM	0,75
26	64QAM	0,8
27	64QAM	0,85
28	64QAM	0,89
29	64QAM	0,92

2.2.1.3 Scheduling algorithm

The scheduling algorithm considered in our simulations is the Maximum Proportional Fair Scheduling (MPFS) one [11]. Unlike the classical proportional fair scheduling algorithm where the instantaneous rate is normalized by the past average throughput, in the proposed algorithm the normalisation is done with respect to the past maximal values. And unlike cumulative distribution function (CDF) based fair scheduling, the knowledge of the CDF of users' rates is not required. We have shown that in the saturated regime the proposed algorithm outperforms the classical ones, while in the non-saturated regime it even

outperforms the multiuser diversity scheduling in term of spectral efficiency and classical fair schedulers in term of fairness.

The algorithm works as follows:

The scheduler chooses to allocate resources to the K users according to w where

$$w = \underset{k=1,\dots,K}{\operatorname{argmax}} \frac{r_{k,n}}{R_{k,n}}$$

In the above equation, $r_{k,n}$ is the rate of user k in allocation period n , and

$$R_{k,n} = \max \{ r_{k,n-j}, \quad j = 0, \dots, M \}$$

2.3 Simulation results

Figure 4 compares the achieved mean cell sum rate with and without the use of the LSA bandwidth. Regarding the small restricted incumbent area compared to the total cells area we can observe that the gain when using the LSA bandwidth is significant and allows benefits of around 80% of the available LSA band.

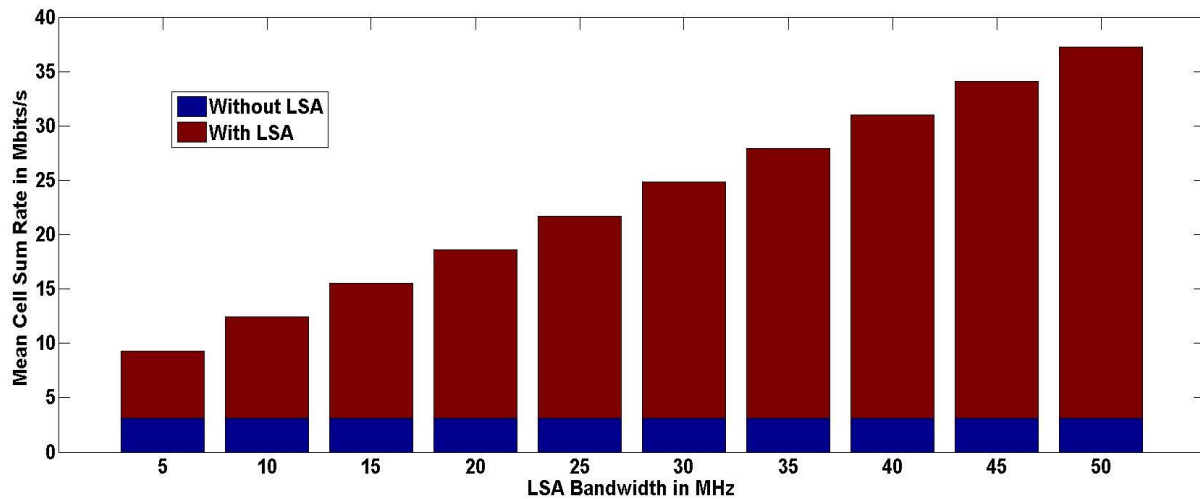


Figure 4: Mean cell sum rate vs. LSA bandwidth

The obtained results may be extrapolated to a larger area containing many incumbents.

Indeed, if we consider a larger area containing different cells of mean serving area A_{BS} and different incumbents of mean exclusion zone area A_{INC} then the average gain in term of sum rate when using the LSA band B_{LSA} can be expressed as

$$G = \left(1 - \frac{A_{INC}}{A_{BS}}\right) \frac{B_{LSA}}{B_{BS}}$$

Where B_{BS} is the dedicated bandwidth the cellular MNO.

Figure 5 illustrates the gain factor in terms of the mean cell sum rate when considering different LSA bandwidth and different incumbent restriction area densities. Here again we observe that there is much room to benefit from the LSA bandwidth easily without sophisticated signal processing techniques.

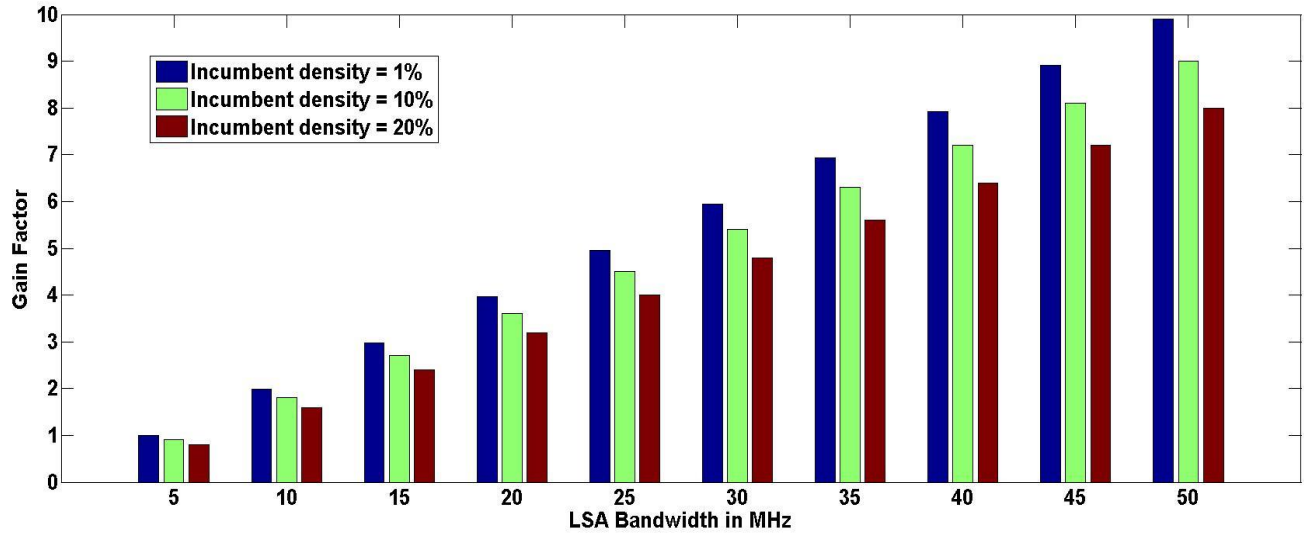


Figure 5: Gain factor Vs. LSA bandwidth

2.4 Conclusions

We developed a system level simulator considering two partially overlapping operators complying with the ADEL LSA rules. The Licensee operator is allowed to use the Incumbent’s spectrum to improve its own network’s capacity, as long as it does so outside the Incumbent’s exclusion zones. To achieve this, a location database, such as the Radio Coverage Map considered in the ADEL architecture [1], is assumed. System-level simulations, using PHY-layer abstraction methods to reduce the complexity of the calculations, show that, depending on the density of the Incumbent’s exclusion zones, significant capacity gains can be achieved as a result of using the customer database.

3 Control Plane considerations for LSA support in LTE and LTE-A

3.1 Introduction

In this section, the signalling and radio network delay aspects from the point of view of LSA licensee i.e. cellular (LTE) operator are considered. Particularly, the focus is on the existing LTE/LTE-Advanced signalling mechanisms that can be reused for employment of LSA spectrum. In that, heterogeneous network topologies with a tier of macro cells and a tier of low-power nodes (LPNs) are analysed. LPNs may be Remote Radio Heads (RRHs) or small cells, representing two distinct baseband architectures – centralised and distributed³. Hence, such a scenario addresses future deployments that will invariably include networks with multiple tiers, which will utilise different baseband architectures with dense deployments of LPNs. In addition, the scenario analyses how two prominent techniques of LTE-Advanced – Carrier Aggregation and Dual Connectivity can be utilised in employing the LSA spectrum. The two features correspond to the two baseband architectures. Carrier Aggregation is applicable to the centralised baseband architecture, while Dual Connectivity maps to the distributed baseband architecture. Before describing the considered deployment scenario, the following section provides a brief outline of Carrier Aggregation and Dual Connectivity of LTE-Advanced, focusing on downlink communication. For a more detailed description of these features, the reader is referred to the enclosed citations.

3.2 Overview of Carrier Aggregation & Dual Connectivity

3.2.1 Carrier Aggregation

Carrier Aggregation is by now a well-defined feature of LTE-Advanced, which, up to Release 13, enables aggregation of different blocks of spectrum to form larger transmission bandwidths of up to 100 MHz with peak data rates of 1 Gb/s on the downlink and 500 Mb/s on the uplink. Release 13 introduces support for up to 32 carriers and maximum bandwidth of 640 MHz, targeting the operation in the unlicensed spectrum [12].

Each of the aggregated frequency blocks is referred to as Component Carrier (CC). For each LTE-Advanced user, one CC is designated as the primary carrier and is responsible for mandatory functionality, such as security key exchange with the core network or radio link monitoring. The serving cell of the Primary CC is called the Primary Serving Cell (PCell) and is the only cell that maintains a dedicated, Radio Resource Connection (RRC) to the network when a UE transmits data. Other CCs are called the Secondary CCs, and

³ Namely, RRHs are representatives of centralised baseband architecture. They pose strict requirements on throughput, delay and jitter between its remote radio unit and centrally located baseband unit. On the other hand, small cells each perform their own radio and baseband functions, and can be connected to the core network and other radio network nodes using a range of different technologies, such as fibre, xDSL or wireless. From the baseband point of view, small cells represent distributed architecture.

their corresponding cells are Secondary Serving Cells (SCells). It should be noted that PCell and SCell designation is UE-specific. Hence, the same cell can be the primary cell for one UE, and a secondary cell for another UE.

The UE aggregation capability determines the number of serving cells that can be configured. To ensure backwards compatibility with LTE, the CCs have the same width as in LTE: 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz [13]. There are a few ways in which CCs can be aggregated. The aggregation can be performed within the same LTE band, using contiguous or non-contiguous CCs - referred to as intra-band Carrier Aggregation. CCs can also be combined using spectrum from different LTE bands, which represents the case of inter-band Carrier Aggregation. Carrier Aggregation is supported on the uplink and downlink, as well as in both LTE Time Division Duplex (TDD) and Frequency Division Duplex (FDD) systems. In Release 12, Carrier Aggregation between TDD and FDD modes is supported, where a primary CC can be e.g. FDD carrier with secondary CC being a TDD carrier, or vice versa. Aggregation of carriers has been defined for specific sets of LTE bands.

In addition, 3GPP has defined UE's Carrier Aggregation bandwidth class, according to the maximum supported number of CCs and aggregated resource blocks. A UE can then support a combination of particular band(s) and bandwidth classes - see for example [14]. In Carrier Aggregation, each CC maintains its PHY configuration. This means that parameters such as modulation and coding schemes are defined separately for each carrier. Such protocol architecture allows the use of different MIMO schemes and power settings for different component carriers.

Regarding the MAC layer, the MAC sublayer responsible for retransmission is set per component carrier. However, there is a single MAC sublayer, responsible for data multiplexing and packet scheduling. Carrier Aggregation is only exposed to this MAC sublayer, and is transparent to the protocol layers above - Packet Data Convergence Protocol (PDCP) and Radio Link Control (RLC), see Figure 6, according to [15], [16]. Single MAC layer requires centralised baseband processing.

Finally, it should be noted that the LTE-Advanced Release 10 signalling and protocols specifications are defined in a generic way, supporting both intra and inter-band scenarios on the uplink and downlink. The RF specifications, however, are band-dependent. They also depend on whether the communication is uplink or downlink. Therefore, each release defines the RF specification for a particular band and a particular UL/DL combination. It should be noted that in Release 13, 3GPP has specified License-Assisted Access (LAA), which relies on Carrier Aggregation and uses combination of unlicensed spectrum in 5 GHz band [12].

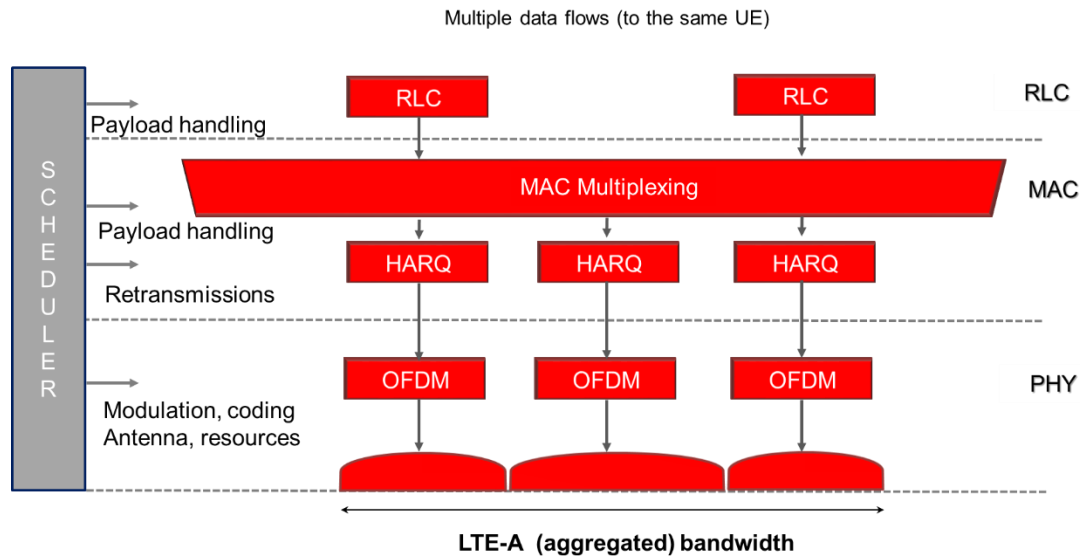


Figure 6 Carrier Aggregation- protocol structure on the downlink

3.2.1.1 Control Plane

Addition and activation of Secondary CCs

In Carrier Aggregation, the addition, and reconfiguration of SCells is performed by dedicated signalling from the PCell. Figure 7 depicts the addition of a SCell. Once SCells are added, they can be activated, using MAC control elements.

Deactivation and removal of SCells

In order to enable fast deactivation of secondary cells, Carrier Aggregation mechanism enables deactivation of SCells – again using MAC Control or using the deactivation timer. Hence, the UE does not need to monitor control and data channels of the deactivated carriers. In this way, the UE battery consumption is reduced, as well as the amount of required signalling for removal and addition of cells [17]. PCell can never be deactivated and is only changed during the handover procedure. Removal of SCells is performed by dedicated signalling from PCell.

Cross-carrier scheduling

Carrier Aggregation also supports cross-carrier scheduling, which means that the scheduling information for the DL is not carried by the associated (secondary) CC, but by another CC and is signalled using RRC signalling. For that, a carrier indicator is used on the control channel of the carrier providing the scheduling information [15]. The carrier indicator field (CIF) is appended to Downlink Control Information (DCI). DCI informs the UE about the DL scheduling assignments, UL scheduling grants and power control [15]. When CIF is appended to DCI, cross-carrier scheduling is used, whereby CIF informs the UE which CC is used for transmission of data. UE transmission can be scheduled using control channel only on one CC.

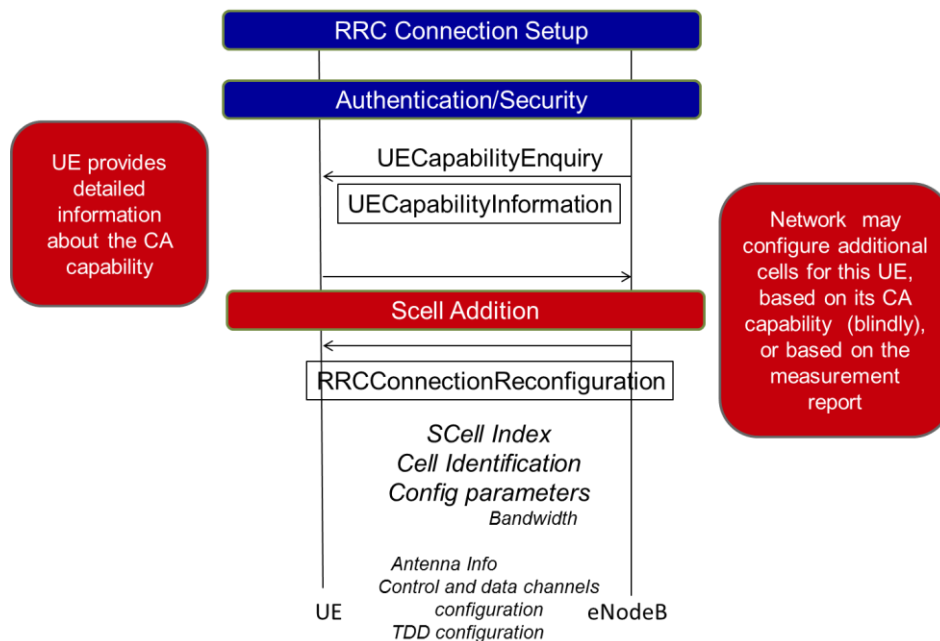


Figure 7 Addition of SCell - overview

3.2.2 Dual Connectivity

Dual Connectivity is introduced in 3GPP Release 12 to support densification of cellular networks through the use of small cells. The aim with Dual Connectivity is also to enable simultaneous utilisation of radio resources in distributed baseband architectures over a range of backhaul technologies with different throughput, delay and jitter characteristics.

Dual Connectivity enables a user to have a simultaneous connection to two nodes, with two schedulers, over a range of backhaul technologies. It is applicable when a user is in connected mode, where one node is designated as a master node - a Master eNodeB. The Master eNodeB is responsible for the signalling connection to the core network. The other node is a secondary node - a Secondary eNodeB, which is added as an additional resource by the Master eNodeB. Both Master and Secondary eNodeBs can have their own timing relations. Dual Connectivity requires implementation of two MAC layers in the UE - one for the Master eNodeB, and the other for the Secondary eNodeB [17]. Furthermore, Dual Connectivity supports Carrier Aggregation within each node.

3.2.2.1 Control plane

In Dual Connectivity, while each node controls its radio resources, only a Master eNodeB maintains the signalling connection to the core network, as depicted in Figure 8. Secondary eNodeB is added to provide extra resources. Only the Master eNodeB can initiate the addition of a Secondary eNodeB. However, the modification and release of the Secondary eNodeB can be initiated by either of the nodes, which is signalled through the X2 interface. The coordination between the Master and Secondary eNodeBs is done using X2 interface and inter-eNodeBs RRC messages.

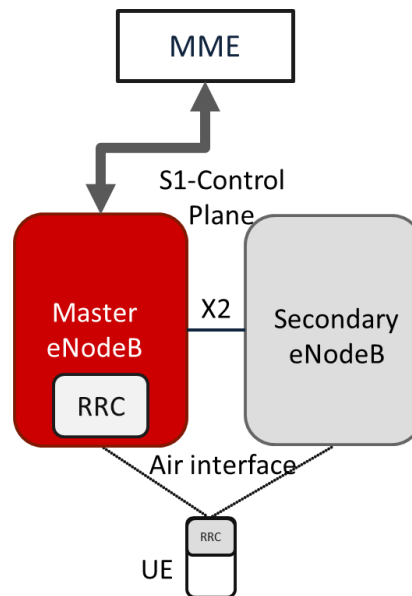


Figure 8 Dual Connectivity - control plane

3.2.2.2 User plane

Dual Connectivity introduces significant changes to the protocol stack on the user plane. Namely, 3GPP has proposed few architectural options in terms of handling the user traffic. One option envisages separate bearers between the core network and a Secondary eNodeB while the other option envisages split bearers between the core and radio access networks⁴.

Figure 9 on the left depicts the architectural option in Dual Connectivity with separate bearers between a UE and an S-GW. In that case, each S1 bearer is terminated in each of the nodes separately. That is, each node is only involved in the transport of data associated with its bearer. Hence, each node performs its own processing - namely, scheduling and buffering is done separately on each node. This option has certain advantages as it does not require processing of the same packets in different nodes, and the requirements for the transport network infrastructure are low. There are also disadvantages. For example, the utilisation of radio resources is not possible in two nodes for the same bearer. Further, the change of

⁴ Namely, in LTE, an Evolved Packet Service (EPS) bearer, which carries traffic with a certain QoS, is a packet flow between a Packet Gateway (P-GW) in the core network and a user [28]. EPS bearer is then mapped onto an Evolved UTRAN Radio Access Bearer (E-RAB) between the UE and a Serving Gateway (S-GW). In the core network, the EPS bearer is mapped onto S5/S8 bearer between S-GW and P-GW. On the radio access side, E-RAB is further mapped onto a radio bearer between a UE and

an eNodeB, and an S1 bearer between the eNodeB and the S-GW. Hence, each service is assigned to a particular EPS bearer, according to its QoS parameters [28]. All services with the same QoS characteristics are assigned to the same bearer [28].

Secondary NB due to e.g. mobility is visible to the core network. The other specified option is the option where an EPS bearer is split between the Master and the Secondary eNodeBs and is depicted on the right of Figure 9. This option enables spectral resource aggregation between the nodes but requires routing, processing and buffering the traffic between the nodes. Furthermore, to avail of the inter-node spectral aggregation, in this case, there are requirements regarding backhaul performance - it has to offer latency below 30 ms [18]. Given the different characteristics of the various types of backhaul solutions, the focus of this analysis is the option with the separate bearers, as this option does not pose any particular requirements on the backhaul.

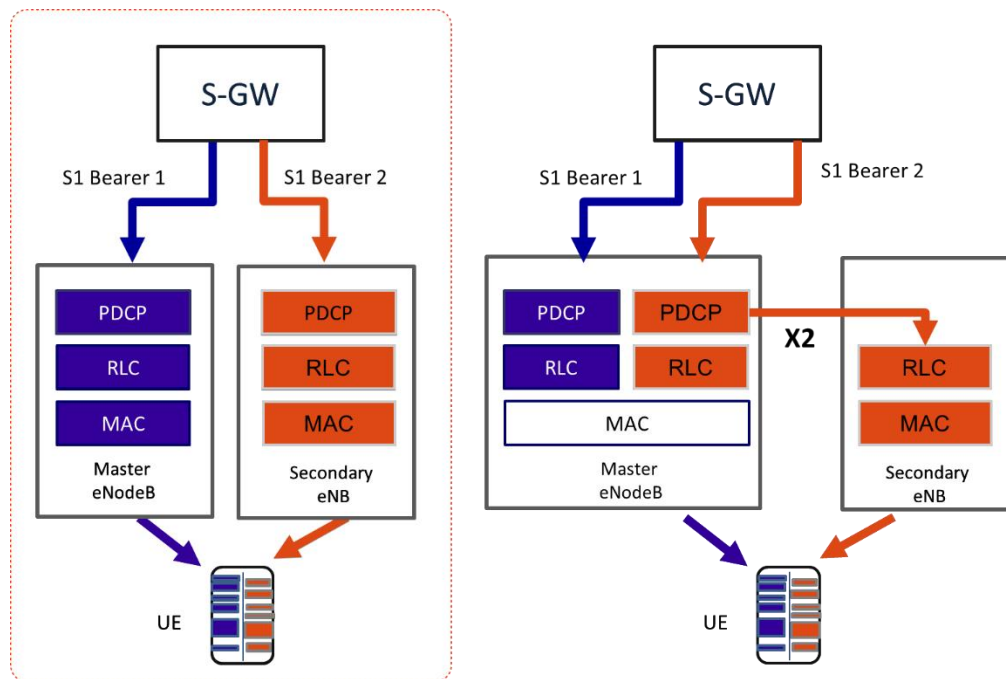


Figure 9 Dual Connectivity - user plane

3.3 Deployment Scenario of an LSA Licensee

Deployment scenario of interest is depicted in Figure 10. It entails heterogeneous network with macro-tier and tier of LPNs – RRHs and small cells. It is envisaged that:

- macro tier utilises licensee's dedicated spectrum,
- LSA spectrum is employed by RRHs and small cells
- Carrier Aggregation and Dual Connectivity techniques are used to enable employment of LSA radio resources
- Carrier Aggregation is applicable to the centralised baseband architecture – i.e. LPNs are RRHs
- Dual Connectivity is applicable to the distributed baseband architecture - i.e. LPNs are small cells.

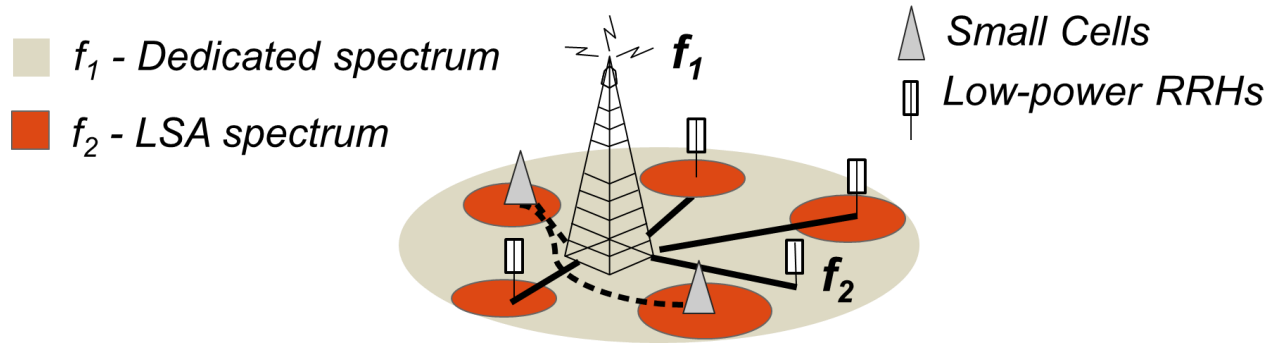


Figure 10 Foreseen deployment scenario of an LSA licensee

The signalling efficiencies in the considered scenario will be analysed from a link and system perspective, according to [19]. It should be noted that in the considered deployment, the operator's dedicated spectrum plays a prominent role. Namely, the dedicated spectrum, employed by the macro tier, provides the functionality found in current networks, namely:

- synchronisation signals for the purpose of synchronisation between a macro cell and all terminals in the cell
- basic system information required by the terminals to access the cell
- control signalling carrying scheduling information and transmission acknowledgements concerning the uplink transmissions
- cell specific (pilot) responsible for cell search, channel quality measurements and channel estimation for coherent demodulation on the dedicated carriers.

The question now remains what control plane and signalling information is required on the LSA carrier. This will also be determined by the baseband architecture and the corresponding technique that is employed i.e. whether it is Carrier Aggregation or Dual Connectivity. In both cases, the objective is to minimise the amount of signalling carried by the LPNs in order to maximise the use of the radio resources for user data. The split between user and control plane in heterogeneous networks was, among first, introduced in [20].

3.3.1 LSA spectrum in centralised baseband architecture with Carrier Aggregation

3.3.1.1 Control Plane & Signalling Aspects

In Carrier Aggregation, synchronisation, basic system information, mobility and security are inherently handled by the PCell. Hence, as mentioned above, it is envisaged that the operator's (i.e. LSA licensee's) dedicated spectrum will be providing these functions.

From a link perspective, there are three aspects that should be taken into account when considering the use of radio resources on any carrier, including LSA:

- cyclic prefix inherent to OFDM to protect against multipath
- LTE's 10% guard band in the frequency domain due to strong side-lobes of OFDM waveform

- LTE's Cell-specific Reference Signal (CRS)⁵⁶.

From a system perspective, there is a question how L1/L2 downlink control signalling⁷ is handled. Although this type of signalling can be carried by the LSA carrier, as mentioned earlier, the aim is to minimise control signalling carried by RRHs. Hence, the inherent capabilities of Carrier Aggregation can be utilised. Namely, considering that cross-carrier scheduling mechanism enables signalling of scheduling assignments using a different component carrier than the one that carries data, the LSA spectrum scheduling assignments can be signalled using licensee's dedicated spectrum. Furthermore, as this analysis is focused on the Carrier Aggregation in the downlink, the control region of the LSA carrier shall not carry any acknowledgements regarding the uplink transmission. Hence, the LSA component carrier is transmitted without control region. In this case, the start of the data region is signalled to the terminals, which is a part of cross-carrier scheduling configuration.

3.3.1.2 User Plane

As explained earlier, in case of Carrier Aggregation, multiple radio bearers are multiplexed and multiple data stream is distributed across component carriers. Considering that in this scenario, only best-effort traffic is analysed – the aggregated transmission bandwidth is provided to the radio bearer carrying best-effort traffic.

3.3.2 LSA spectrum in distributed baseband architecture with Dual Connectivity

It is envisaged that macro nodes, employing operator's dedicated spectrum, act as Master eNodeBs. Small cells, employing LSA spectrum, will perform the function of Secondary eNodeBs. The existing mechanism in Dual Connectivity can then request the activation of the LSA carrier on small cells.

The same link level aspects should be taken into account in this case as in the case with centralised baseband and Carrier Aggregation, namely: cyclic prefix, guard band and CRS.

However, from a system level signalling perspective, the situation is different. Here, cross-carrier scheduling cannot be utilised. Therefore, the LSA carrier will need to include control region for scheduling

⁵ CRS, introduced in LTE Release 8, is the basic signal that facilitates channel measurement and channel estimation for coherent demodulation. The CRS signal can be transmitted on 1, 2 or 4 antenna ports. CRS is transmitted in every downlink subframe and every resource block. In the time domain, it is transmitted in the first and the third last OFDM symbol and in the frequency domain, in each resource block.

⁶ Release 10 introduces new signals for the purpose of coherent demodulation and feedback on channel state information, but they support only certain transmission modes. Hence, they will not be further discussed.

⁷ In LTE, L1/L2 downlink control information carries downlink resource allocation assignments, uplink scheduling grants, acknowledgements in response to uplink transmissions and power control commands. Furthermore, in each subframe, the cell also signals the size of its control region, which may be 1, 2 or 3 symbols long.

assignments. The control region can be smaller than, for example, on the macro tier, as fewer users access each small cell.

Furthermore, an overhead should also be taken into account on the LSA spectrum to cater for Master Information Block (MIB). MIB can be used to signal system information that is specific to LSA spectrum instead of using dedicated (RRC) signalling in all instances. Furthermore, reading MIB from LSA spectrum allows system frame number synchronisation between macro and small cells, which can be used to align discontinuous reception in the UEs.

3.3.2.1 User Plane

As mentioned earlier, the focus of this analysis is the case with separate bearers from the core network to Master and Secondary eNodeBs. While this option does not enable inter-node aggregation of radio resources, it also does not pose any latency requirements on the link between the eNodeBs. For that reason, the bearer carrying best-effort data can only utilise LSA radio resources employed by small cells.

3.3.3 Results

This section presents results of the signalling efficiencies in the two architectures, given the considered deployment scenario. Furthermore, average user throughput (for the best-effort bearer) and the effect of link and system efficiencies are depicted for the case of deployment with 4 LPNs.

3.3.3.1 Signalling efficiency

For calculation of link and system efficiency, the following inputs and assumptions are used. It should be noted that the analysis is done for the FDD mode:

- LTE guard band - 10% of the total bandwidth [21].
- As per the cyclic prefix, normal length cyclic prefix introduces overhead of approximately 6.7% [21].
- CRS introduces approximately 4.8% overhead by occupying 4 out of 84 resource elements in each resource block [21], [22].
- Downlink control region occupies first few OFDM symbols in the subframe, with the maximum supported three (3) symbols per a subframe, and spans the whole bandwidth. With Carrier Aggregation and centralised baseband, dedicated spectrum, employed by macro tier, has the control region of 3 symbols, as it is required to carry assignments for both – dedicated and LSA spectrum, in addition to uplink scheduling grants. In case of Dual Connectivity, the LSA spectrum, employed by small cells, carries its own scheduling assignments. The size of control region is, therefore, assumed to be 1 symbol.
- Primary and secondary synchronisation signals, together with the broadcast channel in the radio frame occupy, in total, 488 resource elements [21]. These are included in the calculation of macro cell system efficiency.
- Broadcast channel used for LSA spectrum system information and synchronisation between Master and Secondary eNodeBs in Dual Connectivity architecture is envisaged to be carried on the broadcast channel, which requires 240 resource elements [21].

Table 6: Link and system efficiency factors for dedicated and LSA spectrum on macro and tier of LPNs

Factor effecting efficiency	Licensee's dedicated spectrum	LSA spectrum in Carrier Aggregation & centralised baseband	LSA spectrum in Dual Connectivity & distributed baseband
Guard Band	.9	.9	.9
Cell Reference Signal	.93	.93	.93
Correction factor according to (Mogensen & al, 2007)	.9	.9	.9
Link efficiency	.75	.75	.75
Control region (L1/L2 signalling)	.79 (3 symbols)	1	.93 (1 symbol)
Synchronisation & System information	0.994	1	0.994
System & link efficiency	.59	.75	.69

3.3.3.2 User throughput with Carrier Aggregation & Dual Connectivity

This section illustrates the average user throughput per best-effort bearer adjusted for link and link/system efficiencies when there are 4 LPNs per macro cell. The computation is done for both cases – centralised baseband with Carrier Aggregation and distributed baseband with Dual Connectivity. The throughput calculations follow [19], which take into account that channel capacity cannot be achieved due to the finite set of modulation and coding schemes and finite error-correction code length. Furthermore, of interest here is the average user performance measured over the time period occupied by multiple scheduling time intervals. For that reason, the use of round-robin scheduler is assumed.

Table 7 depicts the main parameters used in the simulation.

Table 7: Main parameters and their values used in the computation of average user throughput. Full buffer and the use of round-robin scheduler is assumed.

Macro & LPN deployment		4 LPNs per a macro cell, clustered deployment of users within LPNs, according to [23]
Dedicated spectrum (macro tier)	Channel model	Urban macro cell (Model 2), according to [23]
	BS Tx Power	46 dBm
	Spectrum	10 MHz @ 2 GHz
	BS Antenna pattern/gain	Directive antenna, 3GPP model [23] / 14dBi
LSA Spectrum (tier of LPNs)	Channel model	Urban micro-cell, according to [23]
	Spectrum	5 MHz @ 2.31 GHz
	Tx power	30 dBm
	BS Antenna pattern/gain	Omnidirectional antenna, 3GPP model [23]/ 5 dBi

Few trends can be observed in Figure 11, which depicts the average user throughput (for a best-effort bearer) adjusted for link and link/system efficiency:

- There is a difference between the throughputs that the average user can achieve when adjustments for link and for link/system efficiencies have been applied in both cases, as can also be seen in
- Table 6. For the case of Dual Connectivity, the reduction in the adjusted throughput (link vs. system) is approximately 8 % regardless of the density of small cells. In the case of Carrier Aggregation and centralised baseband, the situation is different. Namely, as can be seen from
- Table 6, the LSA spectrum has the same link and link/system efficiency factors in this case. This means that the change in Carrier Aggregation case between link and link/system efficiency adjusted throughputs is affected by the difference in the corresponding adjusted throughputs on the macro tier, which uses dedicated spectrum. For 4 RRHs, the reduction in throughput from link-level to system-level adjustments is 5.6%. As the number of RRHs increases, the overall throughput increases and for 10 RRHs (not depicted here), the results show a small reduction in the system adjusted throughput, compared to the link-level adjusted performance of 2.7%. In this case, the contribution of the throughput by the tier of RRHs employing LSA spectrum is much larger than the contribution of throughput by macro tier. At the same time, the RRH tier with LSA spectrum has the same link and system-level efficiency factors.
- Clearly, as can be seen in Figure 11, Carrier Aggregation provides significantly higher throughput, as a result of the contribution of throughput by macro tier and better signalling efficiency for the

LSA spectrum in the case of system-adjusted throughput. The difference is particularly significant for the low-to-medium cell load (up to 30 users). It can also be observed that the use of LSA spectrum is maximised when employed as proposed in the above scenarios. For example, our results show that with 4 LPNs per a macro cell, the average user throughput goes to several hundred kb/s only with a large number of users (more than 150), regardless of the baseband architecture – a result of the frequency reuse with LPNs. On the other hand, if only macro tier is considered with e.g. 10 MHz of spectrum, the average user throughput is reduced to several hundred kb/s already with 50 users.

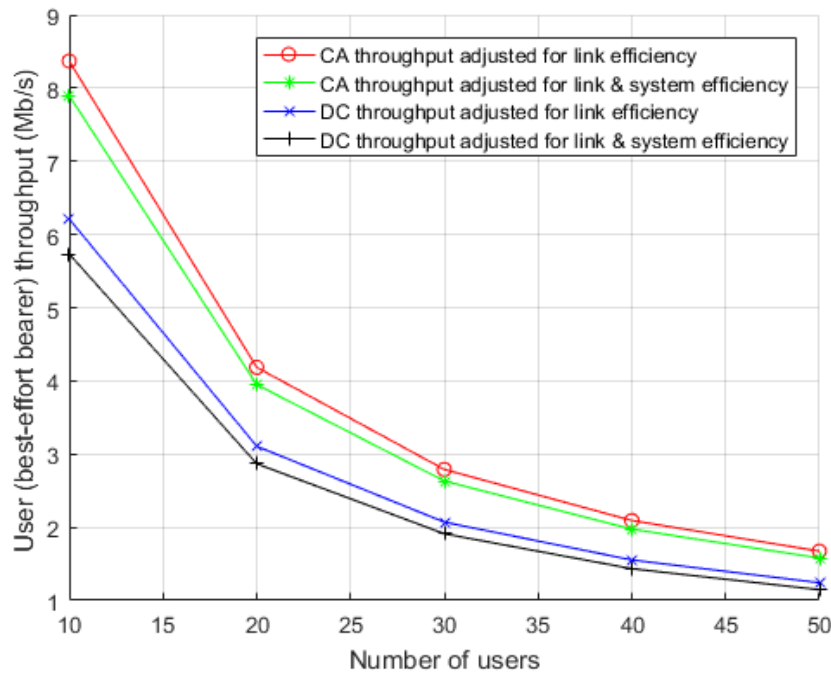


Figure 11 Average user throughput adjusted for link and link/system efficiency factors per

Table 6

3.4 LSA Spectrum Release Delay

LTE and its techniques described in the previous section are just one part of the overall LSA infrastructure. Within the LSA framework, one of the most important aspects is the time required to evacuate the LSA band. For that reason and in order to make the LSA framework more dynamic, the objective should be to minimise the evacuation time, regardless whether it is emergency or a pre-planned evacuation. The evacuation time in the LSA framework comprises of i) the time to signal the band evacuation requirement through the LSA infrastructure domain, ii) the time required to signal the changes from O&M to the base stations, iii) the time required by the adopted LTE technique to clear the band, and iv) the time required

to signal the confirmation of band evacuation. In [24], the evacuation times based on the trial using a real LTE system are discussed, where evacuation delay took between 20 and 30 seconds.

While the aim here is not to discuss possible evacuation times for different types of incumbents, the objective, in principle, should be to minimise the evacuation time. In that respect, this section considers delay on the LTE network side using Carrier Aggregation and Dual Connectivity techniques described in the previous section.

In order to understand what is involved, it is important to consider the signalling flow for both techniques.

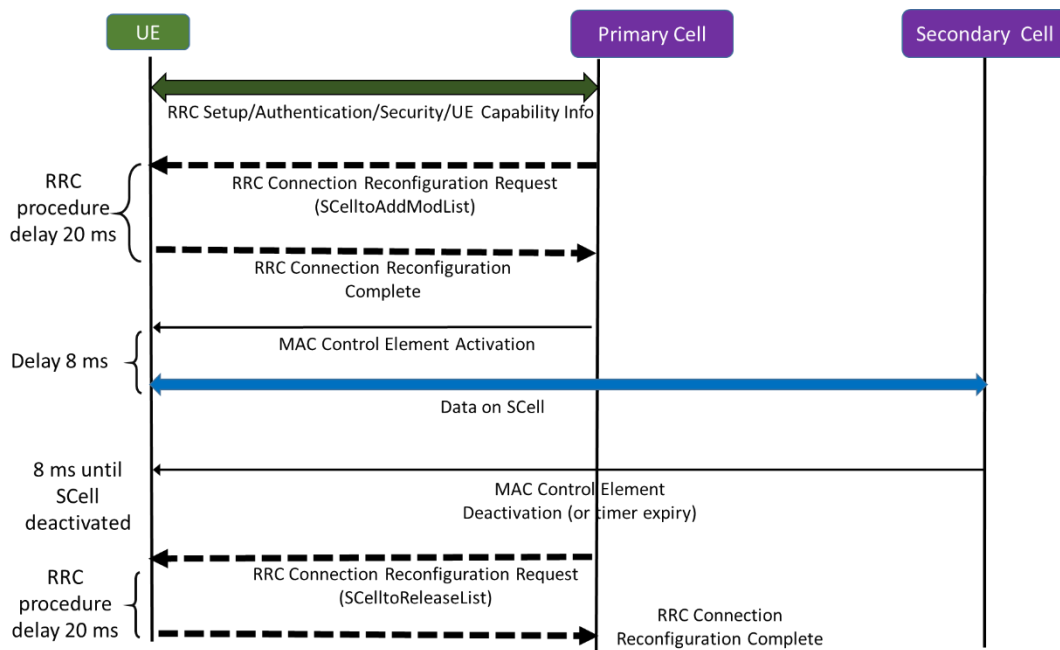


Figure 12 Signalling flow for Carrier Aggregation

As explained earlier in section 3.2.1.1, in Carrier Aggregation, the addition, activation, deactivation and removal of SCell entails dedicated signalling between a user and eNodeB. The RRC procedure incurs a processing delay, particularly in the UE. The RRC processing delay budget is specified in [25] to be up to 20 ms. Furthermore, delay with RRC will also depend on the number of users that can be scheduled within a single transmission interval. Nevertheless, when Carrier Aggregation is used, the release of LSA spectrum resources can avail of fast deactivation mechanism. Fast deactivation envisages that all transmission and monitoring of deactivated carrier ceases 8 ms after the deactivation is received. The deactivation is signalled using MAC Control Element for deactivation of SCells. In principle, the deactivation could be signalled from either dedicated or LSA spectrum. Delay will also be affected by the number of users that can be scheduled within a single transmission interval. This delay component is a function of the control channel capacity, which is directly related to the size of control region of the component carrier used for signalling MAC deactivation.

Hence, delay in the deactivation of LSA spectrum when dedicated spectrum is used to transmit MAC Control Element deactivation is given as:

$$t_{CA_{delay}} = t_{deactDelay} + t_{TTI} \cdot \frac{N_{users_{macro}}}{N_{users_{TTI}}} \quad (1)$$

Here, $t_{deactDelay}$ is the delay in the activation procedure, t_{TTI} is the transmission interval, $N_{users_{macro}}$ is the number of connected users in a macro cell and $N_{users_{TTI}}$ is the average number of users that can be scheduled per TTI in a macro cell.

In case of Dual Connectivity, it is envisaged that Master eNodeB-initiated Secondary eNodeB release should be used for release of LSA spectrum resources. Alternatively, other procedures such as Secondary eNB modification (initiated by the Master or Secondary eNodeB) may be used⁸. Regardless of which procedure may be appropriate, signalling between a Master and Secondary eNodeBs is required as well as RRC Connection Reconfiguration procedure towards UE. This means that delay will not only be affected by the RRC procedure delay and the number of users that can be scheduled on the LSA carrier, but also by the delay on the X2 interface between macro base station and a small cell.

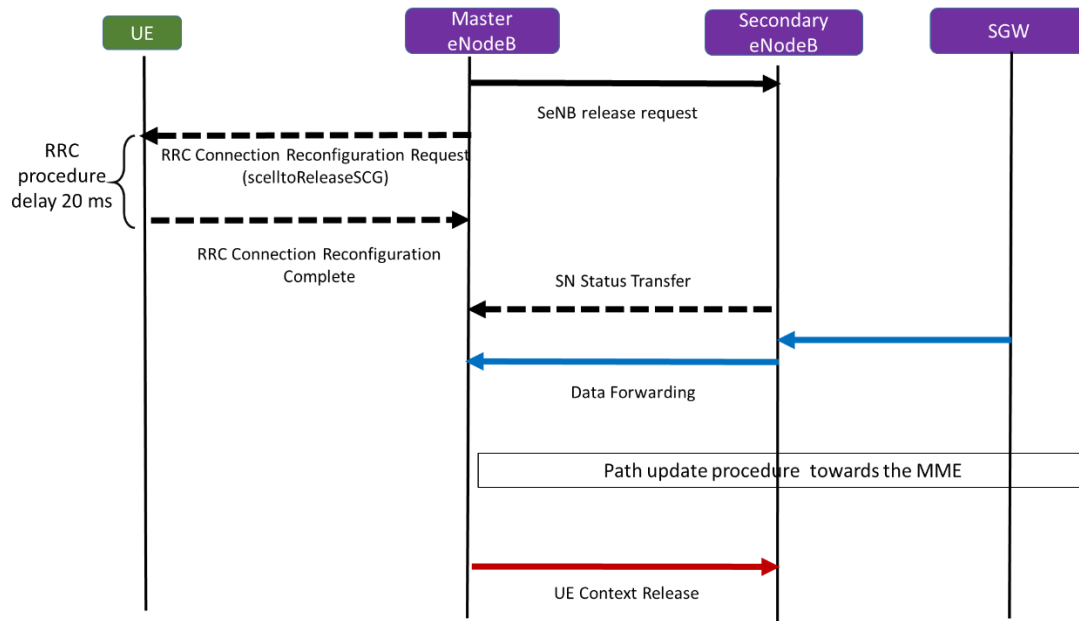


Figure 13 Master eNodeB initiated Secondary eNodeB Release

In this case, the delay in releasing LSA spectrum resources is

⁸ For example, an LSA licensee may decide to employ dedicated carrier instead of an LSA carrier.

$$t_{DC_{delay}} = t_{RRC_{Delay}} + 3 \cdot X2_{delay} + t_{TTI} \cdot \frac{N_{users_{LPN}}}{N_{user_{LPN_TTI}}} + t_{CN_{delay}} \quad (2)$$

Here, $t_{RRC_{Delay}}$ is delay in the RRC procedure, $X2_{delay}$ is delay on the X2 interface between macro cell and a small cell, $N_{users_{LPN}}$ is the average number of connected users in a small cell and $N_{user_{LPN_TTI}}$ is the average number of users that can be scheduled per TTI in a small cell.

Table 8: Parameters and their values used for calculation of the LSA spectrum release delay

Parameter	Description	Value
$t_{deactDelay}$	Deactivation delay after MAC Control Element reception	8 ms
t_{TTI}	Transmission Time Interval in LTE	1 ms
$t_{RRC_{Delay}}$	RRC procedure delay	20 ms
$X2_{delay}$	One-way X2 interface delay	5 ms to 35 ms. For DSL, it can reach 60 ms [26].
$t_{CN_{delay}}$	Delay in the core network due to path update procedure, similar to [27].	10 ms

Figure 14 depicts the delay on the radio interface side using Carrier Aggregation & Dual Connectivity for different number of (connected) users in the macro cell and cases when there are 4 and 10 LPNs per a macro cell.

It is clear that if LSA spectrum is released by means of Carrier Aggregation, delay below 20 ms can be expected even for a high number of connected user in the macro cell. The reason is that Carrier Aggregation avails of the fast deactivation procedure using MAC control element that signals the deactivation, which takes place in the 8th subframe after the deactivation is received, as depicted by Figure 12. Also, delay in this case does not depend on the control region on the LSA carrier as scheduling assignments are transmitted using dedicated spectrum resources. Hence, a wider bandwidth of the dedicated carrier results in the control region that can schedule more users in a single transmission interval (due to a greater number of resource blocks). In case of Dual Connectivity, the delay in releasing LSA spectrum resources depends on the size of control region on the LSA carrier as scheduling assignments for data transmissions use the LSA carrier. Furthermore, delay also depends on the average number users that are connected to small cells, which in turn depends on the number of small cells per a macro cell. Finally, different X2 interface delay will also affect the total delay. By increasing the number of LPNs, more users can be scheduled in a single transmission interval and hence a reduction in delay. The reduction is more pronounced for a high number of connected users. Nevertheless, even with 100 connected users in a macro cell and 35 ms one-way X2 delay, the LSA spectrum release does not exceed 160 ms with 4 small cells per a macro cell.

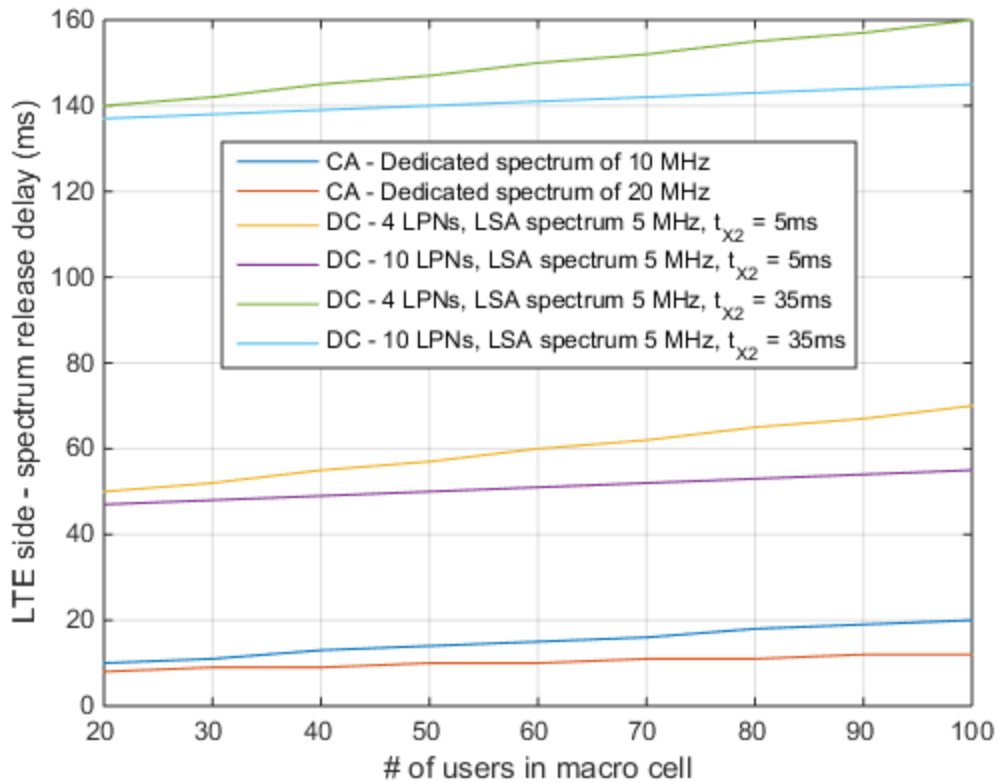


Figure 14 Delay in releasing LSA spectrum resources for Carrier Aggregation and Dual Connectivity with heterogeneous topology (4 and 10 LPNs per a macro cell)

3.5 Conclusions

In this section, we investigated the signalling and control plane of LTE and LTE-Advanced standards and their ability to support Licensed Shared Access. We consider two baseband architectures, centralised and distributed, corresponding to the use of small cells or RRHs. We further consider and compare two prominent technologies introduced in Release 13 (LTE-A), Carrier Aggregation and Dual Connectivity. We evaluate these two technologies against the expected throughput gains in an LSA deployment scenario, as well as against their respective delay requirements in setting up and releasing LSA resources. Our results show that Carrier Aggregation outperforms Dual Connectivity both in terms of the expected throughput improvement, as well as in terms of the time required to activate and release the radio resources. The trade-off with Carrier Aggregation, of course, is the expensive fronthaul infrastructure, whereas Dual Connectivity supports variety of backhaul links.

4 Database-assisted MAC protocol for Licensed Shared Access

4.1 Introduction

The limited spectrum availability is a real constraint for existing and future wireless systems. Spectrum scarcity is one key reason preventing operators from meeting the increasing user demands in capacity and Quality of Service (QoS) offerings, while it induces additional expenditures (CAPEX and OPEX) that network operators reflect on the service prices to their customers. Novel spectrum management techniques such as spectrum sharing are being developed to address the spectrum crunch issue [29].

Typically, the use of spectrum is either licensed or license-exempt. Cognitive radio (CR) offers an alternative approach in spectrum usage, allowing the use of idle spectrum by non-licensed secondary users (SUs) without causing harmful interference to the licensed primary users (PUs). However, CR was regarded with suspicion by mobile broadband operators that were reluctant to allow the use of their expensively acquired spectrum by any SU who claims it will respect the regulatory CR policies. In a similar way, SUs were also reluctant to invest in CR technology since it could not offer them business-grade service-level-guarantees.

The evolution of the CR concept is that of the Licensed Shared Access (LSA). This concept was introduced in early 2011 by Nokia and Qualcomm and aims to provide a framework under which a number of Licensee Operators (LOs) can reuse spectrum allocated to one or more Incumbent Operators (IOs) in accordance with sharing rules which protect both the rights of the IO but also those of the LO. The LSA concept has been and is the main subject of a number of International research projects, such as ADEL [30], and CORE+ [31], but also standardization activities by ETSI [32], the ECC [33], and the CEPT [34]. In the heart of the problem lies the ability to opportunistically and efficiently identify under-utilized resource blocks in the time, frequency, and space domains, as well as the ability to control the level of interference between the primary and secondary systems.

To this end, the exploitation of frequency selective fading has been considered in the literature. [35] analysed the channel capacity under spectrum-sharing constraints for additive white Gaussian noise (AWGN). The authors in [36] extended this analysis to derive the channel capacity bounds of a SU, subject to both average and peak received-power constraints at the PU's receiver. Rayleigh fading and complete CSI at the SU were assumed, while in [37] they extended their work to calculate capacity bounds with incomplete CSI. Complete CSI knowledge was assumed also in [38] which studies the sum-rate maximization problem employing MIMO. In [39] the optimal transmit power allocation problem is analyzed for Rayleigh fading environment, under a long term average transmit power constraint at the secondary transmitter. More recently, the authors in [40] proposed the use of feedback information to inform the selection of beams at the secondary user, while [41] proposed a transmission scheme where the primary and secondary users cooperate to choose the set of beams and spectrum that creates the less amount of interference at the PU receiver.

While the value of exploiting frequency-selective fading has been demonstrated through theoretical analysis, no MAC protocol has been proposed to facilitate the IO-LO cooperation. The work presented in this section fills the gap by proposing a novel database-assisted MAC protocol devised to facilitate the cooperation between the Incumbent and Licensee operators.

The remainder of this Section is organized as follows: in subsection 4.2 we describe our motivation for this research and the present the proposed protocol and system setup; subsection 4.3 presents the results from our system level simulations. Our conclusions are discussed in subsection 4.4.

4.2 System setup

4.2.1 Review of the ADEL architecture

The architecture of ADEL has been defined in Deliverable D3.1 [1]. The proposed architecture defines a number of control entities to facilitate the coordination between the Incumbent operators who hold spectrum licenses allocated to them by the National Regulatory Authority (NRA) and the Licensee operators who seek to have access to the Incumbent Operators' spectrum resources.

Figure 15 shows the high level system architecture of ADEL⁹. The LSA Band manager lies in the core of the architecture. Among other things, it is responsible for allocating resources to the LSA Licensees after collecting usage information from both the Incumbents and the dedicated spectrum sensing networks. The allocation can be either direct, i.e. by allocating specific resources to each Licensee operator, or indirect. In the latter case, the Band Manager conveys usage information to a database that can be accessed by the Licensee operators and it is up to the LSA Controller to decide how to use the available resources, so that it complies with the LSA Sharing Agreement rules.

⁹ For a detailed description of all the architectural elements see [1].

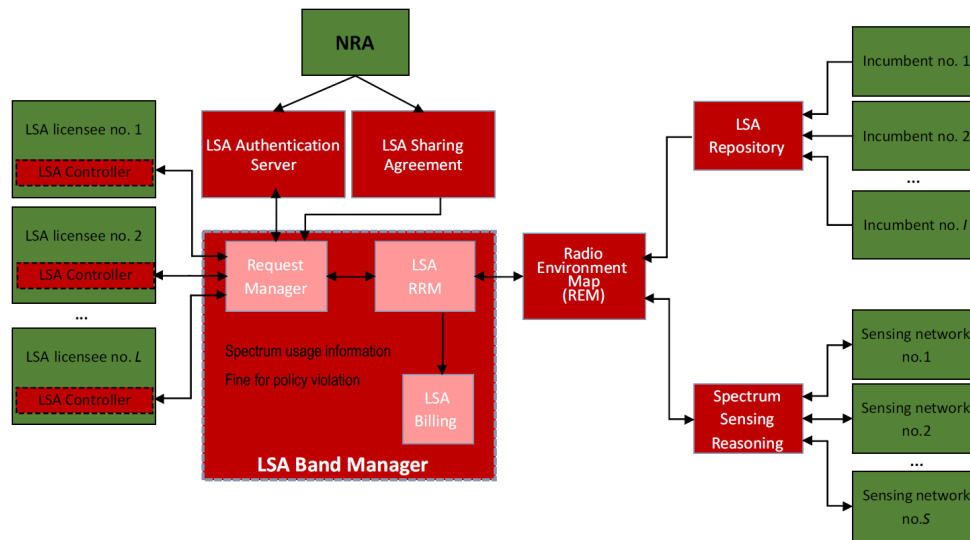


Figure 15: The high level logical architecture of the ADEL system

4.2.2 Motivation

An important element in advanced LSA architecture is the use of a database which allows the sharing of information between the Incumbent Operator (IO) and Licensee Operator (LO) base stations without the need for a direct communication channel between these two systems. Currently, databases are used to provide geo-temporal information on the use of spectrum from the IO. This allows a LO to use the IO’s spectrum during time periods and in areas where it is not being used by the IO. However, access to a shared database is increasingly considered part of the proposed LSA architectures [30]– [34], opening the opportunity to use it for additional information exchange.

We have already experimented with the use of shared databases during the course of the ADEL project. In the 2015 DySPAN challenge competition [4] a shared database was used by the Primary user to provide throughput degradation feedback to the Secondary user. Furthermore, we incorporated a similar concept in our 2016 EuCNC ADEL demonstration [5] where a “super node” equipped with six sector antennas was providing spectrum sensing information to a Tx-Rx pair of nodes. In this work we extend the use of the shared database to take advantage of frequency selective fading. A further extension of this concept is one where the Incumbent operator notifies the Licensee operator on spectrum availability on a near-real-time basis.

Our proposed protocol can be used in both the “Macro cellular” and “Small cells” ADEL reference scenarios (Sections 6.2 and 6.3 in [1]). Furthermore, the extended scenario of using a shared database to exchange spectrum availability information can be applied in the “Railways” scenario (Section 6.1 in [1]).

4.2.3 System description

We consider a system consisting of an Incumbent and a Licensee operator, as illustrated in Figure 16. There are two direct channels (H_{IO} and H_{LO}) and two cross channels (H_{LO-IO} and H_{IO-LO}). Both the IO and LO transmit using the same spectrum while, in comparison to previous works, we assume broadband transmissions using OFDM modulation. OFDM is chosen due to its ability to selectively transmit over

narrowband subcarriers. This allows the LO to selectively fit its transmissions in frequency bands that go under strong attenuation in the HIO-LO cross channel.

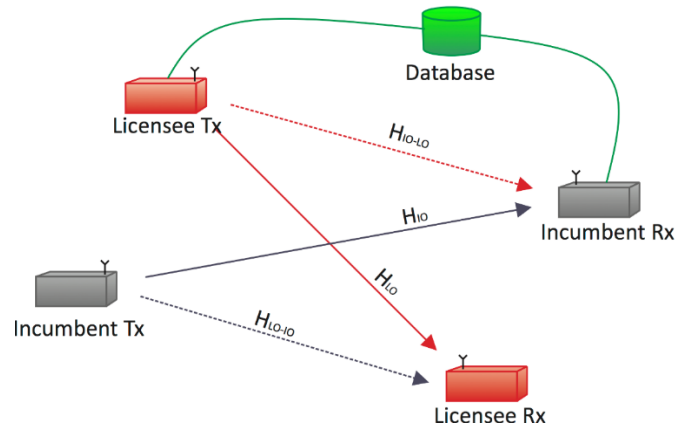


Figure 16: The considered system, consisting of an Incumbent and a Licensee operator.

We assume that no direct communication link exists between the LO and the IO. In a typical Cognitive Radio deployment the LO would have to rely on its own sensing capabilities to determine the IO's transmissions and try to estimate the effect its own transmissions have on the IO's performance. Access to the spectrum is granted to the LO under predefined LSA agreement rules which state the maximum acceptable level of degradation in the IO's capacity due to interference from the LO. In this paper we assume that the two operators have knowledge of their respective direct channels, HIO, and HLO. This is achieved through pilot symbols added in the transmitted signal. It is clear that the LO can further benefit from the knowledge of the characteristics (e.g., the impulse response) of the cross channel HIO-LO, as well as a metric (such as the packet error rate, PER) of the interference it causes on the IO. Knowledge of the channel state information can help the LO determine the optimal combination of frequency, bandwidth, and transmission power that maximizes the LO throughput, while minimizing the interference on the IO. Furthermore, knowledge of the interference the LO causes on the IO allows the LO to adhere to the agreed LSA rules by stopping its transmissions when the interference on the IO exceeds the agreed thresholds.

4.2.4 MAC Protocol Design

Our proposed approach relies on the ability of the IO to estimate the impulse and frequency response of the channel H_{IO-LO} and feed it back to the LO_{Tx} . To achieve this, we propose the introduction of short transmission gaps (Tx gap) in the IO's transmissions during which the LO transmits a training sequence already known to the IO_{Rx}. Using this sequence the IO_{Rx} can estimate the channel H_{IO-LO} , in particular its frequency response. This information is fed back to the LO through the shared database and allows it to identify candidate subcarriers that undergo strong attenuation over the cross channel, which could be used for transmission by the LO.

In addition to the cross channel information, the IO provides on a near-real-time basis information on the interference experienced by the activity of the LO. This can be expressed as the Packet Error Rate (PER) information at the IO_{Rx}, or the ratio between the achieved and the nominal throughput of the IO (normalized throughput). When the level of interference rises above the predetermined threshold the LO stops its transmission and waits for the next Tx gap in the IO's transmission following which it will receive

updated information on the cross channel's frequency response. The different stages of the proposed protocol are illustrated in Figure 17.

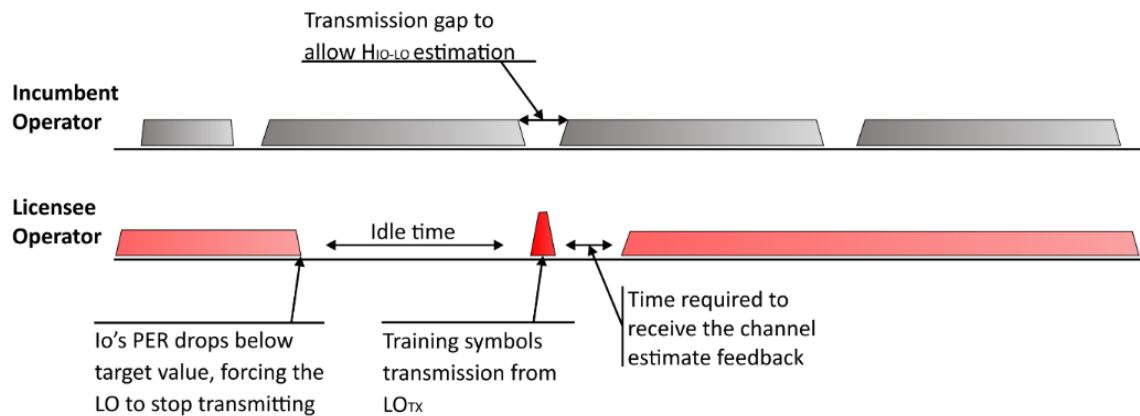


Figure 17: Illustration of the MAC layer procedures

4.3 Simulation Results

To evaluate the performance of our proposed scheme we have built a discrete time, system-level simulator using Matlab. We have implemented an OFDM-based transceiver which is used by both the LO and IO systems. The OFDM transmitter uses up to 64 subcarriers, over 20MHz bandwidth, and adds 25% Cyclic Prefix, as in IEEE802.11n [42]. The IO always uses all the 64 subcarriers. Time is divided in slots and all transmissions occupy an integer number of slots. More specifically, the packets transmitted by the IO occupy 1000 slots, while those transmitted by the LO have length of 500 slots. The training sequence transmitted by the LO, and the Tx gap occupy 10 slots. Finally, the data is modulated using 16QAM modulation.

After each received packet the IO updates the database with the performance metric, which is the normalized throughput. The simulator allows the introduction of delay between the time that a performance measurement is made and when it is available to the LO, in order to simulate the delays included in accessing the database. The database access delay is an important parameter since it has to be significantly smaller than the channel's coherence time. In our simulations, we have fixed this delay to 500 slots.

We assume that the four channels illustrated in Figure 16 experience slowly varying frequency selectivity, simulated using Rayleigh fading with eight taps. As described in Section II, the IO provides the frequency selective channel gain information for the cross channel to the LO via the database. In addition to this, the LO has information on the frequency response of the HLO channel. The LO chooses to use those subcarriers for which the difference between the gains over the HLO and the HIO-LO channels is above an isolation threshold. The choice of the isolation threshold affects the performance; on the one hand, a lower threshold allows the LO to transmit over more subcarriers and more frequently; on the other hand, however, a lower threshold leads to stronger interference on the IO, decreasing the achievable throughput. Figure 18 shows a snapshot where the LO has identified a range of frequencies with enough attenuation over the cross channel to allow a transmission opportunity. In this example, the LO is using 14 of the 64 subcarriers.

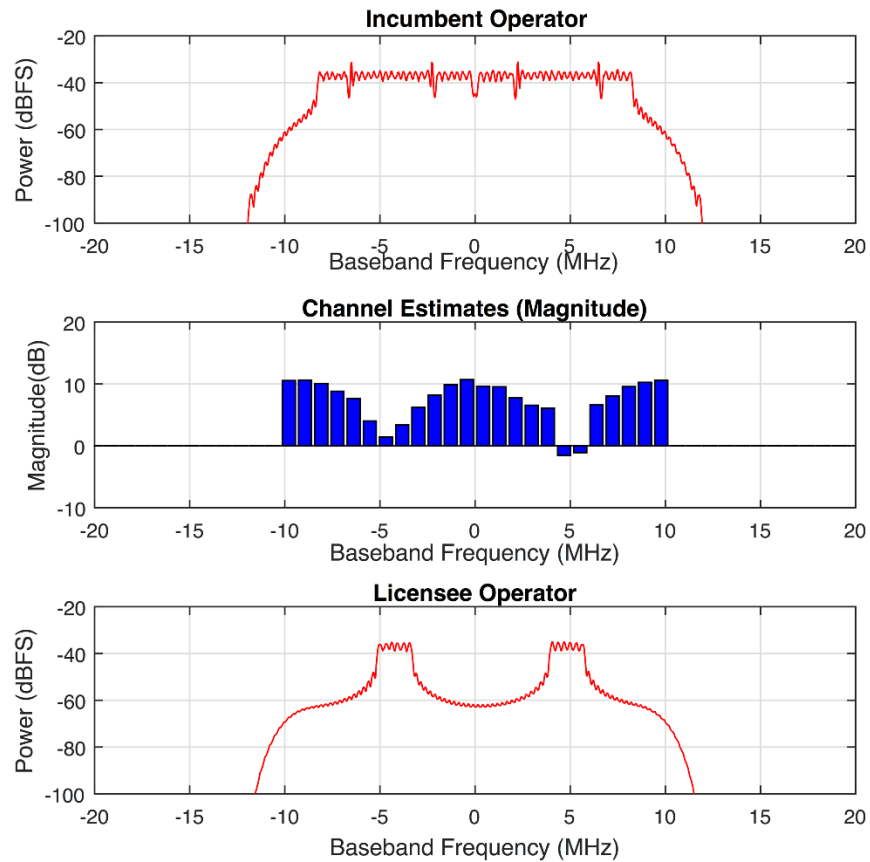


Figure 18: Simulation runtime snapshot showing the Incumbent operator’s transmission spectrum (top); the frequency selective fading of the cross channel (middle); and, the Licensee operator’s transmission spectrum (bottom).

The performance of our proposed system depends, to a large extent, on the power isolation between the two systems. This type of isolation can be achieved in different ways: through the use of directional antennas at either the LO, the IO, or both systems; or, by placing the LO_{Rx} close to the LO_{Tx} , which is often the case in the LSA use cases [43].

Figure 19 shows a complete simulation under the worst case scenario where there is no power isolation between the two systems other than that caused by the Rayleigh fading. The top graph shows the normalized throughput of the IO, the LO, as well as the normalized sum throughput. The bottom graph shows the number of subcarriers used by the LO in every slot. Under this scenario, we have set the isolation threshold at 5dB. The LO therefore transmits only on subcarriers where the aggregate effect of the fading over the HLO and HIO-LO channels creates a power isolation of more than 5dB. This reduces the probability for the LO to transmit, which is evident by the limited number of instances where the LO is using any subcarriers. Furthermore, due to the lack of power isolation between the IO and the LO, simultaneous transmissions are prone to interference which leads to significant reduction of the IO’s throughput. The LO detects the performance degradation and stops its transmissions so that the IO’s normalized throughput remains above the target value (0,9).

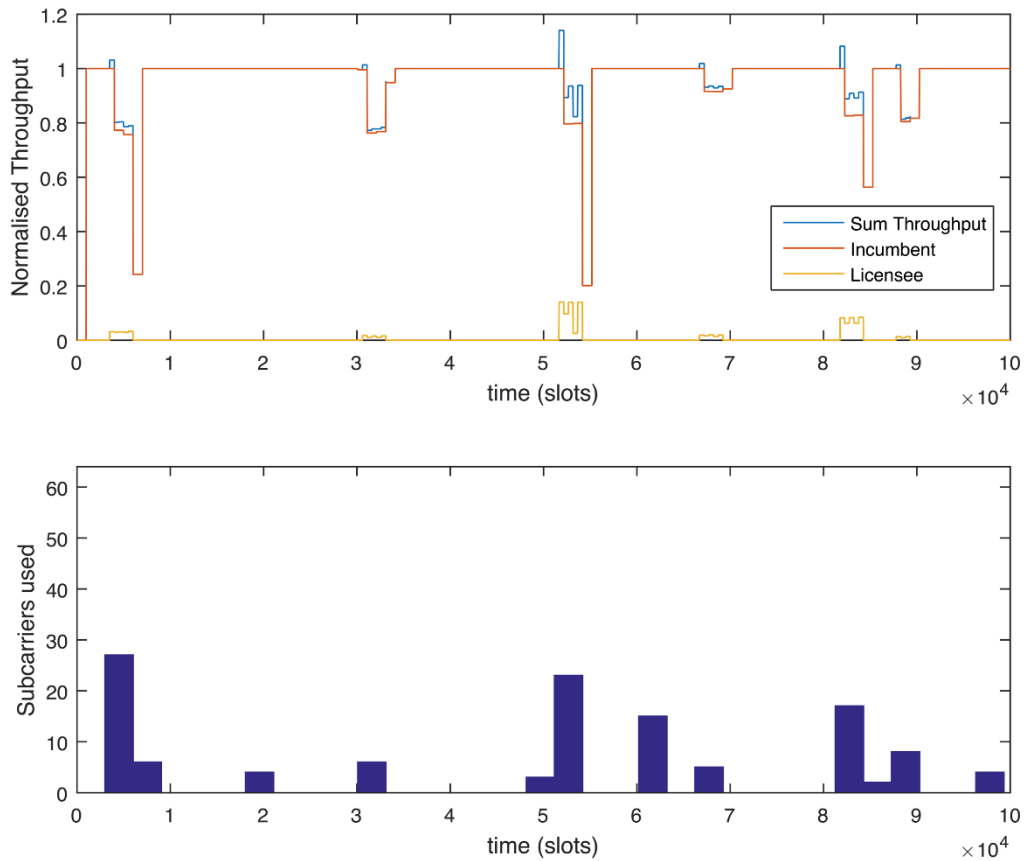


Figure 19: Complete simulation runtime under worst case conditions where there is no gain isolation between the IO and LO

In comparison, Figure 20 shows the results from a simulation where directional antennas are assumed at both the LOTx and LORx. Directional antennas isolate the two systems by introducing a gap between the power received by the targeted recipient and an interfering node. By appropriately aligning the radiation pattern of the antennas we can suppress the interference received over the HIO-LO and the HLO-IO cross channels. We assume that we can suppress both cross channels by 10dB, while we have increased the isolation threshold at 10dB. The results clearly demonstrate that under these conditions the LO can find several opportunities where it can transmit using the IO’s spectrum, without violating the interference levels set by the LSA agreement.

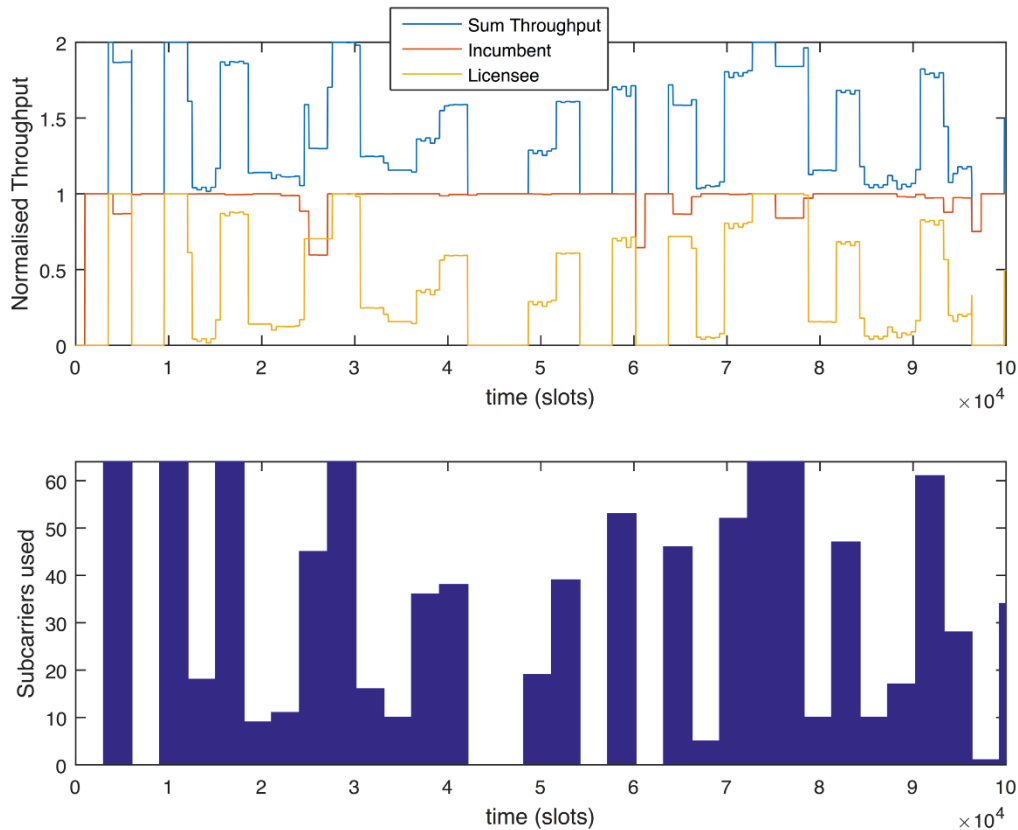


Figure 20: Complete simulation runtime under favorable conditions where there the use of directional antennas provides 10dB isolation over the H_{LO-LO} channel and 10dB isolation over the H_{LO-IO} channel

4.4 Conclusions

In this section we proposed a novel, database-assisted MAC protocol which allows the exchange of some CSI data between two spectrum sharing operators. Under the ADEL architecture, the shared database can be the Band Manager. The aim of our approach is to exploit the frequency selective fading in order to maximize the ability of the LO to use the IO’s radio resources, while respecting and adhering to the interference targets set in the LSA agreement. Our simulation results demonstrate that the approach can provide significant gains, which can be further improved with the use of directional antennas.

5 Summary and conclusions

In this deliverable we have presented our analysis on the anticipated LSA gains from a MAC-layer and Control Plane perspective. We show that the adoption of LSA, and the ADEL architecture in particular, can lead to significant capacity gains, while early adoption of LSA could be achieved under the current LTE and LTE-A signalling protocols.

More particularly, inspired from the Macro cellular reference scenario in ADEL, we study the capacity gain bounds from deploying Location-based LSA in a system of two overlapping Incumbent and Licensee operators in Section 2. Our results show that the gains can be very significant, depending on the density of the Incumbent's exclusion zones. This means that an LSA MNO could, for example, use the spectrum allocated to a M&E operator in such way that the MNO's capacity increases, while respecting the expected sharing rights of the M&E operator.

Then, in Section 3 we looked into the Control Plane (signalling and radio network) delay aspects from the LSA licensee's standpoint. We reviewed the signalling standards for LTE and LTE-A and described the mechanisms that can be used for the deployment of the ADEL LSA system. Given the current trends of network densification, we considered two scenarios encompassing small cells and LPNs such as RRHs, in accordance to the third ADEL reference scenario [1]. In addition, we compared the expected capacity gains and signalling delay of two prominent technologies, Carrier Aggregation (CA) and Dual Connectivity (DC), introduced as part of LTE-A. We showed that Carrier Aggregation (applicable to the centralised case) outperforms Dual Connectivity (applicable in the distributed topology), both in terms of the average achieved user throughput and the delay in setting up and releasing the LSA resources.

Finally, in Section 4 we proposed a novel MAC layer protocol which allows an Incumbent and a Licensee operator to share channel fading information using a shared database. We showed that our approach allows the two operators to take advantage slowly varying fading. In particular, the Licensee Operator is able to transmit over subcarriers that cause minimal levels of interference to the Incumbent Operator. Our simulations show that by using a shared database, it is possible for the Incumbent and the Licensee Operators to coordinate access to the shared spectrum in such way that the Incumbent operator is protected from excessive interference while allowing the Licensee operator to access the shared spectrum. The overall sum-rate throughput exceeds the throughput of the single user, even when tight transmission cooperation is not possible.

6 References

- [1] ADEL D3.1 Reference Scenarios and Network Architecture
- [2] ADEL D4.3 Cognitive spectrum access policy reinforcement mechanisms
- [3] ADEL D5.2 Centralised and distributed Sensing Techniques
- [4] DySPAN 2015 Challenge (<http://dyspan2015.ieee-dyspan.org/>)
- [5] EuCNC 2016 Exhibitions and Demos (<http://www.eucnc.eu/?q=node/134>)
- [6] EuCNC 2016 awards – best booth award presented to ADEL (<http://www.eucnc.eu/?q=node/155>)
- [7] V. Erceg and al., “An empirically based path loss model for wireless channels in suburban environments”,. IEEE JSAC, vol. 17, no. 7, July 1999, pp. 1205-1211
- [8] I. Latif, F. Kaltenberger, R. Knopp, and J. Olmos, “Link Abstraction for Variable Bandwidth with Incremental Redundancy HARQ in LTE”, Proceeding of IEEE WiOpt 2013, pp. 23-28
- [9] K. Brueninghaus, D. Astely, T. Salzer, S. Visuri, A. Alexiou, S. Karger, and G.-A. Seraji. “Link performance models for system level simulations of broadband radio access systems”, Proceedings IEEE PIMRC 2005
- [10] IEEE 802.16 Broadband Wireless Access Working Group, “Evaluation Methodology Document (EMD)”
- [11] H. Anouar, “Queue Maximum Proportional Fair Scheduling for Saturated and Non-Saturated Regimes”, Proceedings IEEE WCNC 2014
- [12] E. Dahlman, S. Parkvall and J. Skold, 4G, LTE-Advanced and the Road to 5G, Elsevier, 2016.
- [13] 3GPP, ““Overview of 3GPP Release 10”, V0.2.1,” 3GPP, Jun. 2014..
- [14] ETSI/3GPP, “LTE (E-UTRA) Evolved Universal Terrestrial Radio Access UE Radio Transmission and Reception (36.101) V 12.9,” ETSI/3GPP, Oct 2015.
- [15] E. Dahlman, S. Parkvall and J. Skold, 4G: LTE/LTE-Advanced for Mobile Broadband,, Academic Press, 2011.
- [16] K. Pedersen and et al, “Carrier Aggregation for LTE-Advanced: Functionality and Performance Aspects,” IEEE Communication Magazine, vol. 49, no. 6, pp. 89-95, 2011.
- [17] ETSI/3GPP, “Evolved Universal Terrestrial Radio Access (EUTRA) TS 136 300: Overall description - Stage 2; V12.5,” Apr. 2015.
- [18] 3GPP, “TR 36.842 Study on Small Cell Enhancements for E-UTRA and E-UTRAN: Higher Layer Aspects; 12.0.,” Jan. 2014.
- [19] P. Mogensen and e. al, “LTE Capacity Compared to the Shannon Bound,” in VTC, 2007.
- [20] H. Ishii, Y. Kishiyama and H. Takahashi, “A Novel Architecture for LTE-B: C-Plane/U-Plane Split and Phantom Cell Concept,” in Globecom, Dec. 2012.
- [21] “3GPP Self-evaluation - Methodology and Results - Assumptions,” 2009. [Online]. Available: ftp://www.3gpp.org/workshop/2009-12-17_ITU-R_IMT-Adv_eval/docs/pdf/REV-090007%20SelfEvaluation%20assumption.pdf. [Accessed 2016].
- [22] ETSI/3GPP, “TS 136 211 Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation, Technical Specification V10.7,” 2013.
- [23] 3GPP, TR 36.814 Evolved Universal Terrestrial Radio Access (E-UTRA) Further Advancements for E-UTRA Physical Layer Aspects, V9.0.0., 3GPP, Mar. 2009.
- [24] CEPT/ECC, “Technological and Regulatory Options Facilitating Sharing Between Wireless Broadband Applications (WBB) and the Relevant Incumbent Services/Applications in the 2.3 GHz Band,” ECC, Mar. 2015.
- [25] ETSI/3GPP, “Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification v12,” 2015.

- [26] ETSI/3GPP, “3GPP TR 36.932 E-UTRA Scenarios and Requirements for Small Cell Enhancements for E-UTRA and E-UTRAN, 12.1,” Oct. 2014.
- [27] D. Han, “Measurement and stochastic modeling of handover delay and interruption time of smartphone real-time applications on LTE networks,” *IEEE Magazine*, vol. 53, no. 3, p. 173–181, 2015.
- [28] M. Alasti, B. Neekzad, J. Hui and R. Vannithamby, “Quality of Service in WiMAX and LTE Networks [Topics in Wireless Communications],” *IEEE Magazine*, vol. 48, no. 5, pp. 104-111, 2010.
- [29] D. Talbot, “The spectrum crunch that wasn’t,” Nov. 2012, available online at: <https://www.technologyreview.com/s/507486/the-spectrumcrunch-that-wasnt/>
- [30] “FP7 project ADEL” [online]. available: <http://www.fp7-adel.eu>
- [31] “The CORE+ funded projects” [online]. available: <http://core.willab.fi>
- [32] “Reconfigurable Radio Systems (RRS); System Architecture and High Level Procedures for operation of Licensed Shared Access in the 2300 MHz-2400 MHz band,” ETSI, Tech. Rep. TS 103 235, Dec. 2015.
- [33] “Licensed Shared Access ,” ECC, Report 205, Feb. 2014.
- [34] “Report A from CEPT to the European Commission in response to the Mandate on ‘Harmonised technical conditions for the 2300-2400 MHz (‘2.3 GHz’) frequency band in the EU for the provision of wireless broadband electronic communications services’: Technical conditions for wireless broadband usage of the 2300-2400 MHz frequency band ,” CEPT, Report 55, Nov. 2014.
- [35] M. Gastpar, “On capacity under received-signal constraints,” in *Proceedings of the 42nd annual allerton conference on communication, control and computing*. Citeseer, 2004, pp. 1322–1331.
- [36] L. Musavian and S. Aissa, “Capacity and power allocation for spectrum-sharing communications in fading channels,” *IEEE Transactions on Wireless Communications*, vol. 8, no. 1, pp. 148–156, Jan. 2009.
- [37] L. Musavian and S. Aissa, “Fundamental capacity limits of cognitive radio in fading environments with imperfect channel information,” *IEEE Transactions on Communications*, vol. 57, no. 11, pp. 3472–3480, Nov 2009.
- [38] J. Tang, G. Bournaka, and S. Lambotharan, “Sum rate maximization for spectrum sharing multiuser mimo network under rayleigh fading,” in *Communication, Networks and Satellite (ComNetSat), 2012 IEEE International Conference on*, July 2012, pp. 30–34.
- [39] Y. He and S. Dey, “Power allocation for secondary outage minimization in spectrum sharing networks with limited feedback,” *IEEE Transactions on Communications*, vol. 61, no. 7, pp. 2648–2663, July 2013.
- [40] M. Abdallah, M. Sayed, M. S. Alouini, and K. A. Qaraqe, “Interference-Aware Random Beam Selection for Spectrum Sharing Systems,” pp. 1–5, Sept 2012.
- [41] M. Sayed, M. Abdallah, K. Qaraqe, K. Tourki, and M. S. Alouini, “Joint opportunistic beam and spectrum selection schemes for spectrum sharing systems with limited feedback,” *IEEE Transactions on Vehicular Technology*, vol. 63, no. 9, pp. 4408–4421, Nov 2014.
- [42] T. Paul and T. Ogunfunmi, “Wireless lan comes of age: Understanding the IEEE 802.11 n amendment,” *Circuits and Systems Magazine, IEEE*, vol. 8, no. 1, pp. 28–54, 2008.
- [43] A. Morgado, A. Gomes, V. Frascolla, K. Ntougias, C. Papadias, D. Slock, E. Avdic, N. Marchetti, N. Haziza, H. Anouar et al., “Dynamic LSA for 5G networks.”