Quality Of Service and MObility driven cognitive radio Systems

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QoSMOS

D2.3

System specification and evaluation criteria

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Editors:	Geneviève Mange (ALD), Péter Horváth (BME), Christophe Rosik (NTUK), Ole Grøndalen (TEL), Juan Rico (TST)
Authors:	Geneviève Mange (ALD), Péter Horváth (BME), Vincent Berg (CEA), Bernd Bochow (FR), Ramiro Robles (IT), Masayuki Ariyoshi (NEC), Christophe Rosik (NTUK), Ole Grøndalen, Per H. Lehne (TEL), Juan Rico, Arturo Medela (TST), Rohit Data (TUD), Ulrico Celentano (UOULU)
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Abstract:

A detailed description of the QoSMOS system based on its reference model by specifying its functionalities and characteristics is given. A discussion on architecture options when mapped to the different scenarios considered results in a selection of specific topologies' combinations for Resource Control and Sensing. Overall QoSMOS system specification is reported by considering the functional components of the QoSMOS system with their interactions, message sequence charts and primitives' layouts. A reference incumbent environment is specified giving the constraints for the performance evaluation of each selected QoSMOS scenario. Performance metrics are defined for use during the overall assessment of the QoSMOS system.

Keyword list:

Cognitive Radio, system specification, scenarios, reference environment, metrics, evaluation criteria

Abbreviations

3G	3rd Generation
3GPP	3rd Generation Partnership Project
ACIR	Adjacent Channel Interference Ratio
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
AGC	Automatic Gain Control
AL	Adaptation Layer
AP	Access Point
APPL	Application
ARQ	Automatic Repeat reQuest
AWGN	Additive White Gaussian Noise
BS	Base Station
CBR	Call Blocking Rate
cdf	cummulative distribution function
CDR	Call Dropping Rate
CEPT	European Conference of Postal and Telecommunications Administrations
CM	Cognitive Manager
CM-RM	CM for Resource Management
CM-SM	CM for Spectrum Management
CN	Core Network
COORD	COORDination
CORBA	Common Object Request Broker Architecture
CQI	Channel Quality Indicator
CSI	Channel State Information
DB	DataBase
DTG	Digital TV Group
DTT	Digital Terrestrial TV
DVB	Digital Video Broadcasting

DVB-T	DVB-Terrestrial
ECC	Electronic Communications Committee
ECMA	European Computer Manufacturers Association
EIRP	Equivalent Isotropically Radiated Power
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UMTS Terrestrial Radio Access
EVM	Error Vector Magnitude
FCC	Federal Communications Commission
FEC	Forward Error Code
FSSE	Fairly Shared Spectrum Efficiency
FuNeMS	Future Networks Mobile Summit
GoS	Grade of Service
GW	GateWay
ICS	In-Channel Selectivity
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ITU	International Telecommunication Union
ITU-T	ITU-Telecommunication Standardization Sector
LOS	Line-Of-Sight
LTE	3GPP Long Term Evolution
MAC	Media Access Control
MCS	Modulation and Coding Scheme
MSC	Message Sequence Chart
MT	Mobile Terminal
NGMN	Next Generation Mobile Networks
NLOS	Non-Line-Of-Sight
NORDIG	NORdic DIGital group
NW	NetWork
OFCOM	OFfice of COMmunications
OFDM	Orthogonal Frequency-Division Multiplexing
OSI	Open Systems Interconnection

OTh	Overloading Threshold
PCRF	Policy Charging and Rules Function
PF	Portfolio Repository
PHY	Physical layer
PoC	Proof of Concept
PR	Protection Ratio
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QoSMOS	Quality of Service and MObility driven cognitive radio Systems
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RAT	Radio Access Technology
RBR	Receiver Blocking Response
RCD	Resource Control Distributed
RCL	Resource Control Local
REG	REGulatory databases
RF	Radio Frequency
RM	Resource Management
RMS	Root Mean Square
RSSI	Received Signal Strength Indicator
SAP	Service Access Point
SC	Sensing Channel
SIR	Signal-to-Interference Ratio
SM	Spectrum Management
SNR	Signal-to-Noise Ratio
SOAP	Simple Object Access Protocol
SoTA	State-of-The-Art
SS	Spectrum Sensing
SSC	Spectrum Sensing Centralized
SSD	Spectrum Sensing Distributed
SSL	Spectrum Sensing Local

TRX	Transceiver
TS	Technical Specification
TV	TeleVision
UE	User Element
UHF	Ultra High Frequency
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
UTRA	UMTS Terrestrial Radio Access
WP	Work Package
WS	WhiteSpace
XML-RPC	eXtensible Markup Language – Remote Procedure Call

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1 Executive Summary

The objective of this deliverable is to give a detailed description of the QoSMOS system based on its reference model by specifying its functionalities and characteristics. This document contains as well evaluation criteria and metrics for the assessment of the overall performance of the system. The contents presented build the base for the detailed system specifications elaborated for implementation purpose which will be available later on in the project.

First the reference model of the QoSMOS system elaborated in the former course of the project is refined and the architecture options when mapped to the different scenarios considered in QoSMOS are discussed. This results in a selection of specific topologies' combinations for Resource Control and Sensing for further focus of the studies.

The work on the overall QoSMOS system specification as such is then reported, considering each functional block of the QoSMOS system and their interactions like the inter-working between both entities of the Cognitive Manager for Spectrum Management and Resource Management.

The Adaptation Layer defined as a media independent layer ensuring the communications between the QoSMOS system entities based on Service Access Points is specified in detail. Its concept with functionalities and internal architecture are illustrated, followed by the corresponding Message Sequence Charts (MSCs) as well as the primitives' layouts and the data structures used.

Further primordial functionalities of the QoSMOS system like Load Balancing procedures, Interference monitoring for Incumbent Protection and Management of Sensing measurements are specified by means of their MSCs and corresponding primitives as well.

For the Transceiver subsystem an analysis of the link budgets and channel models is conducted based on the categorization of the QoSMOS scenarios from the Physical Layer perspective. This leads to the definitions of the characteristics of transmitter and receiver with estimations made for the mean achievable communication ranges.

Finally a reference incumbent environment based on digital terrestrial TV broadcasting network and mobile wireless microphones is specified giving the constraints (including the characteristics of the incumbent transceivers) for the performance evaluation of each selected QoSMOS scenario. This is completed by the definition of system performance metrics categorized in spectrum utilization and service performance which will be used for the overall assessment of the system performance.

2 Introduction and scope

The objective of this deliverable is to give an overall description of the QoSMOS system based on its reference model by specifying its functionalities and characteristics. This document also contains evaluation criteria and metrics for the assessment of the overall performance of the system. This is the base for the detailed system specifications needed for implementation purposes which will be reported later by the project.

Chapter 3 refines the reference model of the QoSMOS system elaborated in the former course of the project [D2.2] and addresses the possible combinations of topologies for Resource Control and Spectrum Sensing envisaged. The resulting architecture options when mapped to the different scenarios considered in QoSMOS are illustrated and a selection of them is worked out for further focus of the studies. Furthermore the application of this architecture design to the integrated Proof of Concept work defined in QoSMOS is shown in this chapter.

Chapter 4 addresses the overall QoSMOS system specification as such, considering each functional block of the QoSMOS system and their interactions like the inter-working between both entities of the Cognitive Manager for Spectrum Management and Resource Management based on the use of Portfolios. Specific functionalities of the QoSMOS system operating in a heterogeneous Radio Access Technology (RAT) environment are addressed. Highlighted is the Adaptation Layer ensuring the communication between the QoSMOS entities due to this central role, which is therefore described in detail by means of its functionalities and internal architecture. For the Transceiver subsystem an analysis of the link budgets and channel models is conducted based on the categorization of the QoSMOS scenarios from the Physical Layer perspective leading to the definition of the characteristics of transmitter and receiver.

In chapter 5 a reference environment with incumbent systems is specified giving the constraints (including the characteristics of the incumbent transceivers) for the performance evaluation of the selected QoSMOS scenarios. Performance assessment criteria are addressed in relation to the functional system requirements elaborated earlier in the project [D1.4]. Finally a description of performance metrics classified in spectrum utilization and service performance is given for the overall assessment of the system performance.

Chapter 6 presents Message Sequence Charts and their related operations detailing the QoSMOS system functionalities addressed in chapter 4 for the Adaptation Layer as well as Load Balancing procedures. These are completed by the refined descriptions of system functionalities addressed earlier in the project [D2.2] like Interference monitoring for Incumbent Protection and Management of Sensing measurements.

Chapter 7 draws conclusions of the work reported and gives an outlook for the further steps.

The Appendix contains besides an example for the Spectrum Portfolio layout and the detailed primitives of the Load Balancing procedure, the description of the internal operations performed by the Adaptation Layer. Furthermore a set of preliminary detailed metrics for the overall assessment of the performance of the QoSMOS system is added there.

3 QoSMOS reference model and architecture options

The QoSMOS reference model, initially proposed in [D2.1] and further refined in [D2.2], has formed the starting point to identify topologies that show how the functional entities are distributed across the network elements, according to the core tasks to be achieved (resource allocation and spectrum sensing).

Based on these first outcomes, the next architecture work has consisted in determining how to map the QoSMOS scenarios to the different network architectural options. In this chapter, the different possibilities are identified by combining the topologies previously mentioned. Then, the possible combinations are rationalized in order to focus only on the differences among them while avoiding duplicating the similarities. Finally, the architecture aspects relevant for the Integrated Proof of Concept are derived, according to the QoSMOS scenario considered.

3.1 Reference model

Figure 1 presents the QoSMOS reference model identifying the functional entities as well as their interactions.

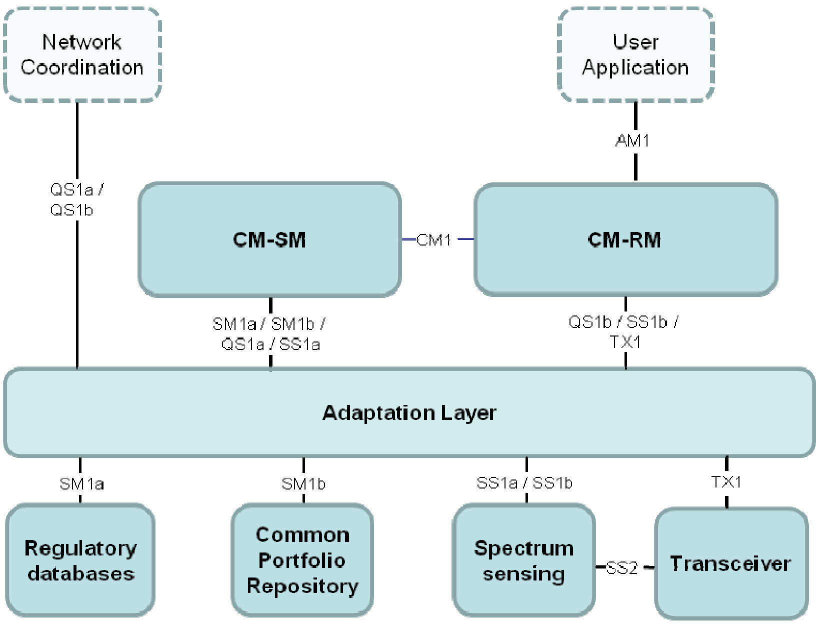


Figure 1: QoSMOS reference model

The role and responsibilities of the functional entities previously depicted are described in Table 1. Additional details, such as the interfaces definitions, can be found in [D2.2].

Table 1: Description of QoSMOS functional entities

Functional blocks	Description
Spectrum sensing (SS)	The SS is responsible for controlling the sensing process by interacting with the sensor, for making decision (about the presence or absence of an incumbent for example) based in sensing measurements, and to report the sensing measurements back to the requesting CM management entities.
Cognitive manager for spectrum management (CM-SM)	The CM-SM is responsible for building the spectrum portfolio based on the external constraints (regulatory policies, operator policies…) and on spectrum sensing results. This spectrum portfolio contains spectrum usage policies and

	spectrum usage information, putting constraints on the decisions which can be taken by the other cognitive entities of the QoSMOS system.
Cognitive manager for resource management (CM-RM)	The CM-RM is responsible for providing service to the application layer according to an agreed level of quality of service (QoS). This includes being responsible for the allocation of the spectrum following the policies contained in the spectrum portfolio, managing the mobility of the users and protecting the incumbent users.
Transceiver (TRX)	The TRX is able to perform synchronized data transmission and to provide unidirectional or bidirectional dedicated broadcast and multicast channels on different spectrum band operated by the supported heterogeneous radio access technologies. Additionally, it provides CM-RM with measurement reports and transceiver capabilities (i.e. capabilities to transmit and receive data).
Common portfolio repository (PF)	The PF is used to store the spectrum portfolio and to exchange context information among network entities. The information includes available frequency bands and spectrum usage policies….
Global & local regulations, policy databases (REG)	The REG is used to provide regulatory information for spectrum assignment (licensee status, usage requirements).
User application (APPL)	The APPL represents any application running on a user terminal providing a service to an end-user, and requiring access to the network. The user application should be able to express its requirements in terms of QoS for the CM-RMs to decide on admitting or refusing the associated service.
Network coordination (NW COORD)	The NW COORD has the overall responsibility of the configuration of an operator's infrastructure network. It includes part of the mobility management, and monitors the overall performance of the networks under its control to eventually decide on the reconfiguration of network segments.
Adaptation Layer (AL)	The AL provides a seamless and RAT-agnostic communication between some of the different functional entities. This mainly applies to the communication in heterogeneous configurations to facilitate the data exchange between different network elements.

Compared with its initial version, as documented in [D2.2], the QoSMOS reference model has been upgraded as following:

- The "Core Network Management" entity has been renamed as "Network Coordination" (NW-COORD) in order to reflect its applicability extended beyond the cellular case.
- CM-SM and CM-RM entities are now able to access to the NW-COORD entity (QS1a & QS1b interfaces) through the Adaptation Layer using a dedicated interface that aims at facilitating the interoperability with the various systems supported.
- The scope of the Adaptation Layer responsibilities, in the case of TX1 interface, is limited to the interactions between the innovative mechanisms implemented in the transceiver and legacy functionalities present in the CM-RM.

3.2 Combinations of topologies

As introduced in [D2.2], the combination of resource control and spectrum sensing topologies has instigated the formation of two architecture options:

- Resource Control topology can be either centralized, distributed, semi-distributed;
- Spectrum Sensing topology can be local, centralized with overlapped or non-overlapped sets (also known as collaborative and cooperative sensing, respectively) or distributed

To show how the QoSMOS reference model entities are mapped to the network elements, two cases have been highlighted in [D2.2]: centralised resource control with centralised collaborative / cooperative spectrum sensing, and distributed resource control with local spectrum sensing, addressing the QoSMOS scenarios “Cellular Extension in White Spaces” and “Cognitive Ad-hoc network” [D1.2].

These topologies can be further combined. As an example, the centralised resource control topologies applied to cases with and without Core Network only differ in the coordination domain while sharing most of the blocks and interfaces: this is reflected by the presence of the network coordination entity and QS1 interface for the Core Network cases. They may therefore be addressed in a unified manner highlighting the commonalities and emphasising then their differences. With this method, it is then possible to reduce the number of topologies' combinations to four options that cover all QoSMOS scenarios (short and long range, [D1.2]), as illustrated in Figure 2.

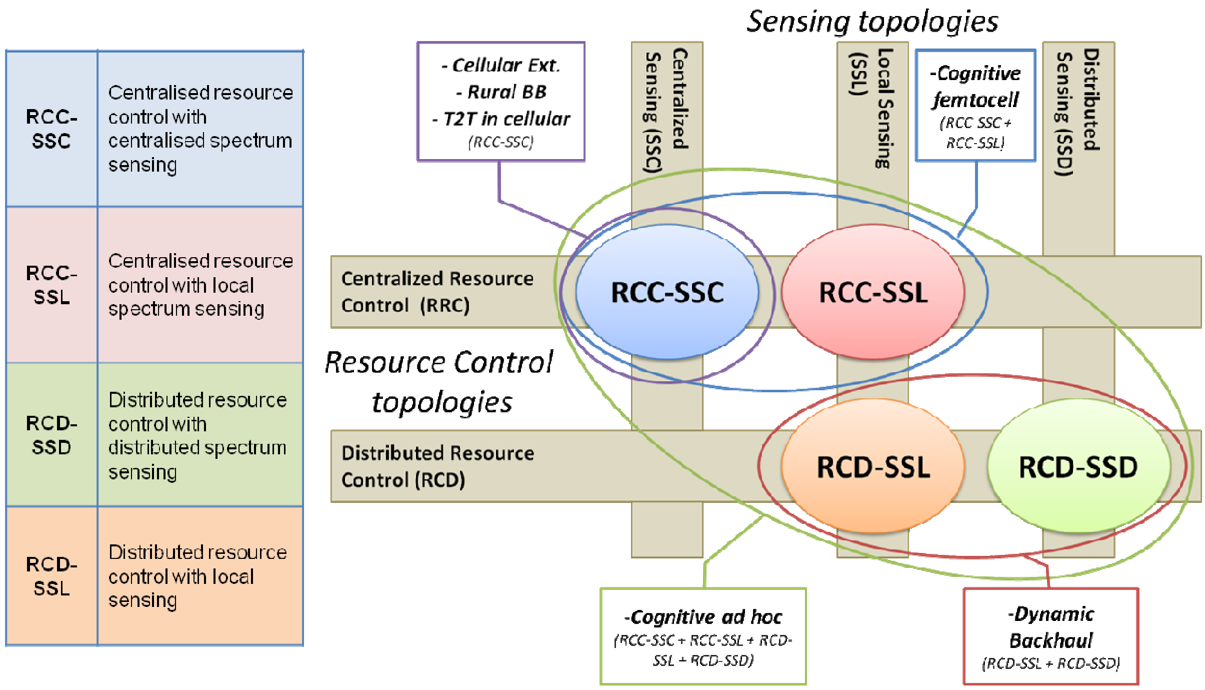


Figure 2: Relations between the topologies' combinations and the QoSMOS scenarios

3.3 Architecture options

The architecture options are based on the topologies combinations previously identified and define how functional entities are deployed within the system elements involved in each topology.

To be consistent with [D1.2], in the following sections, the Access Point (AP) shall be understood as a Base Station for the scenarios “Rural Broadband”, “Terminal to Terminal in Cellular” and “Cellular Extension in White Spaces” [D1.2]. However, for the “Cognitive Femtocell” scenario [D1.2], it encompasses the Femtocell, the broadband Access Gateway and the Femtocell Gateway.

Moreover, in the distributed resource control case, the UE-GateWay (UE-GW) has a slightly different meaning than the regular user equipment. As will be seen shortly below, while the UE-GW is as in the previous cases responsible for the access to CM-SM, the CM-RM capabilities are clearly just the same as in all the UEs. The UE-GW is elected among the candidate UEs to take that role.

Cooperative and collaborative sensing mechanisms are not differentiated as such in the subsequent sections, as they operate in the same architecture, using merely different signalling (i.e. different set of parameters).

3.3.1 Centralised resource control with centralised spectrum sensing

The radio resources in the RCC-SSC topology are centrally controlled within the AP or within the UE-GW. The mapping of the QoSMOS functional entities results in a CM-RM entity located in network elements responsible of allocating the radio resources according to the portfolios provided by the CM-SM. This CM-RM entity covers both the terminating and networking domains. In parallel, the CM-RM entity, located in the UE, exploits the allocated resources to transfer its uplink data, and covers in consequence the terminating domain only. This is illustrated in Figure 3.

Spectrum sensing is also centralized: the measurement’ results, coming from scattered sensors in the UEs or in the AP itself, are merged and analyzed in the UE-GW or in the AP (networking domain). The output is then transferred in the AP / UE-GW, to both CM-RM and co-localised CM-SM.

Data transferred between two CM-RM entities (through RM0 interface) and between two SS entities (through SS0 interface) are mapped onto the TX0 air interface. This is also the case for communications between two AL entities (through AL0 interface), which may be useful in some scenarios to facilitate the discovery of peer entities location.

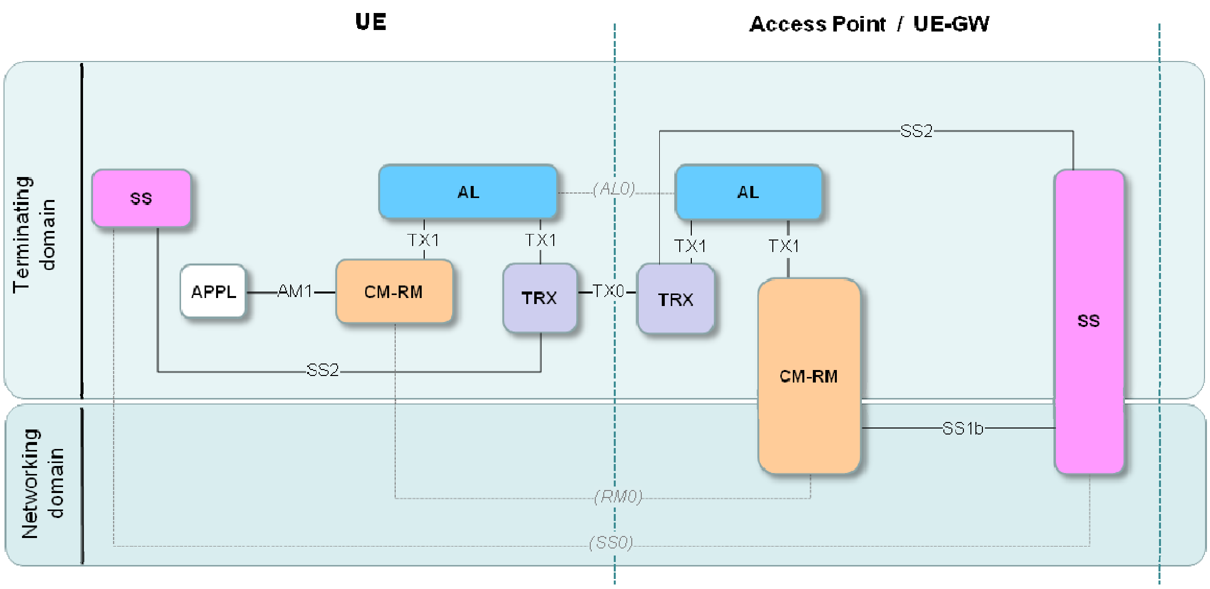


Figure 3: Architecture option for RCC-SSC topology in terminating and networking domains

3.3.1.1 RCC-SSC with core network

Systems comprising a Core Network (CN) provide users with various services, such as data path establishment, authentication and others. As shown in Figure 4 the interaction with the relevant CN elements, described as network coordination (NW COORD) entity in the reference model, is based on two interfaces: QS1a, in the coordination domain, is used to exchange data with CM-SM (like operator policies …), while QS1b, in the networking domain, is used to exchange data with CM-RM (user data, mobility information …). Both interfaces benefit from the presence of the AL, e.g. for converting information to the appropriate format and for establishing the link with the core network entities.

In addition, the CM-SM entity in the CN (within the coordination domain) builds the portfolio of available channels, based on the sensing data collected by the co-localised SS entity (through SS1a interface) and enriched with global information from the common portfolio (PF) or from the regulatory databases (REG). The access to this global information (SM1a and SM1b interface) is then achieved within the coexistence domain through the AL supports the CM-SM for localizing the databases. However, for security purpose, encrypted information is directly transmitted. The AL provides a library to convert the received data, once decrypted, to a unique format to be analysed by the CM-SM.

Remark: concerning the terminating and networking domains within UE and the AP depicted in Figure 4, the details can be found in Figure 3.

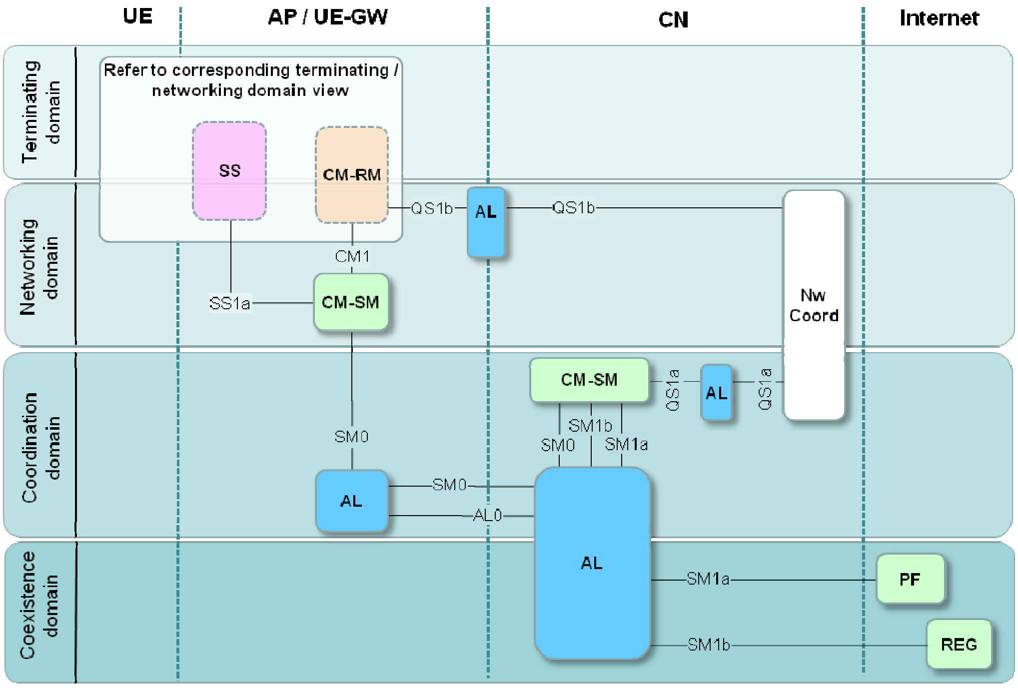


Figure 4: Architecture option for RCC-SSC topology with Core Network

3.3.1.2 RCC-SSC without Core Network

This case addresses the systems that operate without the support of a Core Network, like Wi-Fi type access points.

As shown in Figure 5 the CM-SM entity in charge of building the Spectrum Portfolio is localised in the Access Point / UE-GW, operating in both networking and coordination domain. It gathers sensing data from the co-localised SS entity (through interface SS1a) and spectrum information from the common spectrum repository and the global databases (interfaces SM1a and SM1b). For the same reason than the ones previously mentioned, the AL is employed only to support the CM-SM when localising the global databases.

Remark: concerning the terminating and networking domains within UE and the AP depicted in Figure 5, the details can be found in Figure 3.

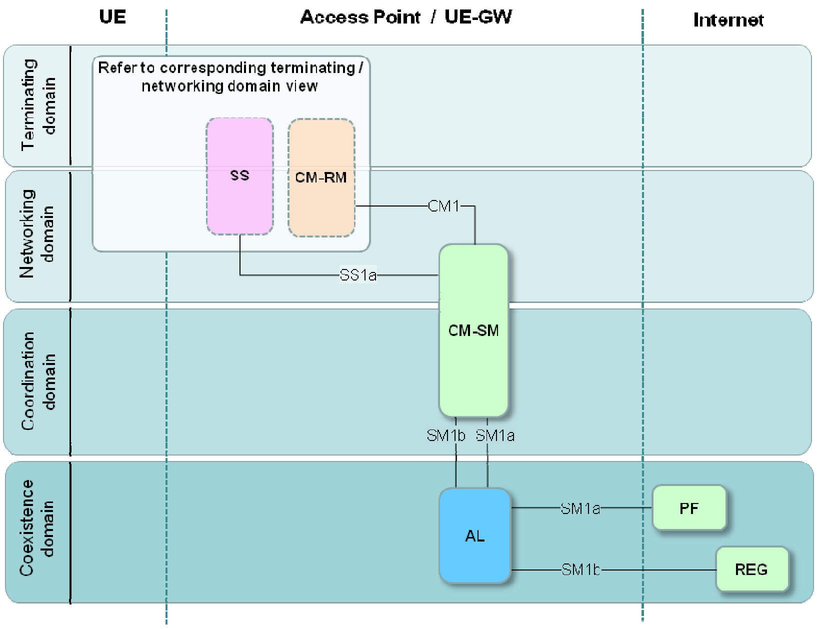


Figure 5: Architecture option for RCC-SSC topology, without Core Network

3.3.2 Centralised resource control with local spectrum sensing

In this topology, the radio resources are controlled, in a centralised way, as described in the previous section. However, the spectrum sensing measurements and decisions are done locally:

- The Access Point (and UE-GW) benefits from local sensing to optimize the utilization of the active channels, according to the radio environment.
- The UE takes advantage of local sensing to improve its reactivity to incumbent apparition by immediately stopping uplink transmission.

As depicted in Figure 6 the UE-case is considered, at this stage, for future work: its advantages in term of incumbent protection are limited, as the centralised resource control cannot be influenced by the sensing decisions done in each element.

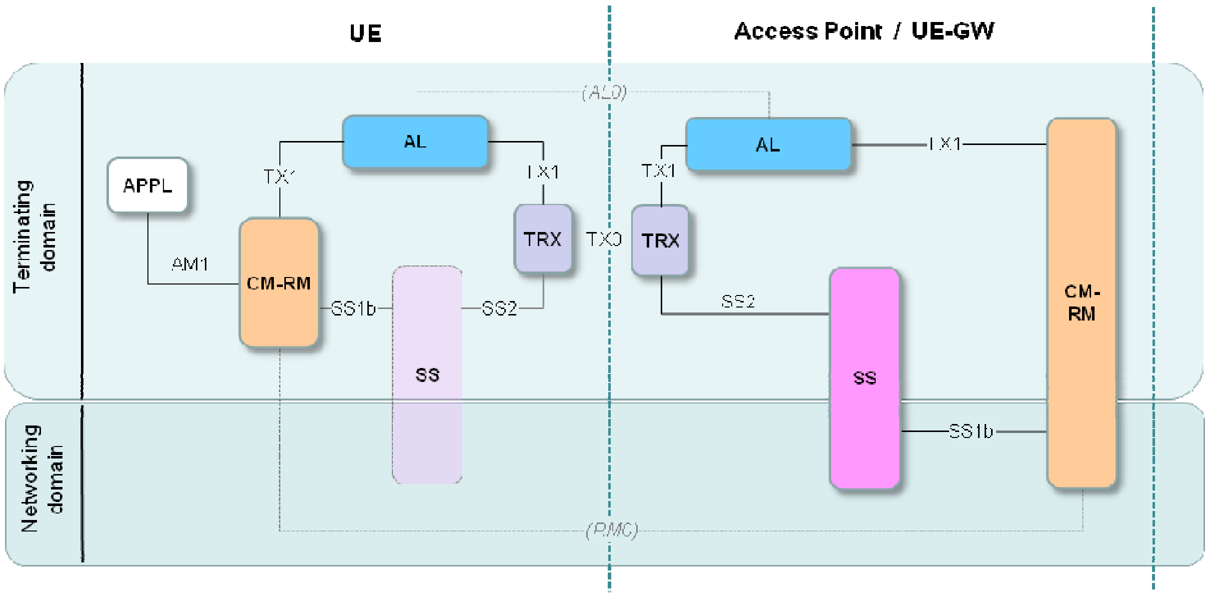


Figure 6: Architecture option for RCC-SSL topology

3.3.2.1 RCC-SSL with core network

The topological view for coordination and coexistence domains is identical to the one described for RCC-SSC case in section 3.3.1.1. However, Figure 6 has to be taken as reference for the terminating and networking domains.

3.3.2.2 RCC-SSL without core network

The topological view for coordination and coexistence domains is identical to the one described for RCC-SSC case in section 3.3.1.2. However, Figure 6 has to be taken as reference for the terminating and networking domains.

3.3.3 Distributed resource control with distributed spectrum sensing

In this topology, the resource control is distributed across the peer network elements. In consequence, the CM-RM entity located in the UE and the UE-GW is split over both the terminating and networking domain as shown in Figure 7.

Each CM-RM has to be connected to a CM-SM entity in order to receive the portfolio. However, it is not necessary that all UEs have an access to the information required to build this portfolio. But a specific UE having this capacity is referred to as UE-Gateway (UE-GW) and includes the core functionality of the CM-SM, residing in the coordination domain.

The CM-SM in the UE is in charge of supporting the CM-RM to make the resource management decisions. Since resources are controlled at the UE, also part of the CM-SM needs to be there (it is unrealistic, due to delays, to have message exchange between UE and UE-GW, together with their processing in between, at every resources allocation decision). This part of the CM-SM also has a role in the corresponding management (updates) of the Spectrum Portfolio. This is more than an “interface” and therefore this may not be done by the AL.

CM-RM entities are connected to each other through the RM0 interface. However, the routing of the information between the peer devices is done through the air interface TX0.

The access to the common portfolio (PF) and to regulatory (REG) databases is done through the AL which assists CM-SM to localise these entities. Afterwards, direct connections are established to guarantee secured data exchanges.

Spectrum sensing measurements and analysis are done in each node in cooperation/collaboration with other nodes. The SS entities cover both the terminating and the networking domains. Then, results and decisions are shared between the SS entities through the SS0 interface (which is also mapped onto the TX0 air interface).

The exchange of information between remote instances of the same entity may be facilitated by the AL capacity (through interface AL0) to know their location in the different deployed network nodes.

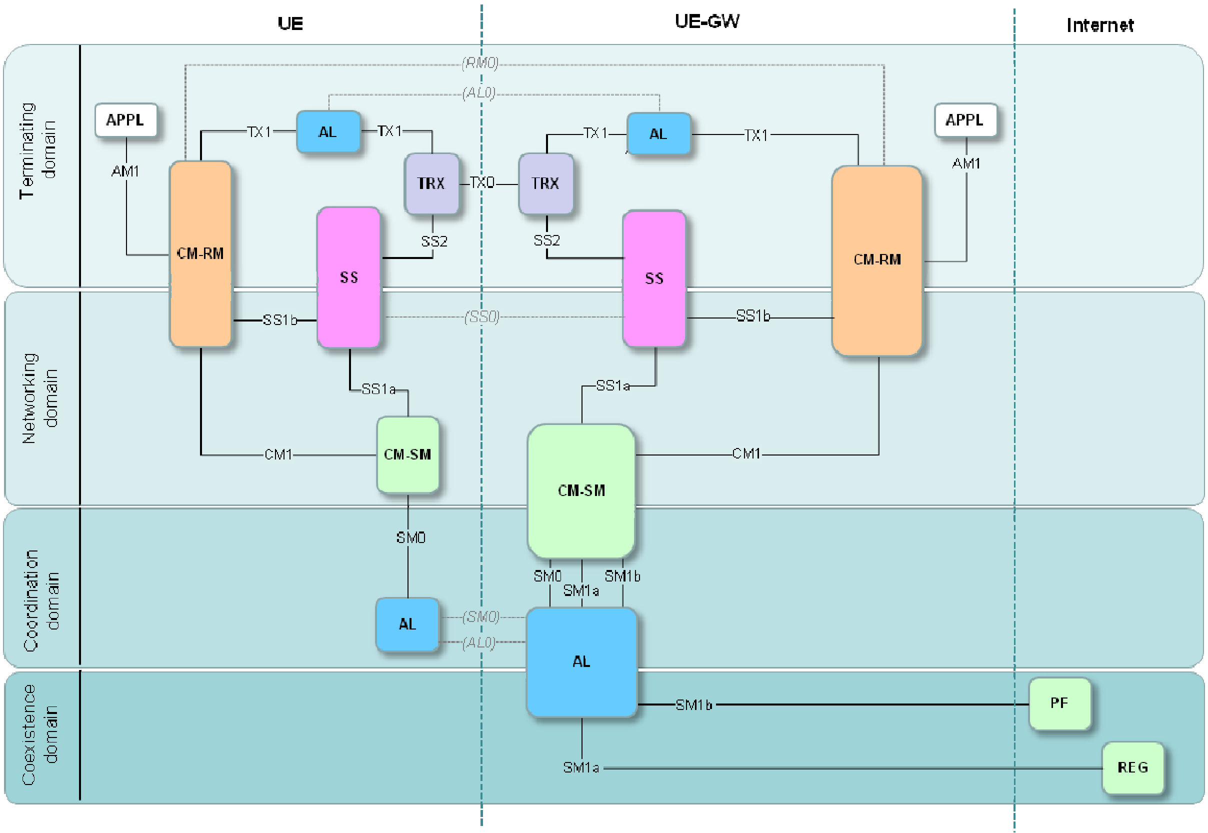


Figure 7: Distributed resource control with distributed spectrum sensing

3.3.4 Distributed resource control with local spectrum sensing

This case is identical to the one defined for RCD-SSD (section 3.3.3) with the exception that spectrum sensing measurements and analysis are done locally and used essentially for the resource allocation without sharing of the sensing decisions between the nodes: no information is exchanged between remote SS entities, and as a consequence, SS0 interface is not supported in this architecture option.

3.4 Rationalization of topologies and architecture options

The previous sections have highlighted that the architecture options, when mapped to the different topologies, share a number of characteristics that, once specified, may be commonly applied to several scenarios. There is then an opportunity to rationalize the architecture work in the project by focusing on a reduced number of architecture options that should produce all the elements necessary to cover the possibilities considered in QoSMOS.

In addition, some regulatory bodies have doubts on sensing techniques, as reported by CEPT in [ECC159]:

> *"Sensing technique, employed by stand-alone equipments, appears not to be reliable enough to guarantee a correct identification of available channels at a given location and to avoid interference into incumbents".*

However, even if cooperative / collaborative sensing techniques completed with the use of a geo-location database are one solution to address this concern, local sensing option shall not be rejected as it covers particular cases:

- In a Wi-Fi-like system, UEs are not always available as sensing nodes (or event not present).
- A better equipped or positioned UE-GW has more capabilities to produce reliable results alone, instead of combining its good-quality measurement with possibly poor measurements of visiting UEs.
- For cases, such as the "Dynamic Backhaul" scenario, in which devices are possibly very distant to each other, combining sensing data are not meaningful, although collecting may help.

Moreover, when referring to sections 3.3.1 and 3.3.2 for describing RCC-SSC and RCC-SSL topologies, the mapped architectures share the same elements for coordination and cooperation domains. In fact, differences are only in the networking domain and more precisely on how the sensing measurements are computed, analysed and transferred to other network elements:

- RCC-SSL performs local sensing measurements and analyses the results in the same network element.
- RCC-SSC executes the sensing measurements in several network elements (cooperative / collaborative sensing) which send the results to a central node for performing the analysis and decisions.

Nevertheless, the RCC-SSC option may consider as well sensing measurements in this central node. In consequence, the management of the local sensing measurements (from an architecture point of view), which is the specificity of RCC-SSL, is also covered by the RCC-SSC option.

Additionally, the RCD-SSD and RCD-SSL cases are quite similar. The analysis is performed in both cases at any UE, but the difference is on the measurements used for the analysis: all the available measurements are used for RCD-SSD, while only local measurements are taken in account in RCD-SSL. From an architecture point of view, this affects only the presence of the SS0 interface, which aims at exchanging sensing information between several SS entities. Consequently, by focusing on the RCD-SSD case, it is possible to define the elements required by the RCD-SSL case.

As a result, further architecture work in QoSMOS should focus on the following cases:

- Centralised resource control with centralised spectrum sensing - RCC-SSC;
- Distributed resource control with distributed spectrum sensing - RCC-SSD.

3.5 Architecture aspects for the Integrated Proof of Concept

As described in the previous section, a rationalisation process has been carried out guaranteeing that all architectures elements, that are required to address the different QoSMOS scenarios [D1.2] and so the Proof of Concepts' needs, are defined in the detailed system specification. In return, the project aims at confirming that the demonstrated functionalities are compliant with the system specification (e.g. this could be done by monitoring the exchange of messages) and participates to the performance assessment of the QoSMOS solutions, based on the performance matrix described in chapter 5.

The Proofs of Concepts implemented in the QoSMOS project include:

- The "Primary Scene and Sensing Engine" Proof of Concept (PoC #1) which aims at showcasing the modelled radio environment;
- The "Flexible Transceiver" Proof of Concept (PoC #2) to test the quality of the transceiver in comparison to simulation results;
- The "Distributed / Collaborative" Proof of Concept (PoC #3) to demonstrate algorithms relative to collaborative/distributed sensing mechanisms;

- The Integrated Proof of Concept (PoC #4) to bring together the components from all other PoCs in order to showcase a live cognitive radio system.

These PoCs will be addressed specifically in the next deliverables issued by the project. The later PoC#4 is system-level oriented and therefore described with some more detail in the following. PoC#4 aims at demonstrating the capacity of the system to detect an incumbent user, to react to its presence by either switching the operating channel to a backup channel or by forcing a handover to a non-interfering system.

The equipments that will be considered are a Femtocell, operating in both 3G and White Space bands, and capable of communicating with remote sensors. User devices are able to detect incumbent apparition and a common database provides information about the available spectrum bands.

The architecture option that addresses this specific use case is the RCC-SSC (Centralised resource control with centralised spectrum sensing) and the derived topological view is depicted in Figure 8, where the following aspects should be noted:

- Both the UE and the Femtocell implement two transceivers: the first one to operate in White Space bands and a second one to support the 3G band. It is not yet stated if the CM-RM is able to support both technologies with the same internal blocks or with different instances. In consequence, the presence of the AL in the TX1 interface is under consideration and will be further studied;
- Sensing measurements are performed in the deployed UEs and then sent to the Femtocell for analysis. Resulted decisions are then transferred to the CM-RM (through interface SS1b) which adapts its radio resources allocation based on this received context information;
- Radio resources are also provisioned based on the portfolio information provided by the CM-SM, which build this structure according to the information extracted from the Common Portfolio Database whose access is facilitated thanks to the AL.

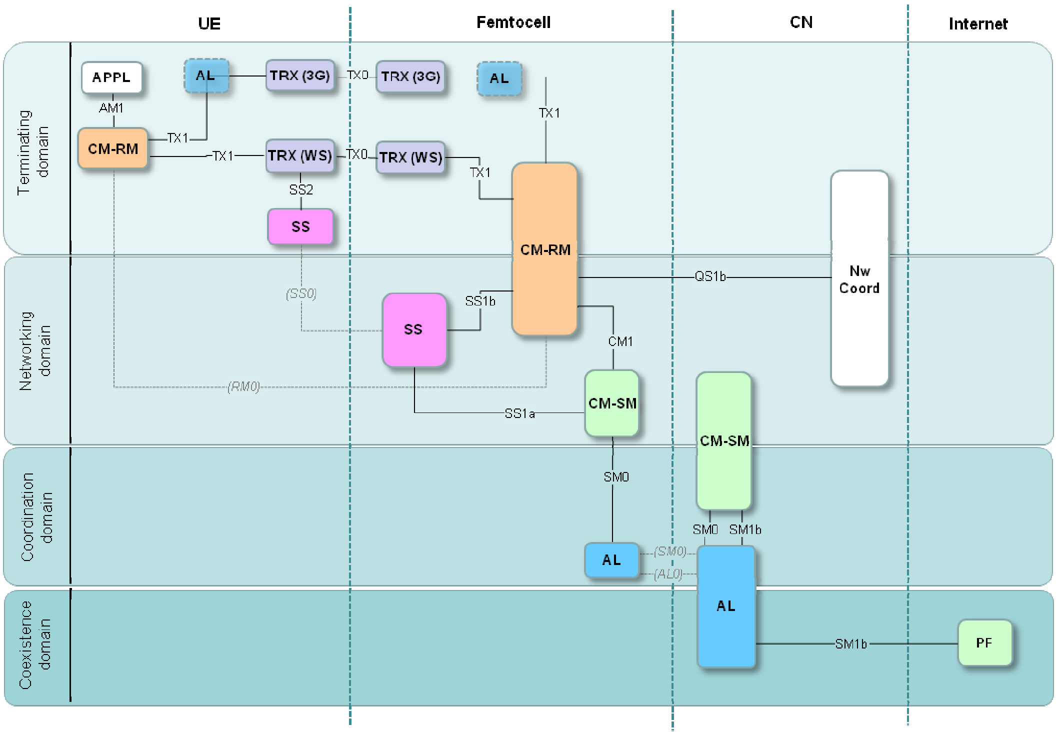


Figure 8: Topological view for PoC#4

4 Overall QoSMOS system specification

4.1 Introduction

In the previous chapter the overall QoSMOS reference model has been presented together with its functional blocks and interfaces in topologies' combinations mapped to architecture options for the different scenarios considered. This chapter addresses in a more specific way the QoSMOS building blocks themselves with their functionalities and characteristics as well as their interactions. The work already done in the project on the internal architecture and functionalities of the two-fold Cognitive Manager (CM) is briefly recalled and referenced but the interaction between its components is described in detail in the following. Similar approach is followed for the Transceiver where the functional background is recalled whereby the definition work for the characteristics of transmitter and receiver is reported in detail. Concerning the Adaptation Layer (AL) the complete functionalities and internal architecture are specified in this chapter.

4.2 Cognitive Manager (CM) for Spectrum and Resource Management

Ensuring incumbent user protection together with providing a level of quality of service to opportunistic users is a challenging task. The multiplicity of the aspects to be addressed and their different nature and peculiarities, as discussed in [WPMC2011], call for the adopted two-fold cognitive manager (CM) for Spectrum and Resource Management. The interaction between the two cognitive managers has been outlined in [D2.2] and is expanded and a thorough analysis is provided in the following sections.

4.2.1 Cognitive Manager for Spectrum Management (CM-SM)

The detailed architecture of the CM-SM has been presented in [D2.2] section 3.2 including topological and logical models with examples for the mapping of its internal blocks to the TV White Spaces case. Further detailed description of the spectrum management framework was given in [D6.2] addressing context filtering, aggregation and communication functions.

4.2.2 Cognitive Manager for Resource Management (CM-RM)

In [FuNeMS2011] the concept for the CM-RM and the requirements derived from the challenges posed has been described. It comprises specifically the detailed architecture of this QoSMOS functional block together with its internal and external interfaces as well as examples for mapping this architecture to the centralized Resource Control case including Incumbent Protection.

4.2.3 Interaction between CM-RM and CM-SM

In [D6.3] the interaction between CM-RM and CM-SM is discussed on an abstract level (i.e. from the perspective of an interaction between cognitive cycles realized by distinct decision engines). It has been shown that the distinctiveness of reasoning and decision-making processes between CM-RM and CM-SM (or multiple instances thereof) depends on how these are observing and acting upon the same environment: interaction between CM-RM and CM-SM may take place by both the exchange of context information through the environment and through protocol-based communication simultaneously, even if no further control information is exchanged between instances of the CM-RM and CM-SM. Thus special care has to be taken on which part of the environment is controlled by which entity, and how side effects of acting upon parameters of this environment may potentially introduce an unwanted impact on other parameters considered for decision-making by a coexisting or collaborating entity.

4.2.3.1 Interaction between generic cognitive engines

Figure 9 depicts the implicit interaction between cognitive engines through the environment assuming that only context information is exchanged between cognitive engines, and that both cognitive engines observe an environment that at least is partly shared and can be described as having countable infinite observable states (e.g. in form of a Markov net). The impact of actions on the environment taken by one of the cognitive engines may or may not be observable by the other cognitive engine and vice-versa.

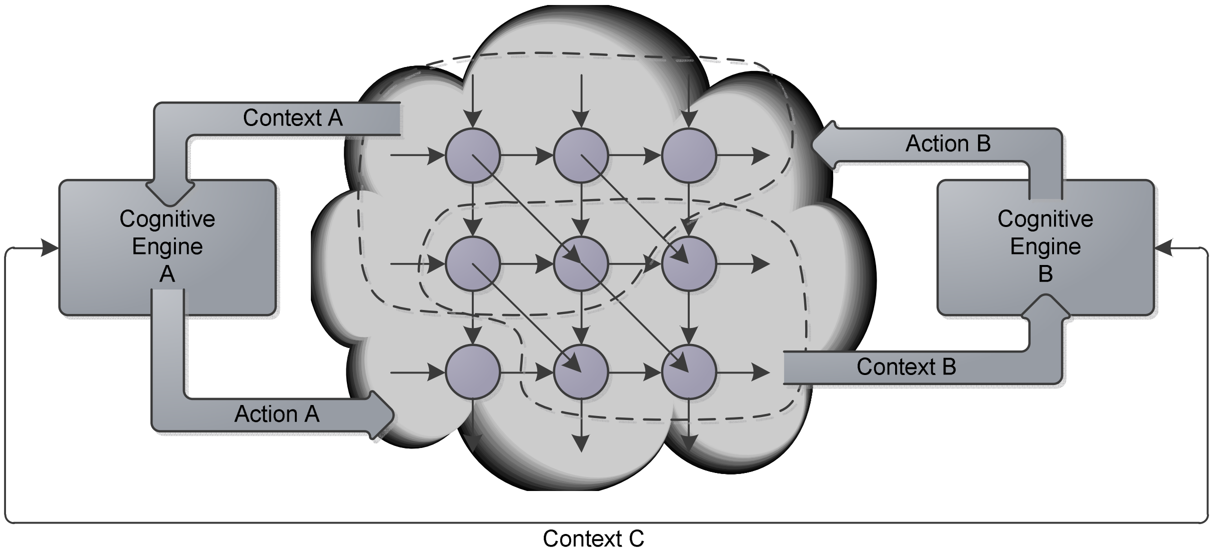


Figure 9: Interaction model for generic cognitive engines

The interaction of cognitive engines through an observed environment can be shown by a simple argumentation: An action is generated from a set of facts by prior reasoning, deciding and applying actions derived from the decision to the environment. For convenience, we here only consider the facts that lead to a decision as a representative of the action to generate. Decision-making and generation of actions from facts is elaborated more deeply upon in [D6.3] and will be addressed in future deliverables.

In the following set and inference notation will be used to describe more formally, and without going too much into details, the interaction of cognitive engines through the shared environment. More details on the notation used may be found in [Devlin1993] and [Andrews2002].

Given that, Action A (A_A) follows from Context A (C_A) and Action B (A_B) follows from Context B (C_B), and including the context exchanged by protocol-based communication (C_C), it follows that:

$$A_A \leftarrow \{\mathrm{F}_{\mathrm{C},AC}(x) : \forall x \in \mathrm{P}(C_A \cup C_C)\}$$

and

$$A_B \leftarrow \{\mathrm{F}_{\mathrm{C},BC}(x) : \forall x \in \mathrm{P}(C_B \cup C_C)\}.$$

That is, the facts A_A, A_B that lead to an appropriate action are derived from a filtered set of context parameters $\mathrm{F}_{\mathrm{C}}(X)$ that is drawn from all possible combinations of observed context parameters, expressed by the power set of the context parameters observed $\mathrm{P}(C_A \cup C_C)$, $\mathrm{P}(C_B \cup C_C)$. Since we cannot assume arbitrary context parameters being orthogonal, the use of power sets here ensures that all possible combinations are considered by the filtering functions.

When imposing actions onto the environment, it follows that there is an impact on the context observed as well as on unobservable context C^U with

$$C = C^U \cup C_A \cup C_B \cup C_C$$

and

$$C' \leftarrow A_A \cup A_B.$$

Herein C' denotes the environments' context after applying the actions decided from A_A, A_B. Hence, the context observed by cognitive engine A is determined by earlier decisions of both engine A and engine B

$$C'_A \leftarrow \left\{ \mathrm{F}_{\mathrm{C},AC}(x) : \forall x \in \mathrm{P}(C_A \cup C_C) \right\} \cup \left\{ \mathrm{F}_{\mathrm{C},BC}(x) : \forall x \in \mathrm{P}(C_B \cup C_C) \right\}.$$

The same holds for context observed by cognitive engine B C'_B, for the 'communicated context C'_C and for unobservable context C'^U. Note, that in practice the 'communicated context' C_C consists of context parameters from both the environment and from outside the environment. The latter is neglected here for clarity, assuming that the parameters from inside and outside the environment are clearly orthogonal (if not, they would be part of the environment by definition).

4.2.3.2 Interaction between QoSMOS cognitive managers

The interaction of CM-RM and CM-SM in a QoSMOS scenario follows the general principles as discussed above. The main difference is in the cascaded organization of cognitive engines and that actions of the CM-SM are not applied directly to the environment but are delegated to a CM-RM entity as shown in Figure 10. It is assumed that having only one entity that directly imposes actions on the environment, a more efficient control of side effects can be achieved, compared to a solution where multiple entities act upon the same environment. Hence, decisions of the CM-SM are based on both directly observed context C_{SM} and 'communicated context'. The latter includes observed context of the CM-RM that has been processed by the CM-RM. Actions of the CM-SM onto the environment thus are described by:

$$A_{SM} \leftarrow \left\{ \mathrm{F}_{\mathrm{SM}}(y) : \forall y \in \mathrm{P}\left(\left\{ \mathrm{F}_{\mathrm{RM}}(x) : \forall x \in \mathrm{P}(C_{RM} \cup C_C) \right\} \cup C_{SM} \cup C_C \right) \right\}.$$

The most common action of the CM-SM will be the deployment of a spectrum portfolio towards the CM-RM.

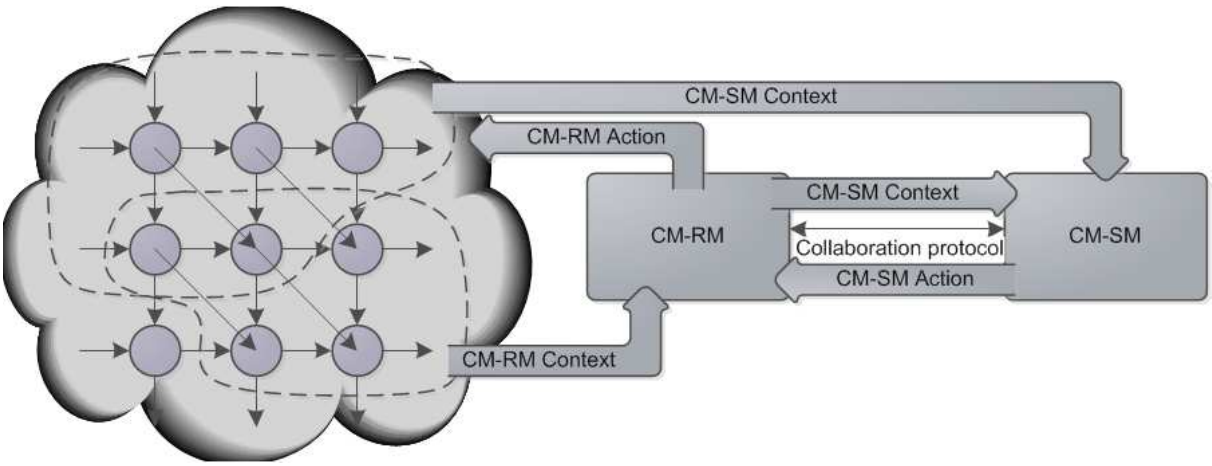


Figure 10: Interaction model for QoSMOS cognitive managers

4.2.3.3 Spectrum Portfolios

In the scope of context communication, Spectrum Portfolios are considered data structures carrying any relevant information related to a number of frequency bands in a single extensible format, including characteristics of the frequency bands considered, their usage parameters, as well as measurements obtained from observing these frequency bands. Spectrum Portfolios are utilized for both context communications between CM-RM and CM-SM as well as for implementing actions of the CM-SM. A Spectrum Portfolio deployed by the CM-SM towards the CM-RM is implemented by the CM-SM in its actions on the environment; subsequently it becomes context of the CM-RM, even if not implemented. Vice-versa, the CM-RM returns context information to the CM-SM in form of Spectrum Portfolios (see next section for a description of the Quality parameter in a Spectrum Portfolio used in exchanging context), which in turn are implemented by subsequent actions of the CM-SM. Hence, the discussion given above can be applied also to the specific QoSMOS model of interaction between cognitive managers.

4.2.3.3.1 With geo-location databases

Special consideration has to be given to the integration of geo-location databases into the interaction model.

- If a geo-location database is deploying Spectrum Portfolios towards a CM-SM without considering the state of the CM-SM it is simply providing context for the CM-SM that is not part of the environments' context.
- If a geo-location database collaborates with a CM-SM, it is accepting context information from a CM-SM, which is derived from context of the CM-RM, and is returning context that depends on the context received. It thus becomes part of the observed environment.

The latter is a major reason why regulatory information – in particular dynamic information – such as policies or usage rights context in general should be deployed to the CM-SM. Interaction between independent CM-SM, CM-RM and geo-location database instances may become rather complex to handle, and the impact of actions might become difficult to control especially in their impact on unobservable context.

4.2.3.3.2 Spectrum Portfolio data structure

A Spectrum Portfolio, which here is formulated as a structured data set describing arbitrary frequency bands and related information is used to represent the communicated context. The Spectrum Portfolio thus is a declarative data structure summarizing all relevant information on contiguous or non-contiguous chunks of frequency spectrum. It both describes persistent as well as volatile information:

- Persistent information includes attributes, ownership, credentials, lawful usage limitations and similar. Only the authority – usually a regulatory authority – that originally issued the Spectrum Portfolio changes persistent information.
- Volatile information includes temporary usage rights, temporary usage limitations, usage rules, information relevant for usage optimization, measurement or observation results regarding spectrum users and similar. The temporary holder of the usage rights or a designee may alter volatile information.

A Spectrum Portfolio is initially created and initialized by the owner of the spectrum it describes. Both permanent and temporary ownership are considered and may be qualified further, that is, may be bound to a certain geographical area, time interval, or communication standard to become applicable. In order to avoid ambiguous ownership or malicious use, a Spectrum Portfolio carries credentials that protects against alteration of a spectrum portfolio or parts thereof. Furthermore to allow for non-repudiation, the issuer of a Spectrum Portfolio (i.e. the spectrum owner or the owner of temporary usage rights) may ask for acknowledging handover of a Spectrum Portfolio. If an operator after reception of a Spectrum Portfolio from the owner of the spectrum wants to deploy this towards a spectrum user (e.g. one of its clients), he may be asked to confirm this handover of spectrum towards the issuer (or owner) of the spectrum. Credentials attached to the Spectrum Portfolio can be used in the course of this exchange process to track (unmodified) Spectrum Portfolios in an acknowledged deployment process and to identify potential malicious use of spectrum.

Details of the Spectrum Portfolio data set are not yet finalized. They will be described further in the next project deliverables. The description given in Table 2 is for informative purposes and details by intention only the uppermost level of data elements.

Table 2: Top level data elements in a Spectrum Portfolio data set

Descriptor	Conditional	Multiplicity	Short Description
Owner	Mandatory	Singleton	Specifies ownership of the Spectrum Portfolio. The owner is identified by its organisation identity (e.g. its name and reference, address etc.). The owner usually is a regulatory authority.
Certificate	Mandatory	Singleton	Credential used to verify origin and correctness of owner, usage rights, user (if present), location (if present), and all policies given. The certificate may include quality and one or more spectrum blocks if the owner of the Spectrum Portfolio mandates this.
User	Optional	Singleton	If present, limits the use of this Spectrum Portfolio to a given user. If omitted each spectrum block needs to define a user on its own.
Location	Optional	Singleton	If present, this set restricts applicability of the Spectrum Portfolio to a well-defined geographical area.
Policy	Mandatory	Multiple	Defines global policies for the Spectrum Portfolio.
UsageRights	Mandatory	Singleton	Defines global usage rights for all users.
Quality	Optional	Singleton	Optionally includes information on the measured quality of spectrum described by the Portfolio and defines parameters and metrics how the measured quality must be determined.
SpectrumBlock	Optional	Multiple	Describes the spectrum portfolio in terms of frequency bands included.
Note — Some of these descriptors may be used also inside other descriptors. In this case, lower level descriptors may inherit from higher-level descriptors, but lower level descriptors must not weaken, extend or relax higher-level descriptors beyond the limits set by higher-level descriptors.			

An example illustrating the top-level layout of a Spectrum Portfolio data set can be found in the Appendix.

4.3 Adaptation Layer

4.3.1 Introduction

The QoSMOS reference model has been described in chapter 3 by means of a set of functional building blocks with clearly defined behaviour when mapped to the scenarios considered in QoSMOS. In order to address the scenarios involving heterogeneous Radio Access Technologies (RATs), such as “Cognitive Femtocell” or “Cellular Extension in White Spaces”, a seamless and RAT-agnostic communication between some of the different functional blocks is needed. This mainly applies to the communication between functional blocks in multi-RAT configurations and to establish the means to facilitate the necessary data exchange between different network elements.

The heterogeneity of the different communication technologies presented in the system poses a challenge related to the data management and representation that can be addressed by an Adaptation Layer (AL). QoSMOS defines such an AL as introduced in [D2.2] and this chapter describes the concept as well as the use of this layer. The AL offers the necessary Service Access Points (SAPs) and data management to the different functional blocks presented in the QoSMOS reference model. Its main scope is to enable the exchange of information and commands between the different entities involved in the opportunistic spectrum management process.

Regarding these aforementioned entities, and focusing on the spectrum availability and management tasks, this concerns the common Portfolio Repository (PF) and the Global Regulatory Databases

(REG) in which several amounts of information received from different operators and various countries will be stored. The management of the data requires a level of abstraction that shall be supported by these functional blocks. The AL enables the collection of information from different RATs through medium specific interfaces and provides a single media independent interface similar to the one exhibited in [IEEE802.21] to the cognitive management entities CM-RM and CM-SM. In addition, it is necessary to convert and analyse measurements and parameters which can be interpreted differently depending on the RAT which is being used, e.g. load levels in access points, SNR limits, etc. The use of this AL eases the management of data fusion for sensing measurement and cooperative sensing in general.

The AL, regardless of whether it is located in the UE or in other network elements, receives and sends information related to spectrum portfolio, spectrum communication usage and configuration of access networks, but also other extra operations can be performed. In summary, the main principles that rule the AL behaviour are the following:

- Abstraction Level. The AL enables transparent communication among the different blocks present in the architecture helping to avoid duplicity of paths dispatching primitives to their final destination.
- Enable information management regardless of the underlying RAT, thus offering the capacity to analyse and convert measurements and parameters depending on the RATs below, accommodating the received data to one given Common Data Model.
- Support event-subscription functionalities for different elements in the architecture, informing them about the changes occurred in the functional blocks they are interacting with.

Based on the QoSMOS Reference Model described in Figure 1, the communication between the AL functional block and all the other components of the architecture is done through a group of defined interfaces, thus providing to the system the technology abstraction required. Figure 11 shows the different interfaces used by the AL for communicating with other blocks in QoSMOS system.

N.B.: The AL interfaces shown in Figure 11 enclose the detailed interfaces described in Figure 1.

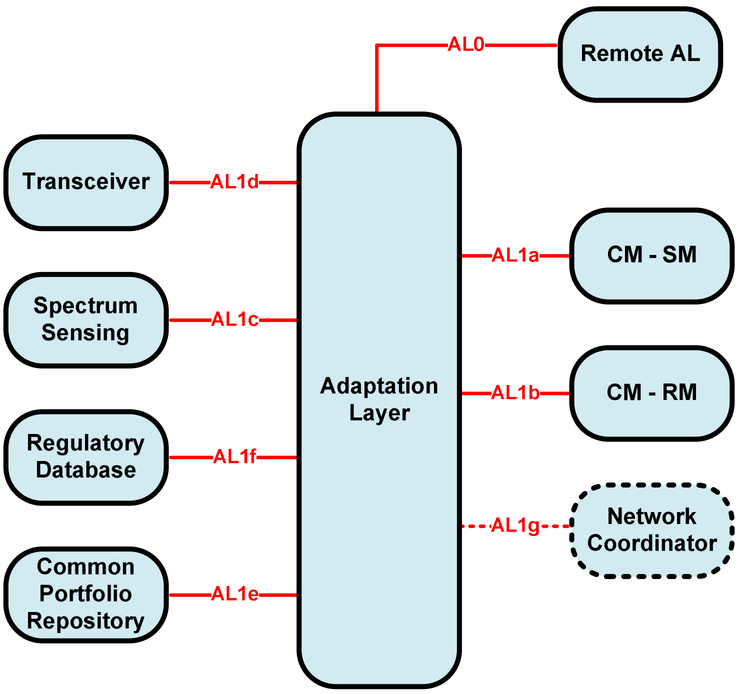


Figure 11: Adaptation Layer in the QoSMOS Reference Model

Another important topic to be studied concerns the different data flows circulating through the AL. A special interface has been defined in order to facilitate communications between entities at remote level. Thus it will be possible to obtain remote sensing measurements for building up or updating the Spectrum Portfolio, as well as remote QoS information and availability from neighbouring networks, getting remote configuration and resource allocation commands, performance and usage reports and spectrum sensing measurements at communication time, etc. The interfaces used by the AL are the ones presented in the Table 3 below:

Table 3: Interfaces between AL and functional blocks

Interface name	Connected blocks
AL1a	CM-SM
AL1b	CM-RM
AL1c	Spectrum Sensing
AL1d	Transceiver
AL1e	Common Portfolio Repository
AL1f	Global & Local Regulations
AL1g	Network Coordinator
AL0	Remote AL

The following sections detail the functionalities associated with the AL concept. In addition, some figures have been included in order to clarify the AL role within the exchange of information in QoSMOS scenarios.

4.3.2 Adaptation Layer Concepts

One of the main questions regarding the Adaptation Layer lies in how it should be deployed and how it is going to enhance overall performance in QoSMOS system. Moreover, it is of large interest to know which kind of data have to be transferred through the AL. This section answers to these questions.

It is assumed that the mobile terminals involved in communications are capable of supporting one or many link layer technologies. Furthermore, it is also assumed that the AL will be located at the different network entities. This way, the proposed architecture is pertinent for the multi-operators case, providing a unified access to the deployed common repositories, and also for the worldwide deployment case, giving means to obtain a unified access to the regulatory databases. In addition, this measure could be relevant for centralized decision making in case the information is not embedded within messages specified by the active RAT.

What is more, given the intention to make the QoSMOS system flexible, the AL may be used to interface with entities external to the system, such as a Network Coordination, in a similar way to the procedure used by the AL to contact the repositories.

4.3.3 Adaptation Layer Functionalities

Based on the three main concepts that guide the behaviour of the AL, there are four key functions performed by the AL. These functionalities are closely related to the concepts and principles already presented. The following subsections will provide a deeper insight on them.

4.3.3.1 Data conversion

The first concept presented has been that the AL will act as an abstraction layer between QoSMOS components. In order to allow this feature, the AL communicates always in the same way with the different blocks, regardless of the final destination of the different packets. The AL employs a general message format to transfer the information among the different entities connected to the AL.

In this process the data will be neither analyzed nor read, assuring privacy and integrity. All information needed by the AL for managing the packets will be inserted into the different dedicated headers created for performing AL tasks.

4.3.3.2 RAT selection

Associated to the RAT agnostic characteristics already presented, the AL must deal with different RAN technologies. The AL will be capable of contacting the selected RAT taking into consideration the routing table in the node. Based on the information obtained from other blocks in charge of monitoring the status of the diverse links, it is possible to include in the AL some procedures capable of triggering events. This feature is useful for the handover process and the selection of the RAT interface, aiming at performing seamless handover keeping the experience of users unaltered. This feature is closely related to message dispatching, depending on the output interface, the different schedulers present in the AL will act sending the messages avoiding lost messages in the interfaces' queues.

4.3.3.3 Event subscription

The AL will be an entity that keeps updated the services available to all the blocks connected to it. The different events happening in the QoSMOS network, such as appearance or disappearance of new modules, new information available, new measures, etc.., should be provided or informed to the diverse blocks associated to the AL. Thus they can access it, request new sources of data or find other possibilities to get information, not only due to the fact that their prior source will be no longer available but also as a way to disseminate every kind of valid and interesting data.

4.3.3.4 Message dispatching

Due to its position in the architecture, the AL plays an important role in facilitating communications between the various entities that appear in the QoSMOS system.

The AL will be capable of selecting the information sent to each block connected to it. As this entity will be aware of the requested/provided information of each block, it is possible to decide whether to send a particular message to a node or not. Taking advantage of this capability, it is possible to reduce the overall load of the whole network, as the AL provides the capacity of implementing different algorithms.

This feature also applies at the selection of the output interface of data packets, as the AL will be able to send messages through the most appropriate interface, thus performing the RAT agnostic capacity stated as a principle of the AL behaviour

Finally, it is important to note that the AL offers the capability of prioritizing messages, which can be understood as a characteristic included into this dispatching tasks. This way, the AL will be able to evaluate and discriminate the messages is receiving and decide which of them should be delivered with a higher priority. The definition of priorities it is not a decision of the AL, so this capability will be supported by the other blocks in QoSMOS system.

4.3.4 Adaptation Layer internal architecture

The Adaptation Layer block comprises a set of components responsible for carrying out the different functions of the entity. They all will be presented throughout this section.

4.3.4.1 General Description

As previously explained, the Adaptation Layer has four main functionalities. In order to properly carry out these tasks, the AL includes two distinct components in its structure (shown in Figure 12). The first one is in charge of interfacing the blocks that will use AL capabilities, while the second one aims at performing all the intelligence of the AL. The first is called AL_END whereas the second one has been named as AL_CORE. The following subsections contain an explanation of the content and features of both of them.

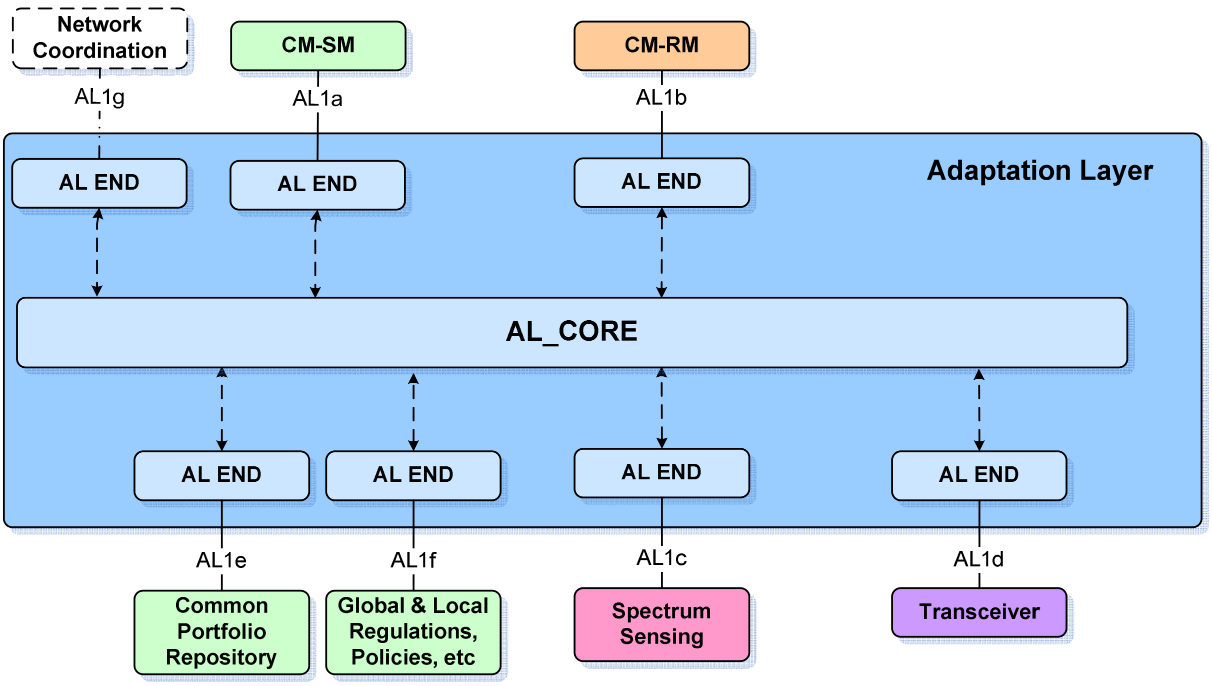


Figure 12: Adaptation Layer Architecture

4.3.4.2 AL internal blocks

4.3.4.2.1 AL_END

As shown in Figure 13, the internal composition of the AL_END is really simple. The entities consist of just the needed interfaces to communicate with the blocks they are connected to. In order to perform all the duties imposed to this intermediate block, it has been designed in the simplest manner possible. It contains two functional entities; the first one, *Translation to QoSMOS Entities*, is in charge of getting the information received from the different elements connected to the AL, and extracts the needed information regardless the interface used for receiving it. Once this first step has been performed, the second, *Mapping to AL Messages*, is made. The activities done consist of integrating the information extracted in the previous step into the internal AL messages that will be needed for its operations. The other way around, the messages are processed by the *Mapping to AL Messages* block and with the meaningful information the *Translation to QoSMOS entities* block creates the final message delivered to the destination. The main features of the AL are performed by the AL_CORE module; by the way, the AL_END has a key role in different aspects.

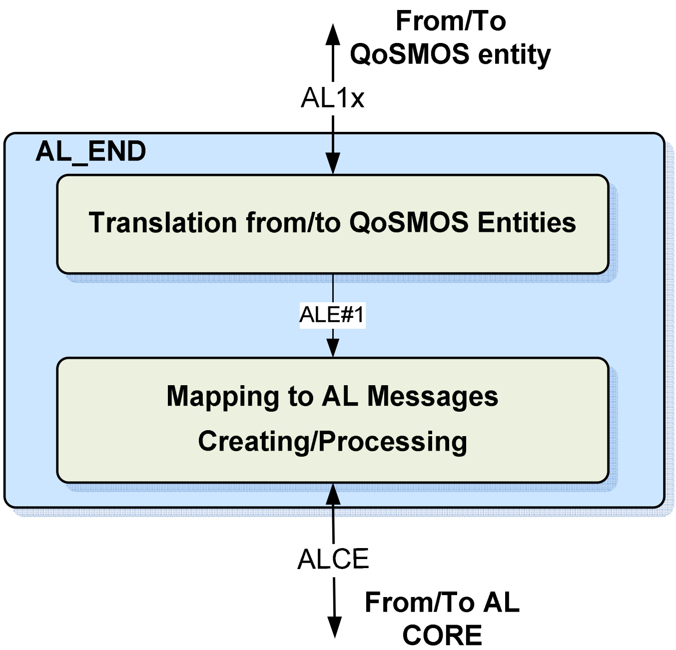


Figure 13: AL_END Components

The following bullets present the contribution to the overall architecture of these modules.

- Register and De-Register the entity on the AL_CORE. As contact point of QoSMOS entities, AL_ENDs are in charge of initiating the registration process of each QoSMOS block intending to use the AL features. It is also in charge of deregistering them, once they are going to be disconnected.
- Convert the data received from different QoSMOS entities to a general data format to be able to transmit to the destination entity through the AL. This data conversion is done between the source entity and the associated AL_END. Then, a second data conversion shall be performed at the destination AL_END to send the original data to the destination entity. This dual data conversion is necessary since the AL *source* END converts the information from the format used by the source entity into an AL-internal format and the AL *destination* END converts this into the format usable by the destination entity. This data conversion does not imply the processing of the data sent, it just suppose the accommodation of the packet to be sent to the transmission particularities of the AL.
- Convert the measurements and parameters depending on the RATs below.
- Capability to accommodate the received data to one given common data model, if necessary.
- The AL_END will be also responsible of forwarding data requests from QoSMOS entities to the AL_CORE in order to allow those entities to work properly within the QoSMOS framework.

Based on the presented functionalities, the AL_END could be seen as an interface between QoSMOS entities and the main functionalities of the AL.

4.3.4.2.2 AL_CORE

The AL_CORE is the module in charge of performing the most critical activities in the AL. It is composed of some different blocks with clear functionalities assigned to each one of them. Figure 14 depicts the internal architecture of the AL _CORE and the interfaces linking it to the AL_END. All the internal blocks will be further detailed.

The AL_CORE duties will be the following:

- Block registration: The AL_CORE will store in its database the information regarding all the nodes directly or remotely connected to the AL, thus being capable of updating the information provided to them based on their interests.
- Event subscription: Related to the previous feature, the QoSMOS entities connected will inform the AL about the data they are proving or requesting to/from other entities connected to the AL, so the AL can update their status based on the information collected.
- Message dispatching: The AL_CORE selects which packet will be sent to which node anytime. The scheduling could be programmable, enabling prioritization of messages based on configurable policies to be provided by other entities in the architecture The decisions made are supported by these policies and the information stored in the database.

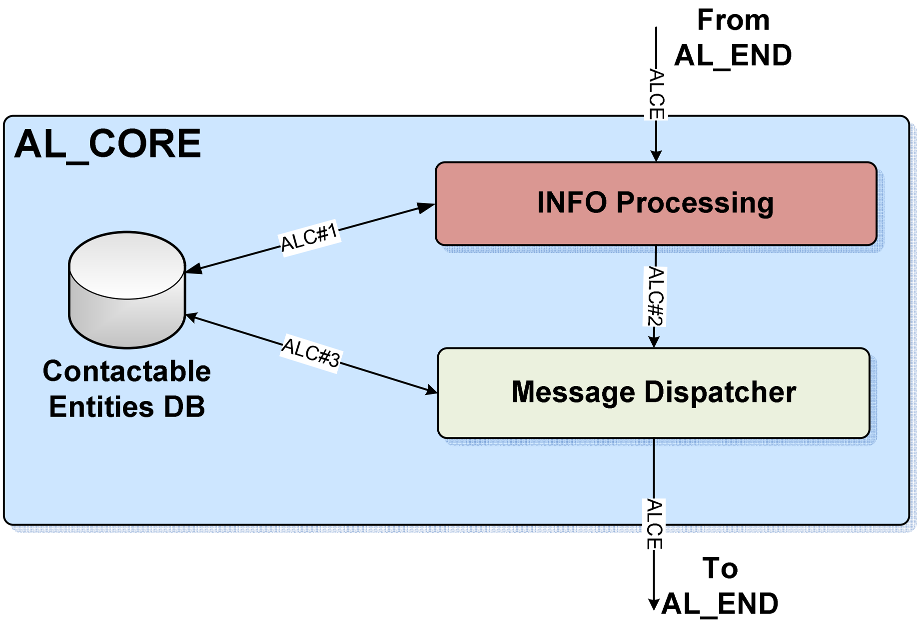


Figure 14: AL_CORE architecture

The functionalities presented are associated to actions in the internal blocks of the AL_CORE. The names of the distinct blocks indicate the operations done there; the following lines will provide a brief overview of them:

- **INFO Processing**: This block is in charge of managing the information contained in the packet received, affecting the activities and content of the database and the dispatching procedure.
- **Message Dispatcher**: aiming at selecting the moment for sending the different packets to their destinations.
- **Contactable Entities DB**: This block is further explained in the next subsection due to the key role it plays.

The messages are received from AL_END through the *Info Processing* block; there the internal AL messages are evaluated performing different actuations depending on the content of the messages.

Most of the times, these messages suppose an update of the *Contactable Entities DB*. Based on the information contained the DB is updated and the proper response is prepared to be sent to the destination. The output interface is the *Message Dispatcher* block, as it has been aforementioned, it will form packets and put them into queues waiting for the moment to be sent.

4.3.4.2.2.1 Contactable Entities DB

The information stored in this database is the basis of the AL operations. An example of the information contained is presented in Table 4.

Table 4: Information stored in contactable DB

Block ID	QoSMOS Entity IP Address	QoSMOS Entity Port	AL_END IP Address	AL_END Port	Data Type	Data Action	Time Stamp
CM-RM	192.168.1.24	8545	126.0.0.1	7800	0x05	Provider	10:24.35 20110804
CM-RM	192.168.1.24	8545	126.0.0.1	7800	0x42	Requester	10:24.35 20110804
SS	192.168.1.12	9478	126.0.0.3	7800	0x42	Provider	10:24.14 20110804
CM-RM	192.168.1.24	8545	126.0.0.1	7800	0x21	SS_Event	10:24.35 20110804

All the information stored in this DB will be provided by the AL_END, based on the needs of each block and the extra information included in the AL in order to facilitate data processing and message scheduling. Each field is explained in the following lines:

- **Block ID** – This value represents the type of QoSMOS entity registered.
- **QoSMOS Entity IP Address and Port** – These fields represent the IP address and the port of the QoSMOS entity registered in the AL. This information will be needed in order to handle not only internal operations, but also information exchange between different entities.
- **AL_END IP Address and Port -** These fields represent the IP address and the port of the AL_END entity which is connected to the QoSMOS entity registered. This information will be needed in order to help the AL_CORE to find the connection to the suitable AL_END which is connected to the QoSMOS entity.
- **Data Type** – This field stores the identification value for some specific data used by one entity. This value will be checked in case those entities appear or disappear, so as to inform the others about the new situation.
- **Data Action** – It is related to the previous field and presents the different actions that can be done with the data offered.
- **Time Stamp** – It is a timestamp representing the last time an entity was contacted. This field is necessary in order to establish periodic contact to detect entities dropping without proceeding with the established deregistration process.

Based on specific needs of the QoSMOS architecture, this database could be modified adding new fields that help in the management of the different operations that the AL should perform.

4.3.4.2.3 AL internal interfaces

In order to perform internal AL activities it is necessary to define some interfaces thus allowing internal components cooperation. The following Table 5 shows them:

Table 5: Internal AL interfaces

Interface name	Connection between blocks	
ALE#1	QoSMOS iface	AL_END AL_CORE iface
ALCE	AL_END AL_CORE	INFO_PROCESSING
ALC#1	INFO_PROCESSING	CONTACTABLE_DB
ALC#2	INFO_PROCESSING	MESSAGE_DISPATCHER
ALC#3	CONTACTABLE_DB	MESSAGE_DISPATCHER

These interfaces will be used in section 6.2 to properly define the primitives exchanged between the AL components to carry out the different tasks the AL is responsible for.

4.4 Heterogeneous RATs environment for the QoSMOS system

[D2.2] describes the challenges in flexibility posed to the system architecture when operating in a heterogeneous RATs environment. The previous section addressed those by specifying the Adaptation Layer and its central role in the QoSMOS system in a detailed manner. This is also completed by the Message Sequence Charts and the associated operations included in chapter 6.

Furthermore [D2.2] provides a list of reactive protection measures that the system should urgently take when the presence of an incumbent user is detected. However, it is also possible to envisage proactive actions that would anticipate the impact of the presence of the incumbent user, by simply taking advantage of various heterogeneous wireless networks presence.

One technique implemented in legacy networks exploiting the coexistence with other RATs is the Load Balancing procedure. This consists in handling the uneven distribution of the traffic load within the network, by triggering UEs handovers to neighbour access points (APs). The objective is then to control the load distribution in such a manner that the available radio resources remain highly utilized, while maintaining the QoS of the connected UEs. To achieve this goal, the network monitors the load of its APs by measuring for instance the Call Blocking Rate (CBR) or the Call Dropping Rate (CDR), compares the results to its internal policies and then decides if it is necessary to trigger actions for redistributing the load in a more balanced manner between the APs.

In the context of an opportunistic network, the policies used for making Load Balancing decisions may be dynamically updated according to the context information. As an example, it may be possible to apply more restrictive policies to APs that have already experienced the presence of incumbent users in their coverage. Then, when the load is considered as too high for an AP, the system may decide to handover some UEs to a neighbour AP using the same RAT (intra-RAT handover), a different RAT (inter-RAT handover) or a different RAN infrastructure (vertical handover).

This combined procedure of Load Balancing with incumbent protection is described in more detail and by means of Message Sequence Charts with corresponding operations in chapter 6.

4.5 Transceiver characteristics

4.5.1 Background

This subsection details the interfaces between the transceiver and other QoSMOS functional blocks like the Adaptation Layer and the CM-RM for proper and efficient cognitive radio operation.

The transceiver module is foreseen to support multiple radio access technologies. The *Transceiver block* (TRX) needs to communicate not only with the *Spectrum Sensing block (SS)*, but also with the *Adaptation Layer (AL)*. The following Figure 15 shows the interfaces between the TRX, SS, AL and the CM-RM.

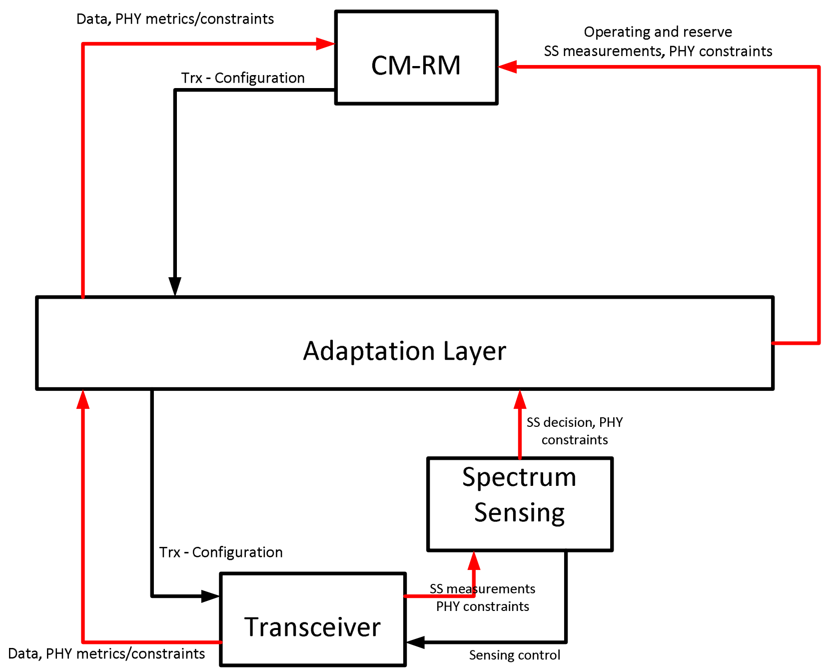


Figure 15: Transceiver interfaces

The red arrows represent either data or sensing paths. The black arrows represent control interfaces. The arrow indicates the logical direction of the information flow.

The TRX block includes all the functions required for the baseband processing of the data to be transmitted or received over the air, up to the conversion between analogue and digital domains. It is expected to be backward compatible to existing wireless standards (to be defined in detail in future work) and exhibit the flexibility, when demanded from a high-level entity like e.g. CM-RM, to evolve to a Cognitive Radio baseband processing block, with the ability to implement the particular functions of such a system.

The TRX block needs to interact with the SS block to gather information about the channel state. The TRX will receive the sensing control signals from the sensing block and it will send sensing measurements and PHY constraints to the SS block. Information regarding the frequency white spaces, the sensitivity of the channel and etc. are sent to the SS block to be compared with the sensing measurements and decide on the control signal. The control interface between the TRX and the SS blocks is a bidirectional interface used for in-band sensing scheduling. The raw sensing path interface between the TRX and SS blocks is used to pass the in-band and out-band raw sensing data gathered by the RF front-end to the SS block. The control interface between the SS and TRX blocks is used to configure the out-band sensing to be performed by the up/down converter modules not being used for data transmission and available bandwidth on up/down converter modules being used for data transmission for possible in-band sensing.

The interface between the AL and the TRX is two-fold. The TRX sends the data, physical layer metrics and constraints to the AL which then passes this to the higher MAC or networking layers. The AL in turn configures the TRX based on the inputs it receives from higher layer blocks and also from the CM-RM. This is done by the TRX-Configuration signal. The SS block again sends the spectrum sensing decisions to the AL to keep it updated.

In the QoSMOS reference model addressed in chapter 3, seven logical interfaces between the model's main functional blocks can be identified:

The Data Path interface between the Transmission Plane and higher AL is a bidirectional interface used for the exchange of transmitted and received data pertaining to the different planes: user, control and management.

The Physical Metrics and Constraints interface between the Transmission Plane and the CM-RM block is used to pass the transmission-related metrics and constraints of the TRX. There is the Adaptation Layer between the TRX and the CM-RM that interfaces these entities. The metrics and constraints include, but are not restricted to, the following:

- Channel State Information (CSI) / Channel Quality Information (CQI)
- Analogue RF specifications, device classification, limitations
- Spectrum aggregation capabilities, if any.

The Transceiver Configuration interface between the Transmission Plane and the CM-RM block is used to configure the transmission-related parameters of the Transceiver, both long-term and short-term. These parameters include, but are not restricted to, the following parameters:

- Operation mode (standard compatible mode or cognitive radio mode),
- List of channels to use and associated specifications
- Maximum and instantaneous transmitted power,
- Modulation and coding scheme to be used

The in-band and out-of-band Sensing Control interface between the TRX and the Spectrum Sensing block is a bidirectional interface that outputs the in-band and out-of-band physical sensing constraints and inputs the control for both types of sensing. The Sensing Data interface outputs all the gathered sensing data to the Spectrum Sensing block to be processed.

When integrating the sensing in the transmission plane, it is assumed that it is not possible to sense possible incumbents from a frequency channel which is used for local opportunistic communication. The spectrum sensing is assumed to be interleaved with data transmission. The opportunistic system periodically senses the transmission band to detect the presence of an incumbent. The sensing period, which sets the maximum time during which the cognitive user is unaware of possible presence of an incumbent, and the time during which opportunistic transmission must be interrupted in order to obtain an accurate and reliable measurement are the two main parameters that disrupt the transmission plane and impact the performance of the CR system.

The interaction between the AL and the CM-RM is straightforward. The AL sends the transmission data, physical layer metrics and constraints, operating/reserve channel spectrum sensing measurements. The CM-RM in return sends the transceiver configuration control signal to the Adaptation Layer to pass it on to the transceiver. As in some cases, the resource allocation and the transceiver block need to work in a closely coupled cross-layer manner with stringent timing requirements (for instance, performing channel dependent scheduling) the AL between CM-RM and the TRX may be entirely transparent.

4.5.2 QoSMOS scenarios and their characteristics

Another key element necessary to design and dimension transceivers for cognitive radios is the propagation link budget. As one of the likely context of future deployment, the TV White Space (TVWS) context is investigated here. The proposed approach is to analyse and to categorize the scenarios presented in QoSMOS Deliverable D1.2 [D1.2] w.r.t. the TVWS transmission constraints. This will help to shape the specifications of the transceiver in a TVWS context.

4.5.2.1 TVWS Specifications and envisaged scenarios

Some countries, mainly the United States of America and the United Kingdom have already proposed maximum power level specifications (Effective Isotropic Radiated Power, EIRP) and out-of-band level of radiation that the TVWS cognitive radios should meet. The currently known TVWS specifications are summarized in Table 6 [FCC2010], [OFCOM2009]. To current knowledge, no other European regulatory bodies have defined specific figures so far. Although CEPT has started a consultation process about TVWS through the ECC group SE43 ‘Cognitive radio systems - White spaces’ [ECCSE43], authorised power level figures have not been published yet.

Table 6: Maximum power allowed in the 470-790 MHz band for cognitive radios (TVWS)

	FCC	OFCOM	Note
Transmit power (fixed) EIRP	36 dBm	Not mentioned	FCC: 30 dBm at the input of the antenna, with a maximum gain antenna of 6 dB
Transmit power (portable) EIRP	20 dBm	17 dBm	FCC: with geolocation capability 20 dBm, 17 dBm without
Transmit power in adjacent bands to DTT signals (portable)	16 dBm	4 dBm	
Out of band radiation	<55 dB Below the in-band level	< -46 dBm	OFCOM: Out of band radiation is between 63 dB and 50 dB below the in-band level

These figures may be used to calculate a link budget in order to get a better understanding of the required power dynamic under TVWS conditions, but also define channel models. Using statistical propagation models, we can then estimate the maximum link distance an opportunistic communication may provide.

It is proposed to classify the QoSMOS scenarios [D1.2] into four categories, according to the propagation conditions:

1. Indoor short range for portable devices (1-100 m): this corresponds to the “Cognitive Femtocell” and the “Cognitive Ad-hoc network” scenarios
2. Medium range for portable devices (1-1000 m): this corresponds to the “Cognitive Ad-hoc network” and the “Terminal-to-Terminal in cellular” scenarios
3. Mobile long range (0.1 to 10 km): this corresponds to the “Cellular Extension in White Spaces” scenario
4. Fixed long range (1-10 km): this corresponds to the “Dynamic Backhaul” and “Rural Broadband” scenarios

For each of these categories the following analysis will be performed: a path loss model is proposed and a link budget is derived. Then statistical parameters of the channels may be deduced from the scenario category and the link budget. These parameters are mainly the time delay spread and the Doppler spread of the channel.

4.5.2.2 Link Budget and results

In order to propose a link budget, some hypotheses have to be made for the transmitter and for the receiver. For the scenario categories where the transmitter is a portable device, three link budgets will be considered: 20 dBm corresponding to the largest power level FCC is considering in this case [FCC2010], 16 dBm corresponding to the adjacent channel scenario for the FCC which can be combined with the largest power scenario of the OFCOM [OFCOM2009], and 4 dBm corresponding to the OFCOM largest transmit power in case of an adjacent incumbent user. It is assumed that the signal is emitted in a band of 8 MHz. For the receiver, further hypotheses are also made. For the SNR required at the receiver a value of 8 dB when accounting for 1 dB implementation loss is taken as base. This corresponds to a maximum data rate of $2.5 b.s^{-1}.Hz^{-1}$ using Shannon's limit theorem. The receiver noise figure is set to 6 dB. The value is derived from consumer UHF silicon TV tuner for which noise figures are between 4 dB and 10 dB. These fundamental link budget parameters are summarized in Table 7. The maximum propagation loss derived using the above mentioned assumptions will be used in the subsequent analysis in various scenarios categories in order to determine the maximum achievable range.

Table 7: Maximum propagation loss with guaranteed performance

Tx EIRP	36 dBm	20 dBm	16 dBm	4 dBm
Rx Noise Power	-105 dBm			
Rx Noise Figure	6 dB			
Required SNR	8 dB			
Rx Antenna Gain	0 dBi			
Cable and Connector Loss	1 dB			
Rx Sensitivity	-90 dBm			
Maximum Propagation Loss	126 dB	110 dB	106 dB	94 dB

The Maximum propagation loss with guaranteed performance is given in for the different cases of transmitter EIRP. Assuming a 0 dBi gain at the receiver the transmission allows for almost 126 dB of propagation loss for fixed transmitters, 110 dB, 106 dB and 94 dB for respectively 20 dBm, 16 dBm and 4 dBm TX EIRP. Average coverage figures will be presented, therefore the median path loss will always be calculated for the middle of the UHF TVWS frequency band (630 MHz) and no shadowing will be accounted for. For a particular user a different carrier frequency and the presence of shadowing might significantly deteriorate or improve the link budget presented in the following paragraphs.

4.5.2.2.1 Indoor short range for portable devices

These types of propagation conditions have been studied by Saleh and Valenzuela [Saleh1987]. They propose to model the path loss by using the following equation:

$$PL(r) = 10\log_{10}\left(r^{-\alpha}\right) - 10\log_{10}\left(G_t G_r \left[\frac{\lambda_0}{4\pi}\right]^2\right) \quad (1)$$

where r is the distance from the transmitter, G_t and G_r are respectively the transmit and the receive gain of the antennas, λ_0, the wavelength of the signal in free space. α is a number that varies from 1.5 to 6. The value of α is function of the topology of the building where the propagation occurs. Typical values for UHF indoor propagations are between 3 and 4 for same floor propagation and 4 to 6 for propagation across multiple floors. These figures may be found in [Sarkar2003], where propagation models have been surveyed.

The distance for which quality of service is guaranteed can then be derived. It is proposed to use either α equal to 3 or α equal to 6. Table 8 contains the resulting cell ranges.

Table 8: Estimated cell ranges for indoor short range cases

Carrier Frequency	630 MHz		
TX EIRP	20 dBm	16 dBm	4 dBm
Maximum Propagation Loss	110 dB	106 dB	94 dB
Cell Range, Indoor, α = 3	523 m	385 m	153 m
Cell Range, Indoor, α = 6	23 m	20 m	12 m

Under these assumptions, the propagation under indoor conditions is thus expected to range from 10 m to 500 m depending on the building topology and materials. These results indicate that even large indoor spaces (airports, malls) can be covered using TVWS communications.

4.5.2.2.2 Medium range for portable devices

This scenario category corresponds to the Cognitive Ad-hoc network and the Terminal-to-Terminal communications in cellular. It is expected to include indoor-to-indoor or indoor-to-outdoor types of transmission. The same type propagation loss model as before may be envisaged with an alpha set to 3. For transmission from indoor-to-outdoor, an extra 10 dB to 15 dB penetration loss is expected due to the outdoor-to-indoor transmission [Okamoto2009]. The results are summarized in Table 9.

Table 9: Estimated cell ranges for medium range cases

Carrier Frequency	630 MHz		
TX EIRP	20 dBm	16 dBm	4 dBm
Maximum Propagation Loss	110 dB	106 dB	94 dB
Cell Range, Indoor, α = 3	523 m	385 m	153 m
Cell Range, Indoor, α = 3 and 15 dB Penetration Loss	166 m	122 m	48 m

The signal is expected for this scenario category to propagate from 50 m up to less than 500 m. With this hypothesis, a quality of service above one kilometre for mobile-to-mobile communications is very unlikely.

Cognitive Femtocells, unlike other scenarios, require a fixed infrastructure. Due to this fact, and since Femtocells are assumed to be very small, the most likely use case for Femtocells will be indoors. While outdoor macro cell coverage is only hindered by the penetration loss of building walls, indoor Femtocells make use of the penetration loss of walls. [Okamoto2009] concluded that in urban environments the frequency dependence of the building penetration loss is negligible between 800 MHz and 2 GHz. In any other scenario, the lowest frequencies are the most popular, since providing indoor coverage from outdoors, or backhauling through walls is a difficult task at low frequencies, but in the Femtocell case penetration loss only decreases interference between outdoor and indoor Femtocell coverage.

Due to this it is possible that cognitive Femtocells will make use of both TV white spaces and higher band frequencies simultaneously to access more bandwidth.

The Cognitive Femtocell application has three unique points:

1. Femtocell downlink power – if cognitive Femtocells transmit with too high transmit power, then though coverage may be good, other users not served by the Femtocell will obviously suffer from interference. On the other hand, if Femtocells do not have enough transmit power, they will not provide coverage in enough rooms inside a building.
2. Femtocell receiver gain – user devices may have a minimum transmit power, below which they cannot operate, and since they can approach the Femtocell very closely, it is necessary to dynamically decrease the receiver gain of the Femtocell base station so that users do not overload it, and/or define the device classes such that a very low power mode is available.
3. Femtocells must be programmed to hand users over if their channel conditions are poor, so the link budget of user uplink transmit power is of less significance. More important is the interference calculations between Femtocells and co-channel macrocells or incumbents if white spaces are considered.

Cognitive Femtocells should be able to operate simultaneously at both the TV white space spectrum and at much higher microwave frequencies.

For comparison, according to [3GPP25.104], the power of an UMTS home node B is limited to a maximum of 20 dBm, or 17 dBm if transmit diversity or MIMO are used. A power level of 8 dBm is always accepted, or 5dBm in case of transmit diversity and MIMO.

4.5.2.2.3 Mobile long range

This scenario category comprises a cellular base station allowed to emit to power levels up to 36 dBm EIRP, and using the derivation from above, 122 dB propagation loss budget. It is suggested for these channel conditions to use Okumura-Hata model of propagation [Okumura1968], [WINNERII]. Path loss is given by the following equation for urban environment:

$$\begin{aligned} PL_{Urban}(d) &= 69.55 + 26.16\cdot\log(f) - 13.82\cdot\log(h_B) - C_H + [44.9 - 6.55\cdot\log(h_B)]\log d \\ C_H &= 0.8 + (1.1\cdot\log(f) - 0.7)h_b - 1.56\log(f), \end{aligned} \tag{2}$$

where h_b is the height of the mobile antenna and h_B the height of the base station antenna. For sub-urban environment path loss is given by the following equation:

$$PL_{Suburban}(d) = PL_{Urban}(d) - 2\left(\log(\frac{f}{28})\right)^2 - 5.4 \tag{3}$$

The maximum expected coverage is then estimated and given in Table 10, assuming a base station located 15 m above ground and antenna of the mobile terminal at 1.5 m, and using the maximum allowed EIRP of 36 dBm (or a maximum propagation range of 126 dB) as defined for fixed transmitters.

Table 10: Estimated cell ranges for mobile long range cases

Carrier Frequency	630 MHz
TX EIRP	36 dBm
Mobile Terminal height	1.5 m
Base Station height	15.0 m
C_H	0
Maximum Propagation Loss	126 dB
Cell Range, Okumura-Hata – Urban	0.97 km
Cell Range, Okumura-Hata -- Suburban	1.70 km

This gives a maximum cell range of 1 km for urban environments and of 1.7 km for suburban environments.

For Non-Line-of-Sight (NLOS) conditions, which will likely be encountered for the “Cellular Extension in White Spaces” scenario, the path loss model for the “Rural macro-cell” scenario, defined in [3GPP36.814], can be applied. The pass loss model defined in [3GPP36.814] is known to scale well down to 450 MHz; hence it is adequate to cover the TVWS. The mean path loss in dB have been found to be

$$\begin{aligned} PL_{Urban}(d) &= 161.04 - 7.1\log(W) + 7.5\log(h) - (24.37 - 3.7(h/h_B)^2)\log(h_B) + \\ &+ (43.42 - 3.1\log(h_B))(\log(d) - 3) + 20\log(f) - (3.2(\log(11.75h_b))^2 - 4.97) \end{aligned} \quad (4)$$

where W is the average street width and h is the average building height.

The shadow fading is given as lognormal, with a standard deviation of

- σ= 8 dB for the NLOS case
- σ= 4 dB for the LOS case within the so-called breakpoint distance
- σ= 6 dB for the LOS case past the breakpoint distance

These figures are in good agreement with the shadow fading data specified by TV broadcast recommendations.

4.5.2.2.4 Fixed long range

In this scenario category the previously mentioned Okumura-Hata propagation model [Okumara1968] may also be used to predict the path loss. The cell range is however larger for two main reasons. The receiver at the customer premises is located at a higher level (usually at the top of the roof), 4 m is a reasonable average value. Secondly the receiver antenna may be highly directional, providing gains up to an extreme 20 to 24 dBi. There is also an option to use a low-noise preamplifier to decrease the noise figure to 1…2 dB instead of 6 dB considered in the other scenarios. Therefore the maximum propagation loss may be typically equal to 146 dB (using 20 dB extra gain in the propagation path loss).

The calculations are summarized in Table 11.

Table 11: Estimated cell ranges for fixed long range cases

Carrier Frequency	630 MHz
TX EIRP	36 dBm
Mobile Terminal height	4 m
Base Station height	15 m
C_H	5.6
Maximum Propagation Loss	146 dB
Cell Range, Okumura-Hata – Urban	4.72 km
Cell Range, Okumura-Hata -- Suburban	8.27 km

This scenario category gives relatively large propagation range up to almost 10 km.

4.5.2.2.5 Conclusions

Based on up-to-date regulatory limits and reasonable assumptions on the devices and antennas, an estimate of the mean achievable communication ranges have been established for the main scenario categories that are considered within QoSMOS. It is confirmed that, despite the limited transmit power, the range expectations can be met using TVWS devices both for short-range and long-range scenarios.

4.5.2.3 Channel Characteristics

This subsection outlines the current understanding on the wireless channel characteristics to be expected in the different scenario categories. The channel models serve as input to the physical layer waveform definition, and also offer the basis for performance evaluation (link level and system level simulations) within the project. We consider path loss models, shadowing models and non-directional multipath statistical fading models for the current initial evaluation.

There are established wideband, directional channel models for the 2…5 GHz frequency range, based on measurements with high-quality channel sounders. Unfortunately, no such measurement campaigns are known to the authors for the TV white space frequencies. In the following, we propose channel models for the scenarios that have been considered within the QoSMOS project.

The objective is then to take each propagation condition and derive characteristics and models that may be then used as channel model for simulation and study.

The following two statistical elements are therefore considered to characterize the channel: time delay spread and frequency/Doppler spread.

4.5.2.3.1 Indoor short range for portable devices

The typical RMS delay spread is expected to be larger for UHF frequencies than for higher carrier frequencies (ISM 2.4 GHz or even 900 MHz). From [Deva1991] one can expect 15-20% larger delay spread at 900 MHz than at 2.4 GHz for indoor environment. As typical delay spreads range from 5-10 ns for residential, 10-100 ns for office spaces and 50-200 ns for large halls for 2.4 GHz / 5 GHz carrier frequency and have been widely accepted as references for Wi-Fi or Hiperlan design, we expect delay spread for indoor to be up to 300 ns, with typical values around 60 ns for UHF channels.

It is therefore proposed to use the Hiperlan channel [Medbo1998] models and spread time scale by 20% to take the effects of the lower carrier frequency into account in the time spread.

Table 12: RMS delay spreads in the Hiperlan channel model

Channel Type	Typical	Open Space	Large Open Space	Very Large Open Space
Average RMS Delay Spread	60 ns	120 ns	150 ns	300 ns

For the effect of Doppler spread, the classical (Jake's) Doppler spread is considered assuming a maximum terminal speed of 2 m/s (or approximately 7 km/h).

[WINNER+] recently reported on a wideband measurement where outdoor-to-indoor propagation was studied at 780 MHz from an elevated base station, and also employing a relay station. The mean RMS delay spread from the BS to the mobiles was 70 ns with a spread of 43.5 ns which is in line with the proposed typical Hiperlan model. For the relay-to-mobile scenario, the mean RMS delay spread is slightly smaller (48.5 ns with 27.6 ns spread). The maximum excess delay was found to be 438 ns and 282 ns for the BS-to-mobile and relay-to-mobile, respectively. The mean K-factor in the BS-to-mobile scenario is 7.68 dB with 5.45 dB standard deviation.

4.5.2.3.2 Medium range for portable devices

From the link budget estimated here above, the same level of time spread is expected as for the indoor short range scenario category.

4.5.2.3.3 Mobile long range

For these conditions of propagation, it is suggested to estimate the RMS delay spread using a model proposed in [Green1997],where the RMS delay spread can be modelled as a lognormal distribution as described in (5):

$$\tau_{RMS} = T_1 d^{\varepsilon} y \tag{5}$$

T_1 is the median value of τ_{RMS} at 1 km.

ε is an exponent between 0.5 and 1

y is a lognormal distribution

For the considered propagation conditions, T_1 is expected to be in the order of 0.3 µs to 1 µs and ε is equal to 0.5 for urban/suburban environment. As the link budget is estimated in a range from 1 km to 1.5 km, typical maximum delay spread is expected to be less than 1.2 µs RMS.

For the Doppler spread, the classical (Jakes') Doppler spread will be used with maximum terminal speed of 40 m/s (~140 km/h).

ITU vehicular channels seem appropriate for simulation of this scenario category. The RMS delay spreads for the ITU channel models are summarized in Table 13.

Table 13: RMS delay spreads in the ITU channel models

Channel Type	ITU Pedestrian A	ITU Pedestrian B	ITU Vehicular A	ITU Vehicular B
Median RMS Delay Spread	0.045 µs	0.75 µs	0.37 µs	4 µs

A recent measurement campaign, conducted in downtown Oulu in a macro cell setting at 775 MHz using high-quality and very wideband sounding equipment [WINNER+] reports on a similar scenario. The maximum range measured was 1.1 km. They observed a mean RMS delay spread of 123 ns, with 73.2 ns spread and the mean K-factor was found to be 5 dB with 6.7 dB deviation. It is also pointed out that past narrowband measurements tend to demonstrate larger delay spreads than those found using wider band sounders.

4.5.2.3.4 Fixed long range

WiMAX fixed channels will be used as proposed in reference [Erceg2001]. These channels reflect both RMS delay spread and Doppler statistics and it should be possible to extend them to the UHF frequency range. For simulation purposes, it is possible to use Stanford University Interim Channel models. Line of sight path is dominated by Ricean fading. The rounded Doppler spectrum of the model should however be scaled in frequency (frequencies reduced by factor 8).

The RMS delay spread varies between 0.1 µs to 2.4 µs depending on the terrain type (hilly or flat), up to 7 km cell size. The coherence time is expected to be larger than 200 ms.

Alternatively, the 802.22 channels [IEEE802.22] might well describe the channel in this scenario. Four cases (“profiles”) are considered in a tap delay line framework. The dominant taps are Ricean, the majority of the other taps exhibit 0.1…0.4 Hz. RMS delay spreads range from 2 µs to 6 µs.

It should be remarked that, as it was pointed out using link budget calculations, the regulatory limits, especially the low allowed transmit power/effective radiated power will ultimately limit the coverage in a rural broadband setting. Hence, even in the presence of excessive multipath, the coverage can be expected to be power-limited.

4.5.3 Transceiver characterisation

In this subsection some fundamental radio frequency parameters are presented that are considered especially important for cognitive devices operating in the TV white spaces. Some of these parameters constitute the system specifications and will be used in the further course of the project.

4.5.3.1 Transmitter characteristics

4.5.3.1.1 Adjacent channel leakage and spurious emission

The Adjacent Channel Leakage Ratio (ACLR) characterizes the spurious emission radiated by a certain transmitter. ACLR is defined as the ratio of the wanted power within the occupied channel to the power leaking into an adjacent channel. The ACLR limits are currently specified by some regulators, as summarized in Table 6.

4.5.3.1.2 Modulation accuracy

The modulation accuracy is in general measured in terms of Error Vector Magnitude (EVM) and characterizes the fidelity of the transmit signal processing chain. The transmitter distortions ultimately limit the best signal-to-noise ratio that can be achieved in the receiver even in the absence of noise. Other quantities derived from this measurement, especially the residual frequency error, is also important in the characterization of the device under test.

There is a trade-off between the amount of allowed adjacent channel leakage and the transmitter EVM: it is known for multicarrier transmission that more aggressive out-of-band filtering to band-limit the signal will lead to higher EVM. This is an important factor as alternatives to OFDM techniques are considered in the project, that inherently exhibit more favourable adjacent channel properties, but the EVM aspects are not yet explored in detail. This aspect should be further studied in the course of the project.

4.5.3.2 Receiver characteristics

4.5.3.2.1 Sensitivity and dynamic range

The reference sensitivity characterizes the sensitivity of the RF transceiver, and is generally measured using a reference configuration employing a robust modulation and coding scheme (MCS); with no noise and channel impairments. The reference sensitivity level is usually defined at the signal-to-noise ratio where the achievable throughput attains 95 % of the nominal throughput that characterizes the reference setup. A worse sensitivity implies reduced coverage.

Based on the current state of the art, the reference sensitivity requirement (QPSK modulation, full TV channel bandwidth) is proposed to be established to -94 dBm which coincides with the reference sensitivity required by 3GPP specification [3GPP36.521] for E-UTRA bands 12 and 20 (upper parts of the TV band) and 10 MHz channel bandwidth. The sensitivity is measured by applying this power level to two receive antenna ports; hence a 3 dB correction is applied as QoSMOS foresees single-antenna terminals initially. This yields to a minimum sensitivity of -91 dBm.

It should be further investigated whether this requirement should be relaxed, e.g. due to non-feasibility of the advanced FEC schemes in the investigated setting. The link budget calculations in the previous subsection have been carried out assuming essentially the same sensitivity (-90 dBm).

The dynamic range is spanned by the reference sensitivity and the maximum input level. The latter can be measured by applying the least robust MCS (together with a specified level of AWGN) and measuring the 95 % throughput level. As a comparison and initial recommendation, LTE requires -25 dBm using 64 QAM and rate ¾ coding.

4.5.3.2.2 Interference-tolerance

The Adjacent Channel Selectivity (ACS) characterizes the receivers' ability to discriminate between wanted signals on the assigned channel and interfering signals present on adjacent channels. The ACS is the ratio of the wanted signal power to the interfering power in an adjacent channel whereas the throughput requirements are still met. For reference, LTE (indirectly) specifies an ACS requirement of +33 dB for the receiver, assuming the relevant channel bandwidths 5 and 10 MHz which are comparable to the TVWS bandwidth.

The combined effect of transmitter-side leakage and receiver-side selectivity can be characterized by the Adjacent Channel Interference Ratio (ACIR), which can be determined as

1/ACIR = (1/ACLR + 1/ACS), provided the channel bandwidths are the same in the calculations. The definition of Adjacent Channel Leakage ratio (ACLR) has been given in the previous section.

These metrics can be used to characterize the tolerance to interference which is caused by the presence of modulated signals on nearby channels. Beyond these metrics, usual blocking characteristics (described in the next section) are defined to assess the tolerance against narrowband interferers at various frequency separation distances from the used carrier.

A last relevant metric is the In-Channel Selectivity (ICS), which normally characterizes the ability of the receiver to discriminate the wanted signal in the presence of a much stronger (15…20 dB above the wanted signal level) interferer which falls within the receive bandwidth. The standard test is usually to place the wanted signal on one side of the nominal carrier, and the interference on the other side. Again looking at the current LTE requirements, although not specified for LTE UEs, this measurement might be relevant in TVWS spectrum pooling/aggregation in which the incumbent falls within the operating bandwidth of the TVWS equipment.

4.5.3.2.3 Receiver blocking

Receiver blocking is the effect of a strong out-of-band interfering signal on the receiver’s ability to detect a low-level wanted signal. Receiver Blocking Response (RBR) (or performance level) is defined as the maximum interfering signal level expressed in dBm reducing the specified receiver sensitivity by a certain number of dB's (usually 3 dB). Consequently, the RBR is normally evaluated at a wanted signal level which is 3 dB above the receiver sensitivity and at frequencies differing from that of the wanted signal.

4.5.3.2.4 Overloading threshold

Overloading threshold (OTh) is the interfering signal level expressed in dBm, above which the receiver begins to lose its ability to discriminate against interfering signals at frequencies differing from that of the wanted signal (i.e., the onset of strong non-linear behaviour). Therefore, above the OTh the receiver will behave in a nonlinear way, but does not necessarily fail immediately depending on the receiver characteristics and interference characteristics.

4.5.4 Interference limits in TV white spaces

The maximum level of interference a radio system can tolerate from another radio system must be determined by means of thorough tests. It is not sufficient to use the average received interference power to predict if a radio system will cause harmful interference into another radio system, since the performance degradation depends on other factors as well (e.g. peak interference power and the burstiness of the interfering signals).

When a new radio system is introduced into a frequency band where another system has been operating for a long time, which will be the case for cognitive radio in the TV white spaces, there are additional factors to be taken into consideration. There will be a lot of equipment for the existing radio system in use and this equipment may have peculiarities that can make it vulnerable for certain types of interference.

TV receivers for example, usually have an Automatic Gain Control (AGC) function to control the amplitude of the received signal before demodulation. Since TV receivers have been designed to operate in a frequency band where the interference levels are almost constant (coming mostly from distant TV transmitters), their AGC will often be severely disturbed by time varying interference signals. Such time varying interference signals can for example come from a cognitive user terminal in the vicinity of the TV receiver.

Determining the maximum allowable interference from cognitive radios into existing radio systems will be even more complicated. Cognitive radios are typically very flexible and can adapt the characteristics of their transmissions (e.g. modulation, bandwidth, burstiness, etc.) according criterions like its user’s needs, minimum power consumption, minimum interference generated, etc. Hence, the maximum allowable interference generated by cognitive radios will depend on how they operate.

In connection with the reallocation of the frequency band 790-862 MHz from TV broadcasting to mobile services (part of the digital dividend) [WRC2007], a number of tests have been done to determine the maximum allowable interference generated by the new mobile systems into TV receivers operating below 790 MHz. This is a situation that has many similarities with introduction of cognitive radios in TV white spaces, and the results of these tests can be used as a first approximation of the required interference limits for cognitive radio.

The measurements have been done for two mobile systems; UMTS and LTE. The results are reported in ECC reports 138 [ECC138] and 148 [ECC148] respectively. Since it is expected that the waveforms used by cognitive radio systems will be more similar to those used in LTE than the ones used in UMTS, we will only consider the results from ECC report 148.

The tests consider two interference effects: receiver blocking and receiver (front-end) overloading threshold (definitions to be found in the previous sections) and three types of TV tuners:

- **“Can” tuners:**
  Classical super-heterodyne tuners housed in a metal enclosure containing discrete components.
- **“Integrated silicon” tuners:**
  IC-based tuners integrating all tuner circuitry into a small package directly to be fitted onto the tuner’s main circuit board.
- **“USB dongle” tuners:**
  Silicon-type tuners implemented in small USB-type devices, e.g. USB sticks.

The results of the receiver blocking tests are given as required Protection Ratios (PRs). It is the minimum value of the signal-to-interference ratio (SIR) required for a specified reception quality under specified conditions at the receiver input (note that the wanted signal and interference powers are measured at different frequencies and in different bandwidths). The results for the overloading threshold are given as the maximum allowable interfering signal levels expressed in dBm. The receiver sensitivity, protection ratios as well as overloading thresholds were determined by ensuring the absence of a picture failure during a minimum observation time of 30 seconds. The protection ratios and overload thresholds are summarized in Table 14 and Table 15.

The required protection ratio depends on tuner type and tuner brand/model. For each tuner type the required PRs for the 10^{th}, 50^{th} and 90^{th} percentile of the tuner brands/models are given. Note that the percentile values refer to the number of brands and not the number of receivers.

Cognitive radio systems should ideally have no noticeable effect on the performance of the incumbent system. It should therefore be expected that regulators will set the interference limits conservatively. Since such limits are not yet specified by the regulators, we have to make educated guesses on what those limits will be in order to be able to evaluate different QoSMOS solutions.

One approach for predicting the maximum allowable interference limits is to use the most conservative results from the tests as the interference limits for cognitive radio in TV white spaces. These are the results for the 90^{th} percentile and portable/mobile reception (a correction factor of 6.4 dB relative to the Gaussian channel numbers then have to be added to take these reception conditions into account [ECC148]). The tuner type with the poorest performance is chosen in each case, which is most often the USB dongle. DVB-T 64-QAM 2/3 is considered as the victim.

One can argue that using the 90^{th} percentile numbers is still not conservative enough since 10% of the USB dongle brands will experience harmful interference. But the USB dongles having such poor performance are usually the cheapest ones and often of very poor quality. Usually ‘cheap’ USB dongles do not meet requirements set by TV regulators such as DTG in the UK or NORDIG in the Scandinavian Countries. These poor TV tuners notably don’t meet the current TV adjacent channel requirements. Since it is not expected that regulators will require protection for DVB-T receivers that do not meet regulators’ requirements, the interference limits obtained from the USB dongles 90^{th} percentile numbers appear as too conservative.

An alternative approach is to base the prediction of the maximum interference limits on the 90^{th} percentile numbers for “Integrated Silicon Tuners”. In this case the limits will probably be too optimistic since 10% of the “Integrated Silicon Tuners” brands will experience harmful interference.

It is proposed to use both the pessimistic and the optimistic predictions when evaluating QoSMOS solutions as this reflects the uncertainty in these parameters. The predictions are given in Table 14 for interference generated by a cognitive BS and in Table 15 for interference from a cognitive UT.

The frequency separation between the channel edges of the wanted and interfering signals is used instead of the frequency offset between the central frequencies of wanted and interfering signals. The results for 5 MHz and 10 MHz LTE systems are very close to being equal for LTE downlink, and almost equal for LTE uplink.

Table 14: DVB-T PR and OTh values in the presence of a Cognitive Radio BS interfering signal

Channel edge frequency separation [MHz]	PR [dB]		OTh [dBm]	
	Pessimistic	Optimistic	Pessimistic	Optimistic
1	-26.6	-26.6	-26	-13
9	-29.6	-33.6	-22	-7
17	-29.6	-37.6	-19	-6
25	-31.6	-41.6	-14	-6
33	-35.6	-42.6	-14	-6
41	-36.6	-43.6	-14	-5
49	-36.6	-43.6	-14	-4
57	-36.6	-44.6	-13	-4
65	-37.6	-38.6	-16	-6

Table 15: DVB-T PR and OTh values in the presence of a Cognitive Radio UT interfering signal

Channel edge frequency separation [MHz]	PR [dB]		OTh [dBm]	
	Pessimistic	Optimistic	Pessimistic	Optimistic
Co-channel	28.4	28.4		
1.5	-5.6	-6.6	-27	-23
9.5	-24.6	-25.6	-47	-46
17.5	-25.6	-28.6	-49	-47
25.5	-24.6	-29.6	-44	-44
33.5	-24.6	-30.6	-43	-43
41.5	-24.6	-31.6	-41	-41
49.5	-23.6	-33.6	-39	-39
57.5	-23.6	-30.6	-39	-35
65.5	-25.6	-30.6	-40	-32

In some cases the pessimistic and the optimistic values are very different, especially for the cognitive BS case. But this reflects the great uncertainty associated with what regulators will decide regarding interference limits in TV white spaces.

5 Evaluation criteria and performance metrics for QoSMOS system performance

This chapter presents the evaluation criteria and performance metrics that will be used for comparing the different solutions considered in the project, which are built on the mapping of functional architectures to topologies and scenarios together with the implementation of the corresponding algorithms. The criteria and metrics are designed in such a way that the overall performance of the system is fairly and consistently assessed on a technical basis. It should be noted that it is the overall performance of the system that is addressed and hence the corresponding criteria and metrics for the components of the QoSMOS system must be derived from the overall criteria and metrics.

In addition to system performance, the different solutions must also be evaluated with respect to costs, but this is outside the scope of this document. Evaluations related to costs will be reported at a later stage in the project.

As described in D1.2 [D1.2] six scenarios have been defined for the scope of the QoSMOS project. These scenarios have been addressed earlier in chapter 3 when discussing topologies and architecture options. However as a preamble to the business case studies to be performed in the further course of the project, the QoSMOS project will focus on the most promising scenarios from a commercial point of view. They were selected from a longer list based on the best score on the following criteria:

- Benefits from QoSMOS technology
- Benefits for actors
- Managed QoS and mobility

The procedure is comprehensively described in QoSMOS deliverable D1.2 [D1.2]. Further, a more detailed assessment has been made to target the most promising scenarios also from a commercial point of view. The commercial criteria used were:

- Market potential
- Best solution
- Technical feasibility
- Economic feasibility
- Regulatory feasibility
- Ecosystem feasibility
- Benefits for the society

The resulting list then contains three distinct scenarios for the QoSMOS project to be used in both business case as well as technical studies:

- Cognitive femtocell
- Cellular extension in white spaces
- Cognitive ad hoc network

A detailed description of the scenarios can be found in D1.2 [D1.2].

5.1 Reference incumbent environment

In order to make a systematic assessment of the QoSMOS system's performance, a reference environment must be defined. This reference environment describes the incumbent environment in which the QoSMOS system shall operate and the constraints the QoSMOS network must fulfil. This reference environment is based on the opportunistic use of TV White Spaces (TVWS). The reason is that TVWS are the first frequency bands which will be utilized in this manner.

Each QoSMOS scenario is then applied onto this reference incumbent environment, so that one complete evaluation scenario consists of the combination of the reference environment and the addressed QoSMOS scenario. In summary:

The reference environment is the incumbent environment in which the QoSMOS solution will operate along with constraints for the QoSMOS network.

The QoSMOS scenarios are used to define a reference deployment for the opportunistic part.

As introduced above the reference incumbent environment consists of a digital terrestrial TV (DTT) broadcasting network and wireless microphones. Both the TV broadcasting network receivers and the wireless microphones are incumbent users for the QoSMOS system. To have a dynamic environment the wireless microphones are assumed to be mobile, which for example will be the case when wireless microphones are used on buses. Even if wireless microphones are to be registered before hand, such dynamics in the behaviour must be anticipated.

The digital TV broadcasting network is divided into circular cells with a radius of 30 km. Each cell is covered by one or more TV transmitters (typically one large transmitter and several smaller ones) using the same frequency (i.e. each cell is a single frequency network).The TV broadcasting network is a frequency planned network where the same frequency is re-used in different cells having the required geographical separation to ensure that they do not cause harmful interference to each other. The cells associated with a given frequency (or more precisely a given 8 MHz channel) are deployed on a hexagonal grid. A QoSMOS system can be deployed in the area between the TV cells by using the same frequency as the TV cells. The reference incumbent environment is illustrated in Figure 16.

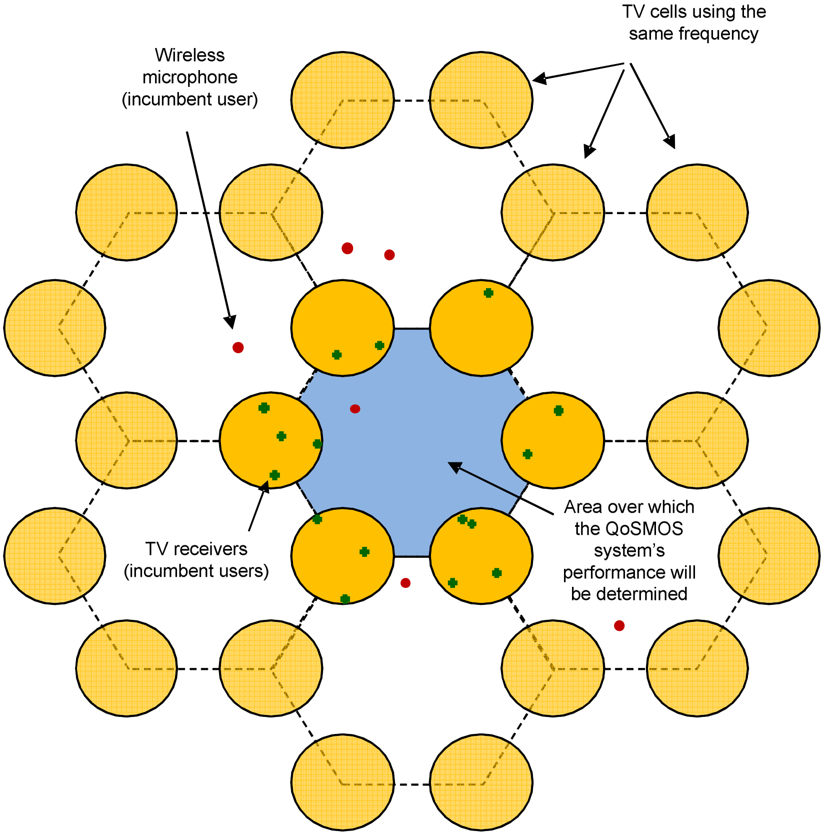


Figure 16: Reference incumbent environment

The main parameters for the reference incumbent environment are given in Table 16.

Table 16: Reference incumbent environment parameters

Parameter	Value
TV cell radius	30 km
Distance between TV transmitters	120 km
TV receiver characteristics	Antenna pattern: ITU-R Rec. BT.419 Antenna height: 10m Antenna gain: 12 dBd (14.15 dBi) Feeder loss: 0 dB Channel bandwidth: 8 MHz Maximum interference at TV receiver antenna port: -100 dBm in 7.6 MHz
Wireless microphone characteristics	Transmitted power: 50 mW Antenna gain: 2.15 dBi (0 dBd) Bandwidth: 200 kHz Maximum interference level: -115 dBm in 200 kHz (from ECC rep. 159) Distance between transmitter and receiver: 20 – 100 meters

The TV receiver characteristics are based on parameters used in LTE 800/DVB-T co-existence studies [ECC159]. The maximum interference level at a TV receiver antenna port is derived using the following assumptions:

- DTT link bandwidth: 7.6 MHz
- DTT receiver noise power (incl. Noise Figure) over link BW: -98.17 dBm
- Shadowing loss: 5.5 dB
- Minimum SNR for DTT receiver: 21 dB
- Required co-channel protection ratio: 28.4 dB (see Table 15)

Assuming that for reasonably good TV reception a margin for shadowing fading of 5.5 dB is required, the maximum allowable interference is -98.17 dBm +5.5 dB + 21 dB – 28.4 dB = -100.1 dBm. This corresponds to an increase of the noise floor seen by the TV receiver by 2.2 dB.

The wireless microphone characteristics are taken from ECC Report 159 [ECC159].

5.2 Performance metrics

QoSMOS solutions shall be evaluated according to two main categories of metrics:

- Spectrum utilization
- Service performance

These are associated to a set of functional criteria, which are given as requirements in Deliverable D1.4 [D1.4]

Preferably, the average value and cumulative distribution function (cdf) of the metrics shall be evaluated. The cdf describes the probability that the outcome of a test (e.g. X) will be found at a value less than or equal to x. A cdf can be estimated by performing a number of measurements or simulated tests and sort the outcomes in suitable bins. The performance of the QoSMOS system shall be measured for each scenario considered under a set of constraints, which depends on the scenario as shown in Table 17. It should be emphasized that the defined QoSMOS scenarios may embrace a much broader range of operational conditions than the ones chosen here. However, the test constraints are defined to limit the test space, but at the same time securing that tests are done in representative conditions.

Table 17: Constraints

Constraint	Cognitive Femtocell	Cellular extension in white spaces	Cognitive ad hoc network
Opportunistic system mobility	None	High	Low
Opportunistic system coverage	Hot spots, single cell	95% of reference area	Dense, short range
Incidents in incumbent system	Wireless microphone appears	Wireless microphone appears	Wireless microphone appears
Opportunistic system load (number of simultaneously active users)	Single user, 50% load, 100% load	Single user, 50% load, 100% load	Single pair of users, 50% of users, 100% of users
Service mix **(percentage users of each service: voice/streaming/ftp/browsing)**	Example: 25/25/10/40	Example: 50/10/10/30	Example: 0/0/25/75

5.2.1 Spectrum utilization

These metrics measure how well a QoSMOS system can utilize a spectrum hole (i.e. an unused spectrum resource defined in frequency, time and space). It is defined as the average spectrum efficiency per unit of area measured in the reference scenario under given constraints. The bit rate here refers to the bit rate that is offered to the applications. Full buffer traffic will be assumed.

Referring back to the QoSMOS system requirements [D1.4], the main requirement leading to these metrics is "P.top":

> *"The QoSMOS system's technical performance should be good enough to meet users' expectations of the service delivered."*

Technical performance is a sum of several factors, and since one of the promises of cognitive radio is better spectrum utilization, this is the main metric we want to assess. In D1.4 an ambitious goal is set for this ("P.spect"):

> *"The peak spectrum efficiency of the QoSMOS physical layer should be as good as or better than current state-of-the-art mobile broadband systems."*

The physical layer is only one component which determines the spectrum utilization. What spectrum utilization the QoSMOS system can achieve depends on several characteristics of the system. It is more convenient to compare solutions based on one or more of these characteristics, which motivates to define a metric for each of them. These metrics can then be considered as sub-metrics to the overall system metric “spectrum utilization”. These characteristics include:

- **Overhead**
  The overhead consists of traffic or time/frequency slots that the system use but that do not directly carry user data, for example QoSMOS protocols’ overhead like packet headers, sensor communication, spectrum database communication, silent intervals (to allow accurate sensing), etc.
- **Frequency re-selection time**

  If an incumbent user appears, the QoSMOS system must stop the transmissions on the frequency in question, identify a new vacant frequency and continue the communication at this new frequency. It might be possible that the system has identified vacant frequencies beforehand, and this will probably reduce this time significantly. The time it takes to identify a new vacant frequency and move the communication there depends on the architecture and the protocols used.
- **Sensing performance**

  Two types of errors may occur which deteriorates sensing performance. If the QoSMOS spectrum sensing function incorrectly determines that an incumbent user has appeared (false detection), it will stop all transmissions and cause some time of unnecessary inactivity that the system use either for discovering that the detection was wrong or for jumping to a new frequency. Alternatively if the QoSMOS sensing function incorrectly fails to detect that an incumbent user has appeared (misdetection), the incumbent may suffer from unacceptable interference until a correct detection has been made. The QoSMOS system may also suffer from reduced performance in this case.
- **Air interface flexibility**

  A flexible air interface can adapt its transmissions so that the incumbent users are not disturbed even at relatively short distances, e.g. by reducing the transmitter power, shaping the transmitted spectrum to a form that causes less disturbance to the incumbent system or avoiding to transmit during time slots which are critical for the incumbent system (e.g. during time slots carrying synchronization signals). Hence, the QoSMOS system can operate closer to the incumbent users which increase the total system capacity and hence the spectrum utilization increase. The QoSMOS air interface must also be robust in order to handle the interference from the incumbent users.
- **Spectrum information latency (from sensors and/or databases)**

  It will take some time before data from the sensors and/or spectrum databases are processed and distributed in the system. The delay introduced will depend on the sensing performance, the system architecture and the protocols used. This delay must be taken into account by the QoSMOS system which must behave conservatively in order to ensure that incumbent users are not disturbed.

Table 18 gives the definitions of the corresponding metrics. All metrics shall be measured using the reference scenario defined in section 5.1.

Table 18: Metrics associated to spectrum utilization

Metric	Definition	Requirement from D1.4
Spectrum efficiency	The average spectrum efficiency per unit of area measured in the reference scenario under given constraints. The constraints depend on the usage scenario considered. It is the long term ratio of the amount of information correctly transmitted to the amount of spectrum used and the time used for such transmission. This metric will measure how efficiently the spectrum is being managed.	P.spect – *Spectrum utilization*
Overhead	The share of the time available for the QoSMOS system which is not used for transferring user data on the air interface. This includes signalling overhead, silent periods for sensing and sensor communications.	
Frequency re-selection time	The time from when an incumbent user appears to when the QoSMOS system starts to transfer user data on a new frequency.	P.chchg – *Handover support (spectrum mobility*
Sensing performance – false incumbent detection	The relative amount of time used for recovering from false incumbent user detections. This depends both on how often false detections occur (i.e. the probability of false detection) and the time the system needs to recover from each incidence. The time is measured from when the system stops transferring user data to the time it is recommenced. *Note: The incumbent user detection probability is a constraint in the reference incumbent environment.*	P.srxsens – *Sensing Rx sensitivity*
Sensing performance – missed incumbent detection	The relative amount of time used from a missed incumbent detection until a correct detection is done. This depends on how often misdetections occur (i.e. the probability of misdetection) and the time needed to detect correctly. *Note: The incumbent user detection probability is a constraint in the reference environment.*	P.srxsens – *Sensing Rx sensitivity*
Air interface flexibility	The necessary protection ratio the primary system needs when interfered by a QoSMOS network.	S.ctxresp – *Context based response capability* S.intf – *Interference avoidance* S.prot – *Incumbent protection* S.sens – *Sensing for incumbent protection* S.pwr – *Transmitter power*
Spectrum information timeliness	The maximum “age” of sensing spectrum information, on which decisions on transmission parameters are made.	A.geoloc – *Geolocation database*
Operator fairness	This metric measures how fair the spectrum allocation policies are towards different types of operators or spectrum bands.	S.coex – *Co-existence*

5.2.2 Service performance

The purpose of these metrics is to evaluate what kind of services can be offered over the QoSMOS system. This relates to what QoS parameters can be offered, e.g. throughput, latency, jitter, etc. under given constraints. Referring back to the QoSMOS system requirements [D1.4], the main requirement leading to these metrics is "B.userv":

> *"The QoSMOS system shall be able to provide services to end users with a quality meeting the user's expectation when compared to that of a conventional system."*

"The user's expectation" is not well-defined and also depends on other non-technical factors (e.g. pricing). Therefore the service performance must be measured using more basic metrics which are identified in Table 19 below. It is suggested to evaluate the Service performance according to the NGMN traffic models as described in Annex A of the White Paper "NGMN Radio Access Performance Evaluation Methodology", [NGMN2008].

Table 19: Metrics associated to service performance

Metric	Definition	Requirement from D1.4
User throughput	Measures the useful capacity in bits/s that is granted to a user. It is measured during the transmission time as the number of bits correctly transmitted during a specific period of time.	P.drate – *Data rates*
End-to-end delay	Total amount of time needed to transfer a certain amount of user information from the source to a certain destination. Measured as the difference between the time when the data was generated and the time when the same data are completely delivered to the other communication end. This metric is very important in delay sensitive services such as video/audio conference	P.lat – *Latency*
Grade of Service (GoS)	Grade of service is the probability of a session being blocked or delayed for more than a specified interval, expressed as a fraction.	P.traf – *Traffic classes* P.qmaintain – *Maintaining QoS* P.qpri – *QoS priority* P.srvrestart – *Service re-establishment*
User fairness	This metric measures how the spectrum allocation policies are fair towards different users. The fairness may e.g. be measured according to Jain's fairness index [Jain1984] or as Fairly Shared Spectrum Efficiency (FSSE). The FSSE is the portion of the system spectral efficiency that is shared equally among all active users (with at least one backlogged data packet in queue or under transmission).	B.userv – *End user services* P.qmaintain – *Maintaining QoS* P.qpri – *QoS priority*
Dropped session probability	The probability that the call or session is disrupted and not re-established.	P.qmaintain – *Maintaining QoS* P.umob – *User mobility* P.term – *Terminal mobility* P.hosupp – *Handover support (physical mobility)*

		P.chchg – *Handover support (spectrum mobility)*
Handover failure	The probability of failure in the process to handover one session from one radio resource (spectrum) to another.	P.chchg – *Handover support (spectrum mobility)* P.srvrestart – *Service reestablishment*

A further set of preliminary performance metrics currently under study in the project and complementing the ones described in the previous sections is contained in the Appendix. The final outcome of the metrics' work will be reported in the next deliverables issued by the project.

6 MSCs and operations

6.1 Introduction

[D2.2] already contained in chapter 6 so-called Message Sequence Charts (MSCs) describing overall and specific functions of the QoSMOS system like spectrum portfolio management, sensing, resource control, incumbent protection. These MSCs have been taken as base for the further work in the project when detailing the functionalities inside each system building block as shown in e.g. [FuNeMS2011] for the CM-RM.

This chapter contains further MSCs corresponding to the QoSMOS system functions specified in the previous chapters of this document. The operations depicted in the MSCs are described as primitives over the QoSMOS system interfaces they are related to. Those will be further detailed by means of their parameters' layouts in the Appendix.

6.2 Adaptation Layer

This section focuses on providing a deeper insight in the data flow of internal AL operations. Through the different MSCs depicted the relationship among entities is presented, as well as the intention of the messages exchanged. Also highlighted is the role of each of the internal elements in the overall AL block behaviour.

6.2.1 Interaction between AL and other entities

The scope of the AL is to facilitate the communication among different QoSMOS entities existing in the architecture. In previous sections the internal behaviour of the AL has been presented; the focus in this section is on the interaction between QoSMOS entities and the AL, and also different entities interconnected through the AL.

6.2.1.1 Connection among QoSMOS entities and the AL

The registration process has been already presented, but there is no connection point between the AL and the QoSMOS entity. This section aims at clarifying the steps done since a QoSMOS entity appears to the moment that it is correctly registered in the AL, being ready to interact with other entities connected to the AL as well.

6.2.1.1.1 Interfaces and discovery process

The communication between QoSMOS blocks and the AL will be based on existing communication protocols. Depending on the particularities of each block, the communication can be performed by using middleware like CORBA [CORBA] in the case of CM-SM, or by establishing direct links through XML-RPC protocol [XMLRPC]. The port where the AL is listening is well identified, and the AL_CORE is known by all the AL_ENDs included in each block. With this scheme the communication is easily performed.

The process to discover and invoke remote objects will be done through uniform mechanisms, while also trying to achieve a high level of transparency in that remote invocation. The goal pursued is to automate a series of common tasks in distributed systems, like object registration, location or activation and management of errors.

6.2.1.2 Message exchange through the Adaptation Layer

This section will provide a detailed explanation of the data flow in the operations performed by the AL. Using the different Message Sequence Charts (MSCs) defined, the diverse messages exchanged by QoSMOS entities within the Adaptation Layer can be depicted.

6.2.1.2.1 Entity registration

The **registration** process is the first step that must be done by all the QoSMOS entities interested in requesting/providing information through the AL. The following Table 20 and Figure 17 represent the messages needed to create the link between the QoSMOS entity and the AL.

Table 20: Primitives in the registration process

Name	From	To	Description
AL1x_Q1REG_INFOX.REQ	Q1	QoSMOS_ALEND	QoSMOS entity contacts the AL in order to use it
ALE#1_Q1REG_INFOX.REQ	QoSMOS_ALEND	ALEND_ALCORE	AL_END creates the message needed to register it into the AL
ALCE_Q1REG_INFOX.REQ	ALEND_ALCORE	ALCORE_PROC	The MSG is processed, and its information evaluated so as to update the different components of the AL.
ALC#1_Q1REG_INFOX.REQ	ALCORE_PROC	ALCORE_DB	Informs the DB about the actions to do
ALC#1_Q1REG_INFOX.ACK	ALCORE_DB	ALCORE_PROC	Confirm the correct update of the DB
ALC#2_Q1REG_INFOX.ACK	ALCORE_PROC	ALCORE_DISP	Prepare the confirmation MSG of the registration process of the new entity
ALCE_Q1REG_INFOX.ACK	ALCORE_DISP	ALEND_ALCORE	Send back the confirmation MSG to the AL_END
ALE#1_Q1REG_INFOX.ACK	ALEND_ALCORE	QoSMOS_ALEND	Send the message to the requester entity
AL1x_Q1REG_INFOX.ACK	QoSMOS_ALEND	Q1	Final delivery of the AL response to the query
ALC#1_INFO_DETAILS.REQ	ALCORE_PROC	ALCORE_DB	Once registered it is needed to provide the information about its needs
ALC#1_INFO_DETAILS.RSP	ALCORE_DB	ALCORE_PROC	Information obtained from the DB to be included in a MSG
ALC#2_INFO_DETAILS.IND	ALCORE_PROC	ALCORE_DISP	Prepare the MSG with the needed information to be sent to the new entity
ALCE_INFO_DETAILS.IND	ALCORE_DISP	ALEND_ALCORE	Send back the confirmation MSG to the AL_END
ALE#1_INFO_DETAILS.IND	ALEND_ALCORE	QoSMOS_ALEND	Send the message to the requester entity
AL1x_INFO_DETAILS.IND	QoSMOS_ALEND	Q1	Final delivery of the information to the new entity

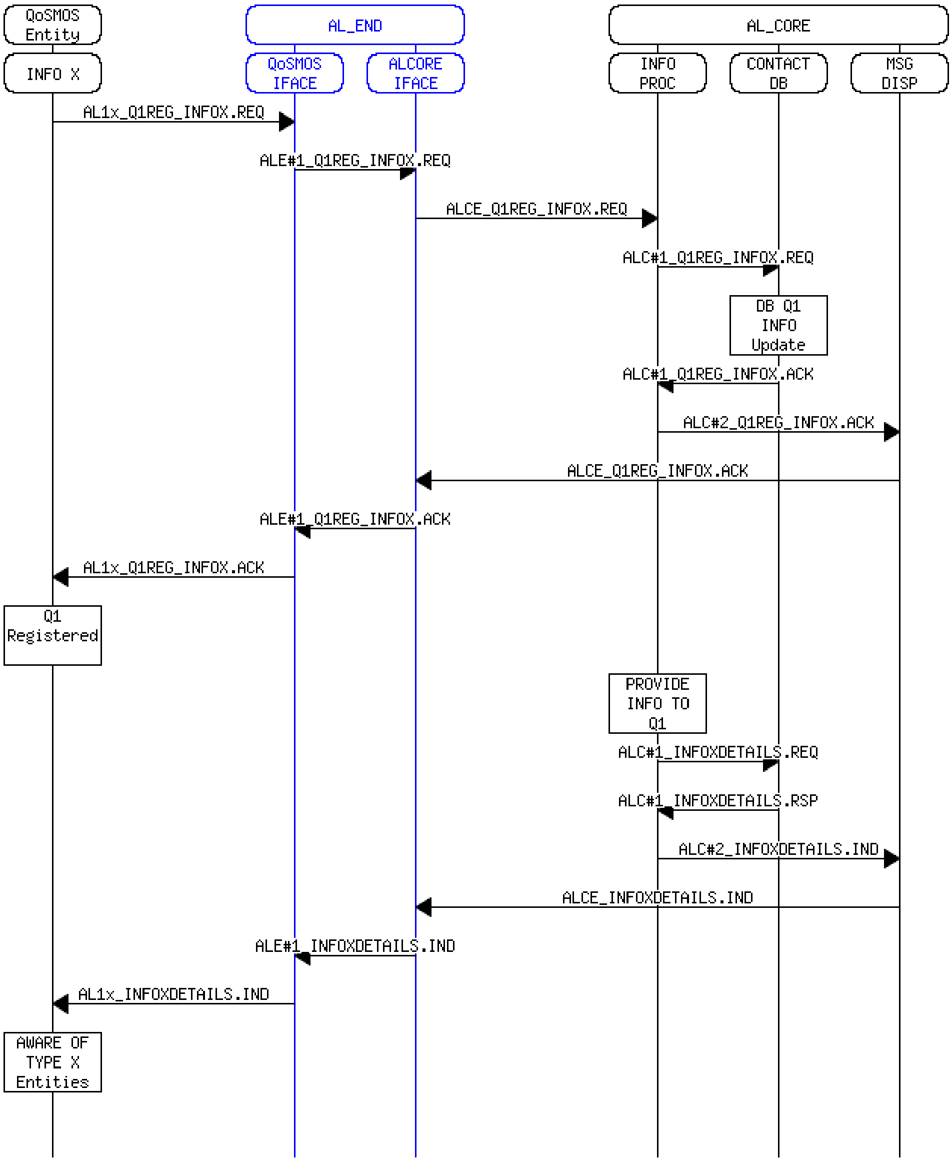


Figure 17: New QosMOS entity connected to the AL

One of the most important aspects of entity registration is the process of informing new entries about the different entities sharing information of the same class, thus offering the possibility of establishing a first link by the AL.

6.2.1.2.2 Entity deregistration

The following message sequence chart (Figure 18) depicts the message exchange between the different Adaptation Layer blocks in case of **deregistration**. Table 21 shows the content and scope of each message included in this process.

Table 21: Primitives in the deregistration procedure

Name	From	To	Description
AL1x_Q1DEREG.REQ	QoSMOS_ALEND	QoSMOS_ALEND	QoSMOS entity contacts the AL in order to use it
ALE#1_Q1DEREG.REQ	ALEND_RCV	ALEND_ALCORE	AL_END creates the message needed to deregister it in the AL
ALCE_Q1DEREG.REQ	ALEND_ALCORE	ALCORE_PROC	The MSG is processed, and its information evaluated so as to update the different components of the AL.
ALC#1_Q1DEREG.REQ	ALCORE_PROC	ALCORE_DB	Informs the DB about the actions to do
ALC#1_Q1DEREG.ACK	ALCORE_DB	ALCORE_PROC	Confirm the correct update of the DB
ALC#2_Q1DEREG.ACK	ALCORE_PROC	ALCORE_DISP	Prepare the confirmation MSG of the deregistration process of the new entity
ALCE_Q1DEREG.ACK	ALCORE_DISP	ALEND_ALCORE	Send back the confirmation MSG to the AL_END
ALE#1_Q1DEREG.ACK	ALEND_ALCORE	QoSMOS_ALEND	Send the message to the requester entity
AL1x_Q1DEREG.ACK	QoSMOS_ALEND	Q1	Final delivery of the AL response to the query

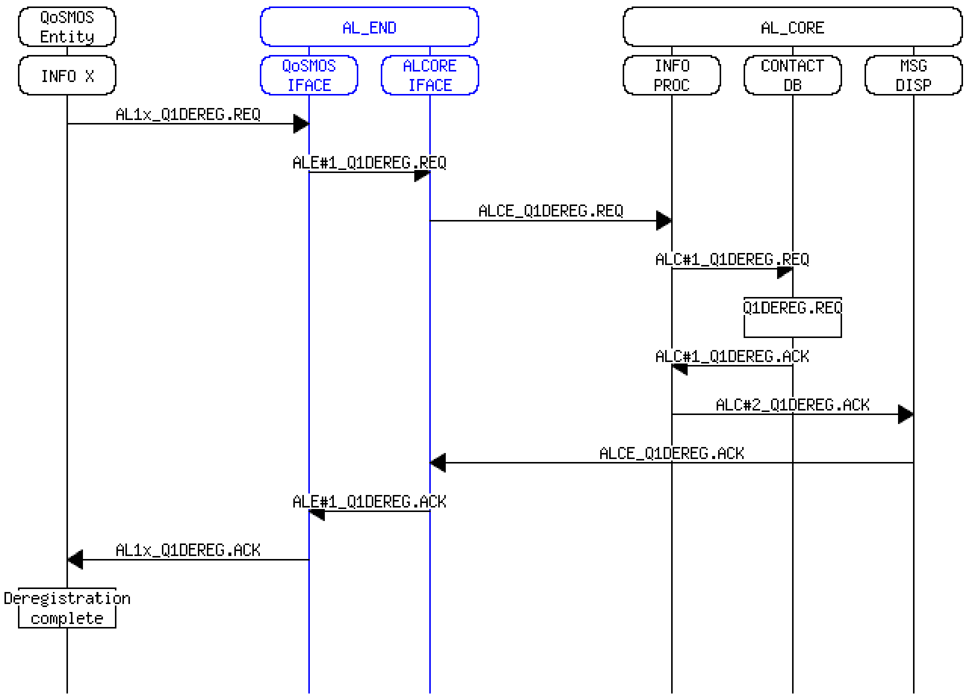


Figure 18: Entity Deregistration

It is also important to note that the deregistration process implies the update of the information contained in the Contactable Entities DB. In order to assure the freshness of the information stored,, all nodes interacting with the deregistered block should received a packet notifying the changes. Therefore when an entity disappears, all the interested nodes will update their providers/subscribers contacts due to the event triggered. These two processes, event subscription and event triggering, will be explained in sections 6.2.1.2.5 and 6.2.1.2.6.

6.2.1.2.3 Context User Provider/Requester

The activity of QoSMOS entities could be dynamic and the need of information could vary along their life. This fact implies demanding the AL the existence of a procedure capable of updating the data requested or provided to the different entities that can be contacted through the AL. Figure 19 and Figure 20 show how these procedures are carried out, and Table 22 describes the steps made to execute the provisioning action.

Table 22: Primitives in the Context User Provider procedure

Name	From	To	Description
AL1x_PROVIDE_INFOZ.IND	Q1	QoSMOS_ALEND	QoSMOS entity contact to the SAP to the AL to announce the info provisioning.
ALE#1_PROVIDE_INFOZ.IND	QoSMOS_ALEND	ALEND_ALCORE	AL_END creates the message needed to warn about this info provisioning
ALCE_PROVIDE_INFOZ.IND	ALEND_ALCORE	ALCORE_PROC	The MSG is processed, and its information evaluated so as to update the different components of the AL.
ALC#1_PROVIDE_INFOZ.IND	ALCORE_PROC	ALCORE_DB	Informs the DB about the actions to do
ALC#1_PROVIDE_INFOZ.ACK	ALCORE_DB	ALCORE_PROC	Confirm the correct update of the DB
ALC#2_PROVIDE_INFOZ.ACK	ALCORE_PROC	ALCORE_DISP	Prepare the confirmation MSG of the info provisioning process of the new entity
ALCE_PROVIDE_INFOZ.ACK	ALCORE_DISP	ALEND_ALCORE	Send back the confirmation MSG to the AL_END
ALE#1_PROVIDE_INFOZ.ACK	ALEND_ALCORE	QoSMOS_ALEND	Send the message to the requester entity
AL1x_PROVIDE_INFOZ.ACK	ALEND_SND	Q1	Final delivery of the AL response to the query

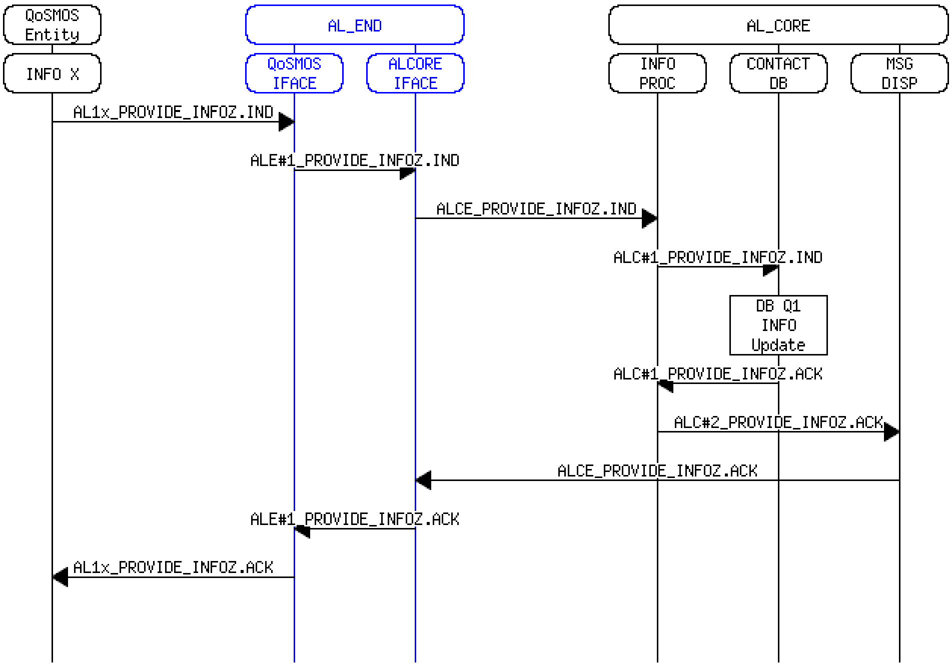


Figure 19: Context User Provider procedure

Mostly the same messages will be exchanged during a Context User Requester process, where the main difference lies in the content of the message sent by the QoSMOS Entity that initiates the communication. In this case, the information flow is exactly the same than in the previous case.

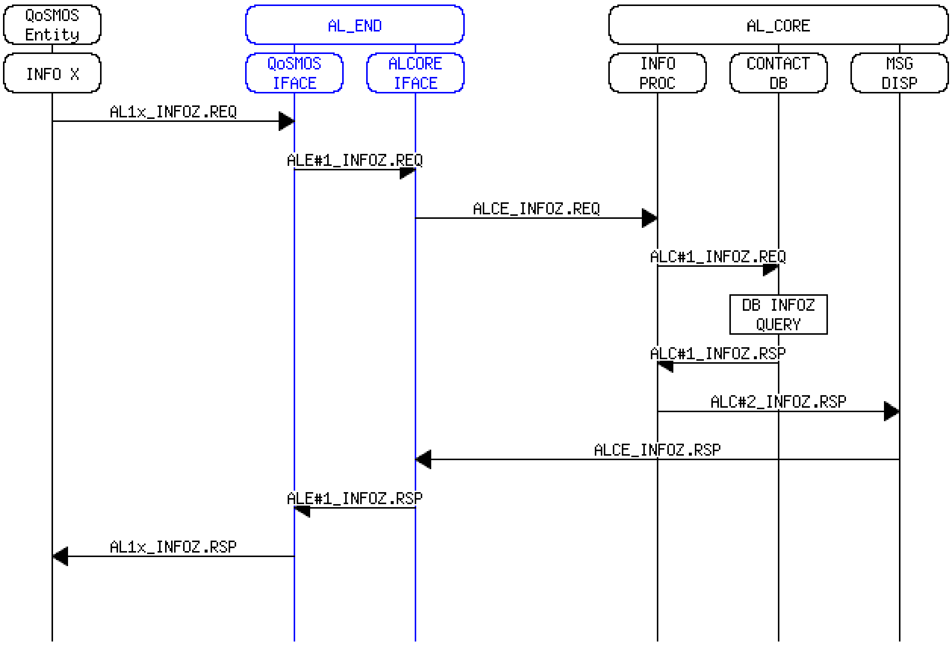


Figure 20: Context User Requester

6.2.1.2.4 Keep Alive

The MSC shown in Figure 21 displays the actions that take place the moment a **Keep Alive** message is delivered to the AL. Periodically, all QoSMOS entities registered in the AL must send a message informing about their availability. This message just inform about the status of the node and the connection in order to keep an updated Contactable DataBase. The flow is presented in Table 23 and depicted in Figure 21.

Table 23: Primitives in the Keep Alive procedure

Name	From	To	Description
AL1x_Q1ALIVE.IND	Q1	QoSMOS_ALEND	QoSMOS entity sends the alive indication to the AL.
ALE#1_Q1ALIVE.IND	QoSMOS_ALEND	ALEND_ALCORE	AL_END evaluates the message and forward it to the AL_CORE.
ALCE_Q1ALIVE.IND	ALEND_ALCORE	ALCORE_PROC	The MSG is processed, and its information evaluated so as to update the components of the AL.
ALC#1_Q1ALIVE.IND	ALCORE_PROC	ALCORE_DB	Informs the DB about the actions to do
ALC#1_Q1ALIVEUPDATE.ACK	ALCORE_DB	ALCORE_PROC	Confirm the correct update of the DB
ALC#2_Q1ALIVEUPDATE.ACK	ALCORE_PROC	ALCORE_DISP	Prepare the confirmation MSG of the info provisioning process of the new entity
ALCE_Q1ALIVEUPDATE.ACK	ALCORE_DISP	ALEND_ALCORE	Send back the confirmation MSG to the AL_END
ALE#1_Q1ALIVEUPDATE.ACK	ALEND_ALCORE	QoSMOS_ALEND	Send the message to the requester entity
AL1x_Q1ALIVEUPDATE.ACK	QoSMOS_ALEND	Q1	Final delivery of the AL response to the query

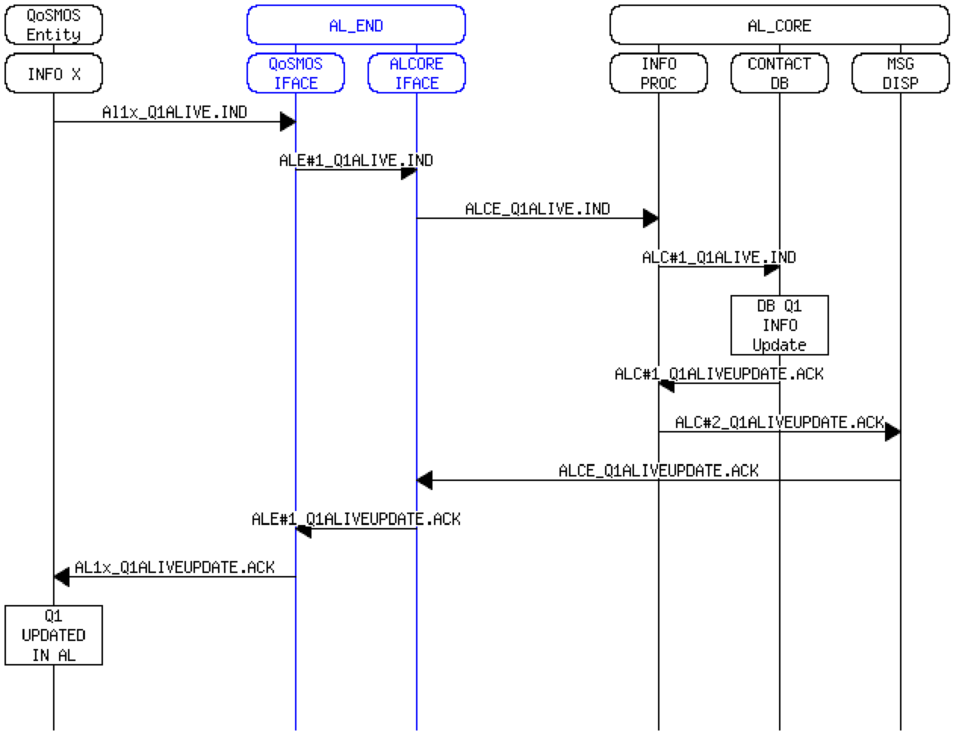


Figure 21: Keep Alive message to the AL

If the AL does not receive a keep alive message from a node during a fixed period of time, it will start a contact process, in case of not succeeding, the deregistration process will be launched by the AL, triggering an event informing about the disappearance of that entity.

6.2.1.2.5 Event subscription

As previously stated, it is mandatory to provide an event subscription procedure in order to allow entities to be immediately updated when some specific action occurs. The way to proceed is presented in Figure 22, and properly explained in Table 24.

Table 24: Primitives in the Event subscription procedure

Name	From	To	Description
AL1x_EVENT_SUBS.REQ	Q1	QoSMOS_ALEND	QoSMOS entity contact to the SAP to the AL to ask for an event subscription.
ALE#1_EVENT_SUBS.REQ	QoSMOS_ALEND	ALEND_ALCORE	AL_END creates the message needed to warn about this event subscription.
ALCE_EVENT_SUBS.REQ	ALEND_ALCORE	ALCORE_PROC	The MSG is processed, and its information evaluated so as to update the different components of the AL.
ALC#1_EVENT_SUBS.REQ	ALCORE_PROC	ALCORE_DB	Informs the DB about the actions to do

ALC#1_EVENT_SUBS.ACK	ALCORE_DB	ALCORE_PROC	Confirm the correct update of the DB
ALC#2_EVENT_SUBS.ACK	ALCORE_PROC	ALCORE_DISP	Prepare the confirmation MSG of event subscription process.
ALCE_EVENT_SUBS.ACK	ALCORE_DISP	ALEND_ALCORE	Send back the confirmation MSG to the AL_END
ALE#1_EVENT_SUBS.ACK	ALEND_ALCORE	QoSMOS_ALEND	Send the message to the requester entity
AL1x_EVENT_SUBS.ACK	QoSMOS_ALEND	Q1	Final delivery of the AL response to the query

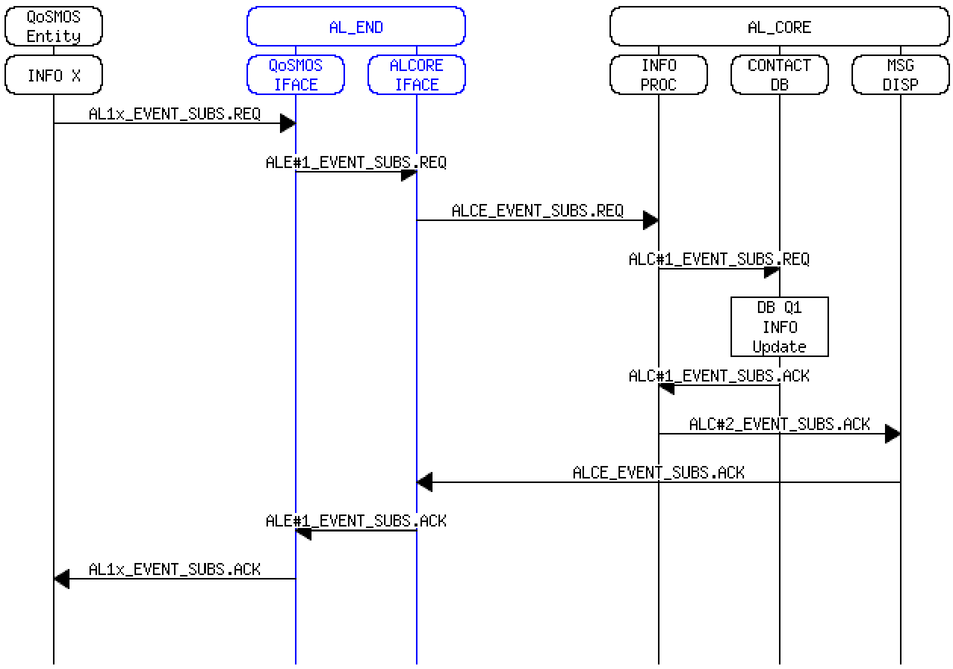


Figure 22: Event subscription procedure

6.2.1.2.6 Event triggering

The aforementioned events have to be initiated in a specific way. Once an event is triggered the entities interested in that specific situation should be updated in the shortest time possible. Table 25 and Figure 23 explain how this process is performed overcome by the AL.

Table 25: Primitives in the Event triggering procedure

Name	From	To	Description
ALC#1_EVENTXDETAILS.REQ	ALCORE_PROC	ALCORE_DB	AL_CORE asks for details of the event to its Database
ALC#1_EVENTXDETAILS.RSP	ALCORE_DB	ALCORE_PROC	AL_CORE Database sends event details to INFO PROC
ALC#2_EVENTXDETAILS.IND	ALCORE_PROC	ALCORE_DISP	The MSG is processed, and its information

			evaluated so as to update the different components of the AL.
ALCE_EVENTXDETAILS.IND	ALCORE_DISP	ALEND_ALCORE	AL_CORE sends the indication of events MSG to the AL_END
ALE#1_EVENTXDETAILS.IND	ALEND_ALCORE	QoSMOS_ALEND	Send the MSG to the proper entity
AL1x_EVENTXDETAILS.IND	QoSMOS_ALEND	Q1	Final delivery of the AL response to the query

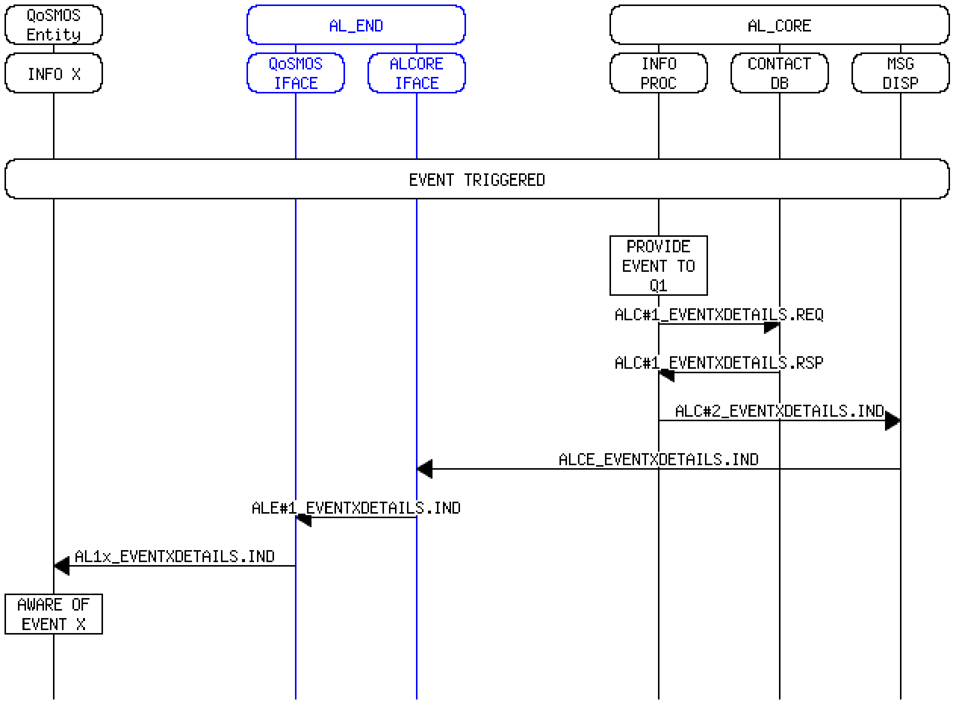


Figure 23: Event triggering procedure in the AL

6.2.1.2.7 Data exchange through AL

Finally, Figure 24 gives a view on the messages exchanged during the process employed to **send a data packet** through the AL. A certain QoSMOS Entity wants to send a message and informs its AL_END about it. This AL_END will be in charge of formatting the data before proceeding with its dissemination to the AL_CORE, where INFO PROC will check which entities in the system could be interested in receiving this information, and sends a REQUEST to the CONTACT DB where it warns about the type of information subscribed. The moment INFO PROC receives a RESPONSE from the CONTACT DB, it sends the message to the SEND block that will be responsible of disseminating this information to all the QoSMOS Entities interested in it, reaching them through their respective AL_ENDs.

The AL_ENDs have to parse the data before submitting it to their attached entities. The moment they receive properly the information, send back to the AL_END and ACK which will be destined to the

AL_CORE, that as a final step of the process shall inform of the success of the operation to the QoSMOS Entity that originated the message exchange.

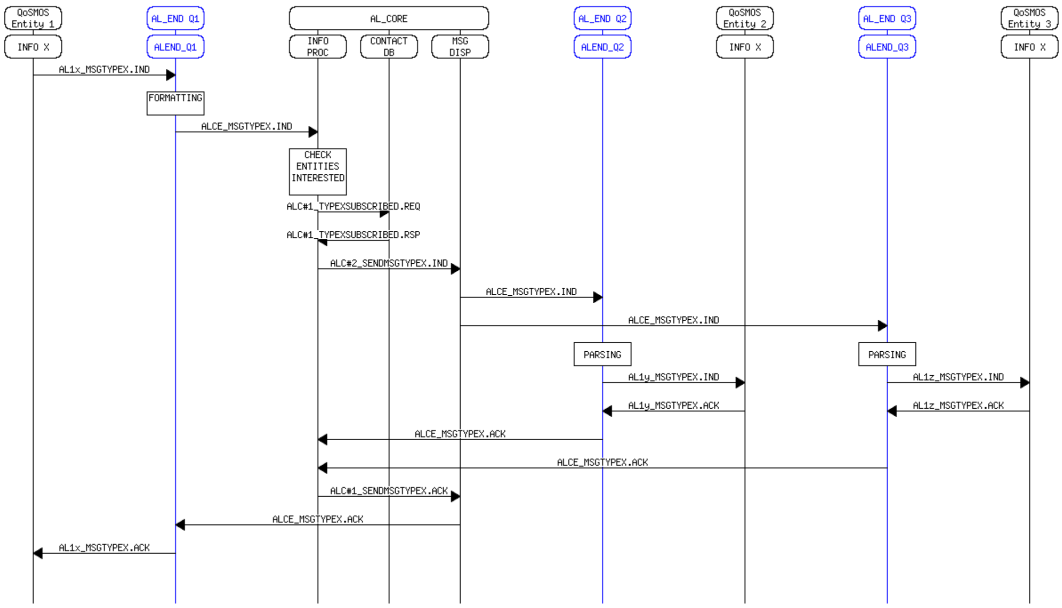


Figure 24: Data Packet sent through the AL

6.3 Interference monitoring for Incumbent Protection

Incumbent protection is a key requirement for the opportunistic spectrum access. The basics of the procedures for the incumbent protection have been addressed in [D2.2]: initial decision; eviction decision requirement; channel switching; Tx power reduction; QoS degradation; forced handover; and dropping of users. As an amendment, this section describes an updated procedure for the interference monitoring which is a part of the "Cellular Extension" QoSMOS scenario.

The interference monitoring is the process of measuring the possible interference level at the incumbent receiver, which aims at adjusting the transmission parameters (e.g., transmission power) at the operating AP to adapt a changing transmission environment [D3.2]. The monitoring will be performed at the monitoring nodes near the incumbent receiver. Figure 25 shows two phases of procedures for the interference monitoring: the preparation phase; and the running phase. The preparation phase is for each AP which has monitoring capability to register its sensor information to the portfolio repository. This is supposed to be done when an AP is set up in the system. When an AP is newly installed the new sensor information can be registered also by this message, even if other monitoring nodes have been doing the interference monitoring as in the running phase.

In the running phase, the CM-SM in the AP can request the CM-SM in the core network to identify neighbouring APs which is located near the incumbent receiver and could perform interference measurements. The CM-SM in the core network may further send the portfolio repository the inquiries for the candidate APs for the measurements. After identifying the potential "Monitoring Node APs," the CM-SM in the core network sends them a sensing measurement request so that these APs start monitoring interferences. The reports are sent back to the CM-SM in the core network. After receiving the measurement results, the CM-SM estimates CIR at the incumbent receiver and updates allowable transmit power of the opportunistic transmission. According to the updated allowable transmit power, CM-RM in the operating AP updates transmission parameters such as transmit power and/or channel to use, etc. These informations are sent back to the CM-SM in the core network and also stored in the portfolio.

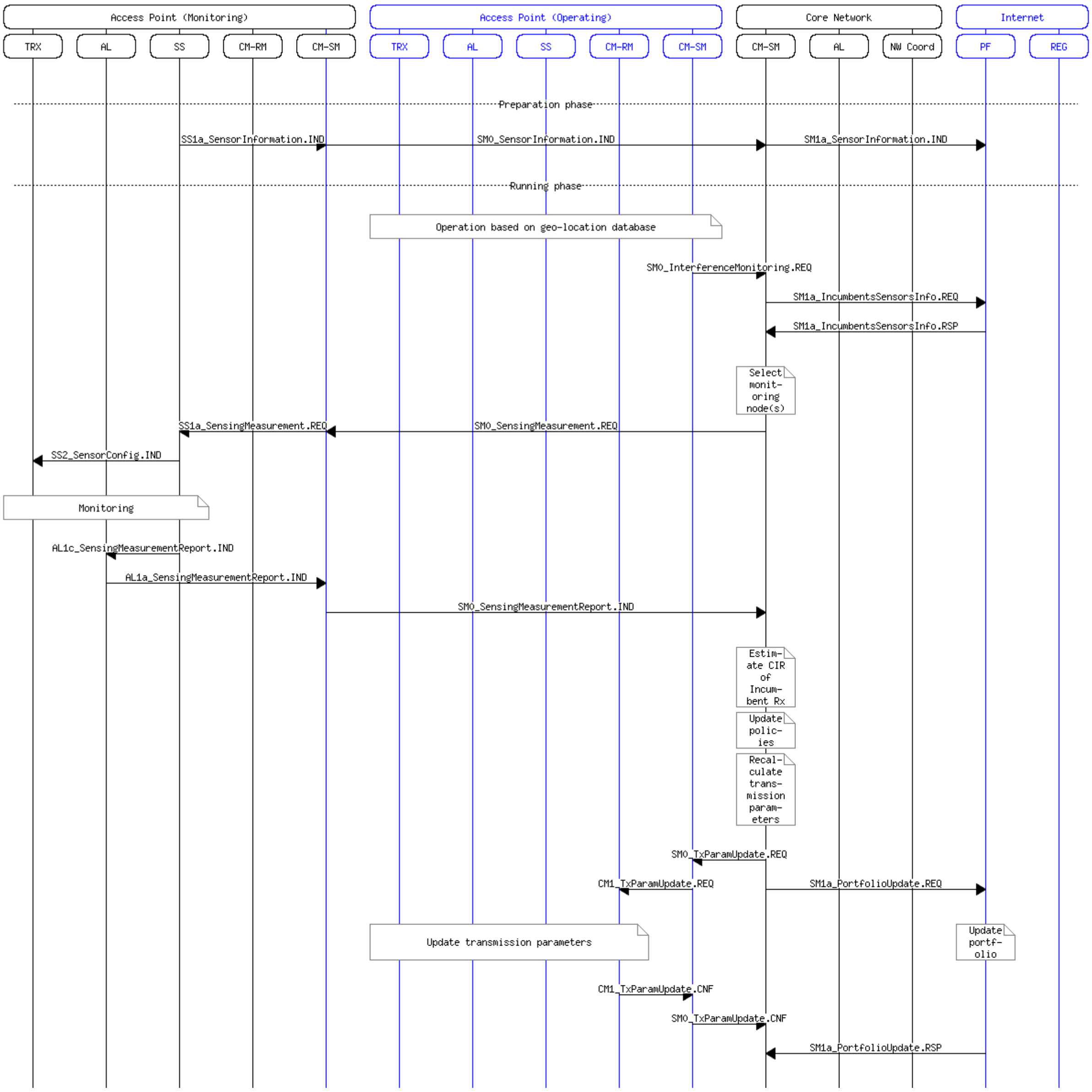


Figure 25: Procedures for Interference Monitoring

Table 26 lists the primitives involved in this procedure.

Table 26: Primitives involved in Interference Monitoring

Primitive name	Source	Destination	Description
SS1a_SensorInformation.IND	SS	CM-SM	Notify the local CM-SM in the AP about the sensor position and interference monitoring capability.
SM0_SensorInformation.IND	CM-SM	CM-SM	Notify the CM-SM in the CN about the sensor position and

			interference monitoring capability.
SM1a_SensorInformation.IND	CM-SM	PF	Register the sensor information on its position and measurement capability.
SM0_InterferenceMonitoring.REQ	CM-SM	CM-SM	Request the master CM-SM in the CN for initiating interference monitoring.
SM1a_IncumbentSensorsInfo.REQ	CM-SM	PF	Request the PF about the candidate nodes for interference monitoring.
SM1a_IncumbentSensorsInfo.RSP	PF	CM-SM	Respond to the CM-SM about the candidate nodes for interference monitoring.
SM0_SensingMeasurement.REQ	CM-SM	CM-SM	Request the monitoring node to perform interference measurements.
SS1a_SensingMeasurement.REQ	CM-SM	SS	Request the sensor to perform interference measurements.
SS2_SensingMeasurement.REQ	SS	TRX	Request the actual transceiver to perform interference measurements.
AL1c_SensingMesurementReport.IND	SS	AL	Report the interference measurement results from the sensor.
AL1a_SensingMesurementReport.IND	AL	CM-SM	Inform the local CM-SM in the AP about the interference measurement results.
SM0_SensingMesurementReport.IND	CM-SM	CM-SM	Inform the master CM-SM in the CN about the interference measurement results.
SM0_TxParamUpdate.REQ	CM-SM	CM-SM	Request the operating node CM-SM to update transmission parameters according to the interference monitoring results.
CM1_TxParamUpdate.REQ	CM-SM	CM-RM	Request the operating node CM-RM to update transmission parameters according to the interference monitoring results.
CM1_TxParamUpdate.CNF	CM-RM	CM-SM	Acknowledge that CM-RM updates the transmission parameters.
SM0_TxParamUpdate.CNF	CM-SM	CM-SM	Report the acknowledgement of the updates in the transmission parameters in the operating node.
SM1a_PortfolioUpdate.REQ	CM-SM	PF	Request the PF to record the updates made in the operating node.

SM1a_PortfolioUpdate.RSP	PF	CM-SM	Acknowledge to the CM-SM that the PF updated accordingly.

6.4 Load balancing and incumbent protection in heterogeneous environment

The way of taking advantage of a heterogeneous RATs environment for load balancing and incumbent protection has been introduced in section 4.4.

This procedure can be divided in three steps: the first step is the detection and the evaluation of the quality of the various RATs; the second one takes the load balancing decisions; and the last one executes the handover decisions.

The two first steps are illustrated by Figure 26 and Figure 27 resp. which address the Centralized Resource Control architecture operating with a core network for the QoSMOS cellular scenario. The third step refers to handover procedures that have already been described in [D2.2].

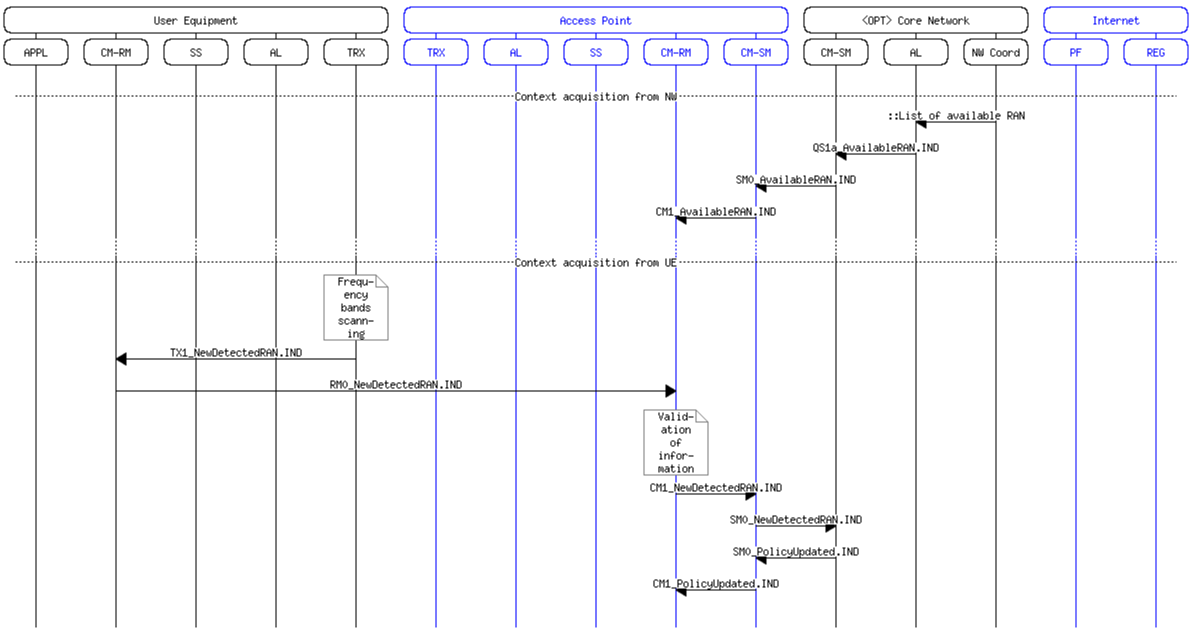


Figure 26: Detection and evaluation of heterogeneous RAN

In Figure 26, the list of available RATs is maintained by NW_Coord entity in the core network: This entity is aware of the existing agreements with neighbour infrastructures but also has a detailed knowledge of the various RATs it has deployed. This information is then processed by the CM-SM located in the CN which extracts the content appropriate to each Access Point, and enriches it with the operator policies it is aware of. The data is then sent to the CM-SM entity located in the AP which transfers it to the co-localised CM-RM entity.

In parallel, the user equipment (UE) may scan the frequency bands to find unknown RATs (e.g. Wi-Fi access points). This operation is controlled by the CM-RM located in the UE and its results are reported to CM-RM located in the AP, which validates the presence of the new RAT by collecting and cross-checking the information from several sources (i.e. from neighbour access points, core network or CM-SM). A notification is then sent back to the CM-SM, which in return indicates the operator policies relative to the new RAT(s).

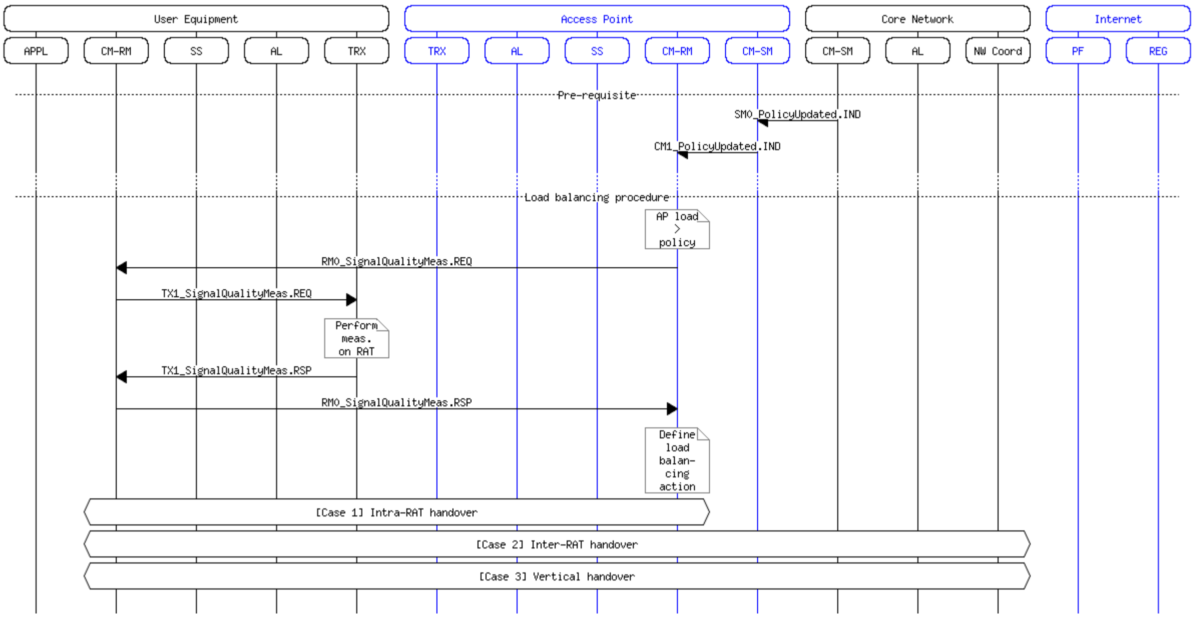


Figure 27: Load balancing procedure

The load balancing procedure is triggered when the AP load exceeds the limitation defined by the operator policy. In this case, the AP selects the UE(s) to handover and requests them to perform signal quality measurements in order to evaluate the possible solutions. Then it initiates the handover procedure (intra-RAT, inter-RAT or inter-system) to the targeted AP that would provide the best QoS.

Table 27 lists and briefly describes the primitives involved in this procedure. The parameters associated to these primitives are defined in the Appendix (section 8.2).

Table 27: Primitives involved in the Load Balancing procedure

Primitive name	Source	Destination	Description
QS1a_AvailableRAT.IND	AL	CM-SM	Notify QoSMOS system about the available RATs.
SM0_PolicyUpdated.IND	CM-SM	CM-SM	Provide updated usage policies (operator policies, regulator policies …).
SM0.AvailableRAT.IND	CM-SM	CM-SM	Notify the access point about the RATs available in its vicinity.
SM0_NewDetectedRAT.IND	CM-SM	CM-SM	Inform CM-SM about the detected RATs.
CM1_PolicyUpdated.IND	CM-SM	CM-RM	Provide usage policies applicable to the access point.
CM1.AvailableRAT.IND	CM-SM	CM-RM	Notify CM-RM about the RAT(s) available in its vicinity.
CM1_NewDetectedRAT.IND	CM-RM	CM-SM	Inform local CM-SM about the RAT(s) detected in the access point vicinity.

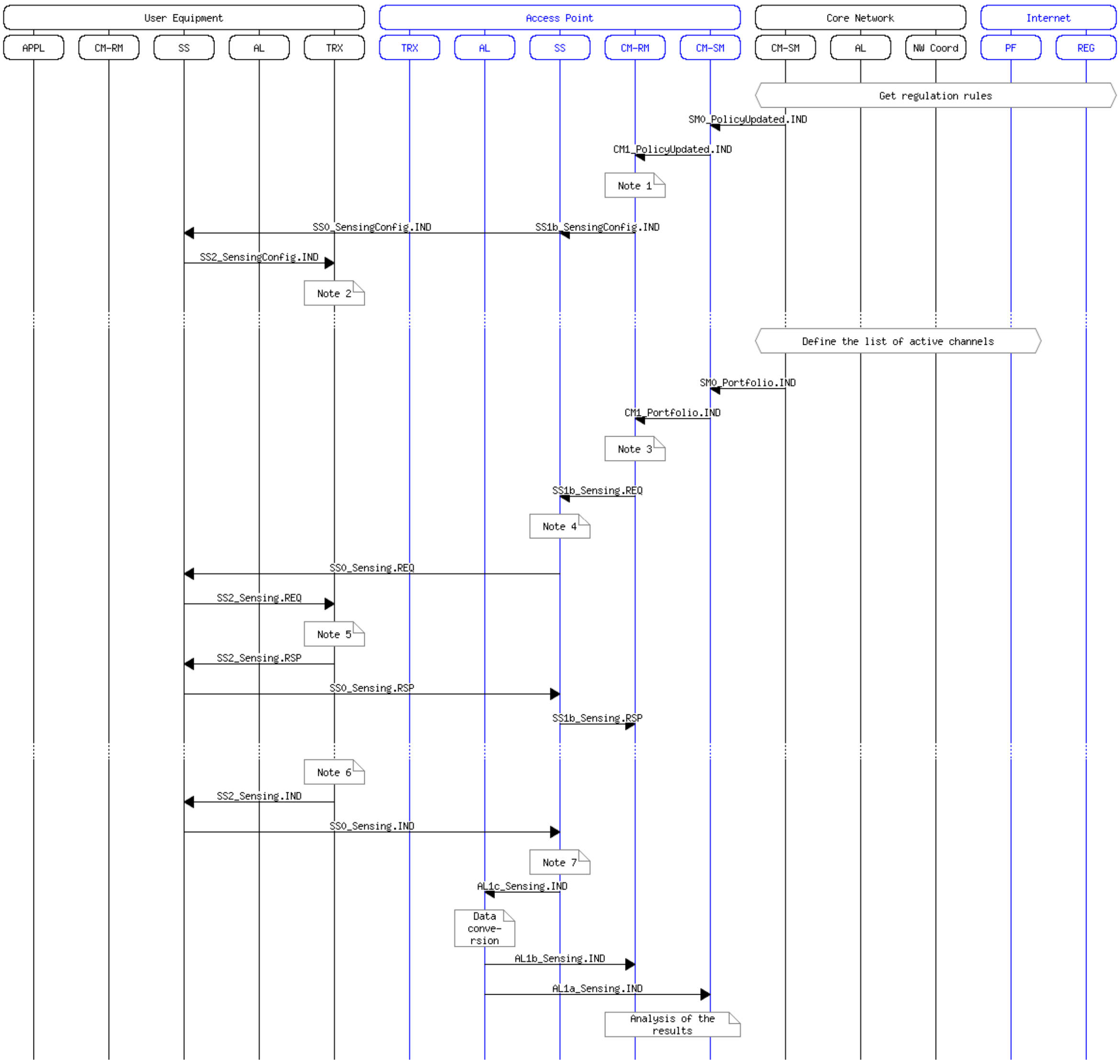
RM0_SignalQualityMeas.REQ	CM-RM	CM-RM	Request the deployed nodes to perform measurements on the available RAT.
RM0_SignalQualityMeas.RSP	CM-RM	CM-RM	Return measurement results relative to the available RAT.
RM0_NewDetectedRAT.IND	CM-RM	CM-RM	Notify centralised CM-RM about new detected RAT by a deployed node.
TX1_SignalQualityMeas.REQ	CM-RM	TRX	Request TRX to execute signal quality measurements.
TX1_SignalQualityMeas.RSP	TRX	CM-RM	Return signal quality measurements results.
TX1_NewDetectedRAT.IND	TRX	CM-RM	Inform local CM-RM about new detected RAT(s).

6.5 Management of Sensing measurements

The overall operations performed for the different modes of Spectrum Sensing by the QoSMOS system have been described in chapter of [D2.2]. In this section the management of measurements for the Sensing procedures will be further detailed by means of the MSCs for in-band sensing and for out-of-band sensing.

In the example depicted in Figure 28, in-band sensing measurements are requested by the CM-RM to detect the incumbent users communicating in the active channels defined by the CM-SM through the Spectrum Portfolio. The CM-RM entity is in charge of requesting the active sensing measurements from the SS entity, defining the measurements' reports at a pre-determined periodicity. The CM-RM also analyses the policies sent by the CM-SM for scheduling the data transmission according to the specified quiet periods.

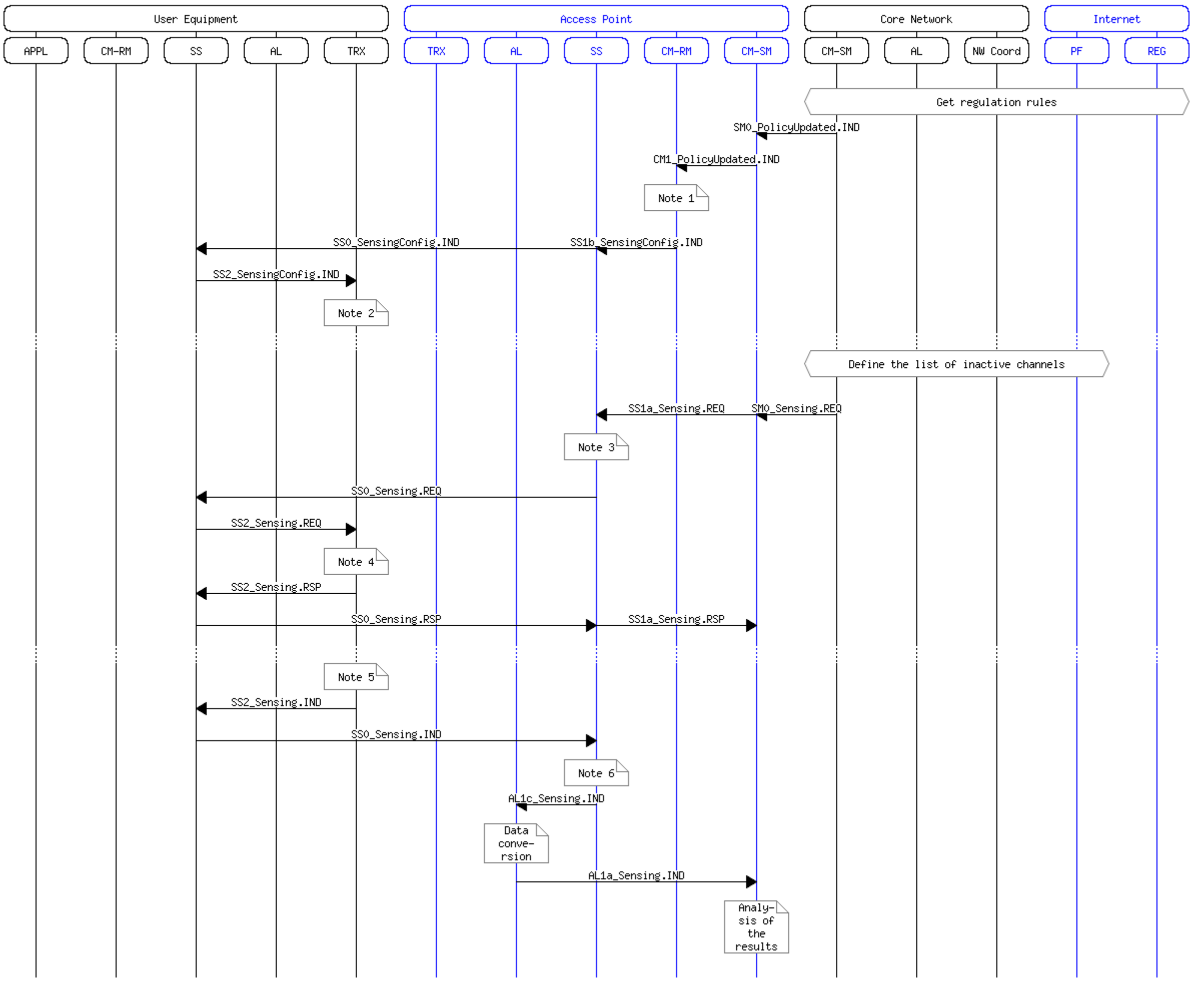
Upon the reception of the measurements' request, the SS entity determines the most appropriate nodes where to perform these sensing measurements, and for each of them the method to be used (collaborative or cooperative) as well as the periodicity, the duration and the range of frequencies. It is then up to the TRX to execute the measurements during the quiet periods (pre-defined or not) and to report the results to the SS entity according to the requested periodicity. The results are sent back to the CM-RM entity through the AL adaptation layer which performs the data conversion and dispatches the results to both the CM-RM and the CM-SM entities.



Note 1	*CM-RM determines the transmission gap pattern.*
Note 2	*TRX schedules the transmission gaps.*
Note 3	*CM-RM defines the operating and reserve channels and determines the reporting periodicity.*
Note 4	*SS selects the sensing nodes. It determines the frequencies to be monitored, the measurements periodicity and duration and then, selects the sensing algorithm to apply.*
Note 5	*TRX schedules the sensing measurements.*
Note 6	*TRX executes and then reports the in-band sensing measurements.*
Note 7	*SS perform the fusion and the analysis of measurements results.*

Figure 28: In-band sensing measurements

The control of out-of-band sensing measurements is quite similar to the in-band sensing case except than the measurement request can come from the CM-SM as well in order to monitor inactive channels. This is illustrated in Figure 29.



Note 1	*CM-RM determines the transmission gap pattern.*
Note 2	*TRX schedules the transmission gaps.*
Note 3	*CM-RM defines the operating and reserve channels and determines the reporting periodicity.*
Note 4	*SS selects the sensing nodes. It determines the frequencies to be monitored, the measurements periodicity and duration and then, selects the sensing algorithm to apply.*
Note 5	*TRX schedules the sensing measurements.*
Note 6	*TRX executes and then reports the in-band sensing measurements.*
Note 7	*SS perform the fusion and the analysis of measurements results.*

Figure 29: Out-of-band sensing measurements

The primitives involved in the procedures for sensing measurements as described above are listed in Table 28.

Table 28: Primitives involved in sensing measurement

Primitive name	Source	Destination	Description
SM0_PolicyUpdated.IND	CM-SM	CM-SM	Indicate new updated policies
SM0_Portfolio.IND	CM-SM	CM-SM	Indicate new portfolio to deploy
SM0_Sensing.REQ	CM-SM	CM-SM	Request sensing measurement on

			inactive channels.
CM1_PolicyUpdated.IND	CM-SM	CM-RM	Indicate new updated policies
CM1_Portfolio.IND	CM-SM	CM-RM	Indicate new portfolio to deploy
SS1a_Sensing.REQ	CM-SM	SS	Request to perform sensing measurement for inactive channels
SS1a_Sensing.RSP	SS	CM-SM	Confirm reception of the measurement request
SS1b_Sensing.REQ	CM-RM	SS	Request to perform sensing measurement for active channels
SS1b_SensingConfig.IND	CM-RM	SS	Indicate configuration information for sensing measurements (i.e. idle periods)
SS1b_Sensing.RSP	SS	CM-RM	Confirm reception of the measurement request
SS0_SensingConfig.IND	SS	SS	Indicate configuration information for sensing measurements (i.e. idle periods)
SS0_Sensing.REQ	SS	SS	Request to perform sensing measurement
SS0_Sensing.RSP	SS	SS	Confirm reception of the measurement request
SS0_Sensing.IND	SS	SS	Provide sensing measurements results
SS2_SensingConfig.IND	SS	TRX	Indicate configuration information for sensing measurements (i.e. idle periods)
SS2_Sensing.REQ	SS	TRX	Request to perform sensing measurement
SS2_Sensing.RSP	TRX	SS	Confirm reception of the measurement request
SS2_Sensing.IND	TRX	SS	Provide sensing measurements results
AL1a_Sensing.IND	AL	CM-SM	Provide sensing measurements results after data conversion
AL1b_Sensing.IND	AL	CM-RM	Provide sensing measurements results after data conversion
AL1c_Sensing.IND	SS	AL	Request data conversion and data dispatching

7 Conclusions & outlook

First results of the work reported in this QoSMOS deliverable concern the refinement of the QoSMOS reference model leading to a selection of architecture options which can be applied to the scenarios envisaged in the project and to the Proof of Concepts to be developed. These are based on the topologies' combinations "Centralised resource control with centralised spectrum sensing" and "Distributed resource control with distributed spectrum sensing" which will be in the focus of future architecture work in the project.

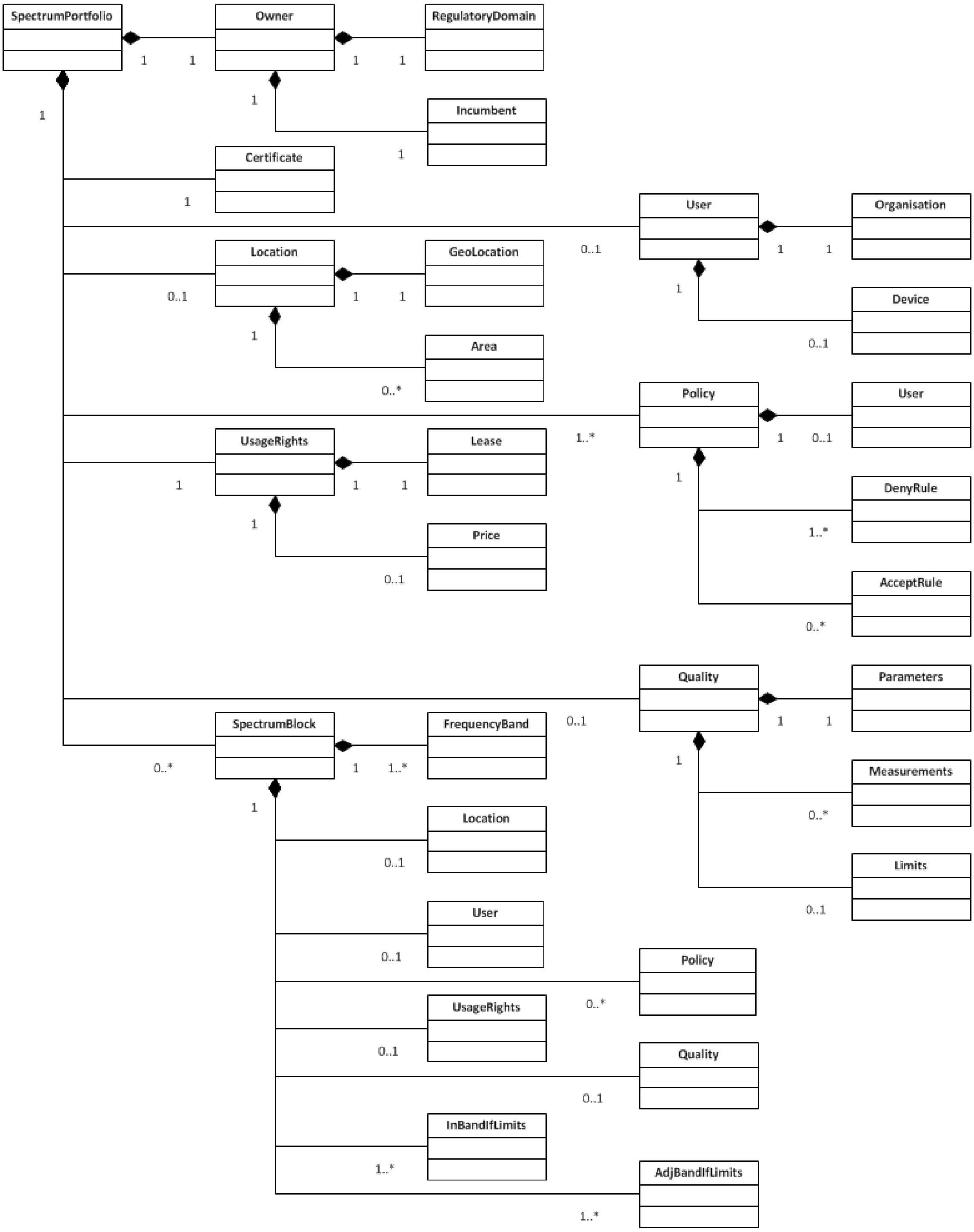
Addressing the overall specification of the QoS system the interaction between CM-RM and CM-SM will be based on the cascaded organization of the cognitive managers when exchanging the Spectrum Portfolio for which a Top Level design layout is given which will be further developed for implementation needs. The detailed specification of the Adaptation Layer as a media independent layer ensuring the communications between the QoSMOS system entities based on Service Access Points is achieved by means of its functionalities and internal architecture as well as the MSCs, primitives' layouts and data structures which will allow its implementation in the Proof of Concepts foreseen in the project.

The definition of the transceiver characteristics result from the reported discussion on the propagation models and link budget models selected for the QoSMOS scenarios from the Physical layer point of view. This will serve the subsequent work for implementation and performance assessment in the project in order to confirm the feasibility of the estimations made for the mean achievable communication ranges.

Finally a reference incumbent environment based on digital terrestrial TV broadcasting network and mobile wireless microphones defines the assessment conditions and the constraints for the overall performance evaluation of each QoSMOS scenario considered in the Proof of Concept work. This is completed by the definition of system performance metrics categorized in spectrum utilization and service performance which will be implemented in the next step.

8 Appendix

8.1 Example of Spectrum Portfolio layout



8.2 Description of the primitives involved in the Load Balancing procedure

8.2.1 QS1a interface

Primitive name:	QS1a_AvailableRAT.IND
Source:	*AL*
Destination:	*CM-SM*
When generated:	*Each time the Core Network is informed about the presence of a new RAT in its vicinity.*
Effect on receipt:	*Derive for each deployed access point the list of available RATs applicable to their coverage.*
Parameters	**Description**
NbOfAvailableRAT	*Indicate the number of available RATs in the system vicinity.*
ListOfAvailableRAT	*List of available RATs, describing the used technology, the operating frequency, the geographical coverage.*

8.2.2 CM1 interface

Primitive name:	CM1.AvailableRAT.IND
Source:	*CM-SM*
Destination:	*CM-RM*
When generated:	*Upon reception of QS1a_AvailableRAT.IND.*
Effect on receipt:	*Identify the available RATs and ask to the deployed node to perform signal quality measurements.*
Parameters	**Description**
NbOfAvailableRAT	*Indicate the number of available RATs in the system vicinity.*
ListOfAvailableRAT	*List of available RATs, describing the used technology, operating frequency.*
Primitive name:	**CM1_PolicyUpdated.IND**
Source:	*CM-SM*
Destination:	*CM-RM*
When generated:	*Upon reception of SM0_PolicyUpdated.IND.*
Effect on receipt:	*Apply the received policies/restrictions to the active channels. As an example, the operator may define some priority to the available RATs.*
Parameters	**Description**
NbOfPolicies	*Indicate the number of updated policies.*
ListOfPolicies	*Provide the list of policies (operator, regulator …) to be apply when operating or monitoring the active channels received within the portfolio.*
Primitive name:	**CM1_NewDetectedRAT.IND**
Source:	*CM-RM*
Destination:	*CM-SM*
When generated:	*When the deployed node has notified a new detected RAT (reception of RM0_NewDetectedRAT.IND).*
Effect on receipt:	*Inform CM-SM about this new presence.*
Parameters	**Description**
NbOfDetectedRAT	*Indicate the number of detected RATs in the access point coverage.*
ListOfDetectedRAT	*List of detected RATs, describing the used technology and the, operating frequency.*

8.2.3 TX1 interface

Primitive name:	TX1_SignalQualityMeas.REQ
Source:	*CM-RM*
Destination:	*TX1*
When generated:	*Upon reception of RM0_SignalQualityMeas.REQ.*
Effect on receipt:	*Configure the measurement scheduling.*
Parameters	**Description**

MeaType	*Configure the type of measurement to perform*
MeasPeriodicity	*Configure the periodicity of the measurements, and so, of the reporting.*
FrequencyCharacteristics	*Define the characteristics of the frequencies to monitor*
TrxGapScheduling	*Define, for connected mode, the gap in the transmission to be used for executing the measurements.*
Primitive name:	**TX1_SignalQualityMeas.RSP**
Source:	*TX1*
Destination:	*CM-RM*
When generated:	*Once measurements have been performed and results are available.*
Effect on receipt:	*Report the measurements results to the centralised CM-RM.*
Parameters	**Description**
MeasType	*Indicate the type of measurement that has been performed.*
FrequencyCharacteristics	*Define the characteristics of the frequencies that have been monitored.*
MeasResults	*Provide the measurements result.*
Primitive name:	**TX1_NewDetectedRAT.IND**
Source:	*TX1*
Destination:	*CM-RM*
When generated:	*Once a new available RAT has been detected.*
Effect on receipt:	*The information is transferred to the centralised CM-RM.*
Parameters	**Description**
NbOfDetectedRAT	*Indicate the number of detected RATs in the access point coverage.*
ListOfDetectedRAT	*List of detected RATs, describing the used technology and the, operating frequency.*

8.2.4 SM0 interface

Primitive name:	**SM0_PolicyUpdated.IND**
Source:	*CM-SM*
Destination:	*CM-RM*
When generated:	*When CM-SM is notified about the new updated policies. It derives then the information for each deployed access point, according to the configured active channels.*
Effect on receipt:	*CM-SM derives the information for each deployed access point, according to the configured active channels and transfer the information to each local CM-SM.*
Parameters	**Description**
NbOfPolicies	*Indicate the number of updated policies.*
ListOfPolicies	*Provide the list of policies (operator, regulator …) to be apply when operating or monitoring the active channels received within the portfolio.*
Primitive name:	**SM0.AvailableRAT.IND**
Source:	*CM-SM*
Destination:	*CM-RM*
When generated:	*Upon reception of QS1a_AvailableRAT.IND.*
Effect on receipt:	*Ask to CM-RM to monitor these new available RATs.*
Parameters	**Description**
NbOfAvailableRAT	*Indicate the number of available RATs in the system vicinity.*
ListOfAvailableRAT	*List of available RATs, describing the used technology, operating frequency.*
Primitive name:	**SM0_NewDetectedRAT.IND**
Source:	*CM-SM*
Destination:	*CM-RM*
When generated:	*When CM-RM notifies a new detected RAT (reception of RM0_NewDetectedRTN.IND).*
Effect on receipt:	*Update the list of available RATs.*
Parameters	**Description**
NbOfDetectedRAT	*Indicate the number of detected RATs in the access point vicinity.*
ListOfDetectedRAT	*List of detected RATs, describing the used technology and the, operating frequency.*

8.2.5 RM0 interface

Primitive name:	**RM0_SignalQualityMeas.REQ**
Source:	*CM-RM*
Destination:	*CM-RM*
When generated:	*In both idle and connected mode, when it is necessary to periodically monitor the quality of a signal (generated, as example by a neighbour RAT).*
Effect on receipt:	*Configure the transceiver to perform the measurements.*
Parameters	**Description**
MeaType	*Configure the type of measurement to perform*
MeasPeriodicity	*Configure the periodicity of the measurements, and so, of the reporting.*
FrequencyCharacteristics	*Define the characteristics of the frequencies to monitor*
TrxGapScheduling	*Define, for connected mode, the gap in the transmission to be used for executing the measurements.*
Primitive name:	**RM0_SignalQualityMeas.RSP**
Source:	*CM-RM*
Destination:	*CM-RM*
When generated:	*Once measurements results have been reported by the local CM-RM.*
Effect on receipt:	*CM-RM analyses the measurements results.*
Parameters	**Description**
MeasType	*Indicate the type of measurement that has been performed.*
FrequencyCharacteristics	*Define the characteristics of the frequencies that have been monitored.*
MeasResults	*Provide the measurements result.*
Primitive name:	**RM0_NewDetectedRAT.IND**
Source:	*CM-RM*
Destination:	*CM-RM*
When generated:	*Upon reception of TX1_NewDetectedRAT.IND.*
Effect on receipt:	*Transfer the information to the CM-SM.*
Parameters	**Description**
NbOfDetectedRAT	*Indicate the number of detected RATs in the access point vicinity.*
ListOfDetectedRAT	*List of detected RATs, describing the used technology and the, operating frequency.*

8.3 Adaptation Layer internal operations

Once presented the different components of the AL, this section explains the operability of them and how the AL performs its functionalities. In order to provide a clear view of all these aspects, the messages shared by the entities will be presented, as well as the data flow charts (MSC) depicting how the information provided in these messages is processed by the AL.

8.3.1 Entity registration/deregistration

The first action that should be done by any user of the AL is registering. This process is composed by two main phases:

1. Detection of the AL_END. This process will be performed including a daemon into the machines running the different QoSMOS block.
2. Registration into the AL_CORE. Once the AL_END has been contacted, the internal procedure is triggered and the information is sent in order to be stored in the contactable database.

0	8	16	32	40	48	56	64	72	80	88	96	104	112	120	127	135
0x01	Length		Seq ID	NodeId							# inter.	Topic Name 1	Topic Action 1	Topic Name 2	Topic Action 2	...
T	L		V													

Figure 30: Registration Request of QoSMOS entity packet

Figure 30 presents the different fields composing the packet sent from the AL_END to the AL_CORE. These fields are:

- **Type** – one byte field identified by the hexadecimal code “0x01”.
- **Length** – two bytes that include the whole length of the packet at application level.
- In the **Value** field the following information has been included:
  - **Seq ID** – this is the identifier of the request. This field is needed in order to allow the application at AL_CORE side of confirming actions related to specific packets.
  - **Node ID** – this field includes identifier, IP address and port of the requester block. Aside from the IP address and port, the node ID contains an extra byte with the value assigned to the QoSMOS entity involved in the registration process.
  - **#inter** – this one byte field points to the number of data types associated to the block.
  - **Topic Name** – one byte that identifies the data structure.
  - **Topic Action** – one byte showing the action to be done with the data type presented in the previous field.

Once the AL_CORE has correctly updated its database, it is mandatory to give some feedback to the AL_END by sending a packet (see **Figure 31**) accepting or rejecting all the propositions included in the original registration packet.

0	8	16	32	40	48	56	64	72	80	88	96	104	112	120
0x02	Length		Seq ID	NodeId							# inter.	Topic1 ACK/NACK	Topic2 ACK/NACK	...
T	L		V											

Figure 31: ACK/NACK packet response to Registration

Deregistration process is similar to the registration one; the QoSMOS entity informs the AL_END, and this module sends the deregistration packet shown in **Figure 32**.

0	8	16	32	40	48	56	64	72	80	88
0x05	Length		Seq ID	NodeId						
T	L		V							

Figure 32: Deregistration Request Packet

In this case it is only necessary to send the **Node ID** due to the fact that the information is already on the database and the AL will be capable of managing this new event. The confirmation process is simple as well (see **Figure 33**).

0	8	16	32	40	48	56	64	72	80	88	96
0x06	Length		Seq ID	NodeId							ACK/NACK
T	L		V								

Figure 33: Deregistration confirmation

In both cases, those messages should be confirmed by the AL_CORE by sending an ACK message.

8.3.2 Service announcement and information update

Once registered in the AL, the different registered blocks can start their interaction with the new one. In order to let them know the information handled by these new block, the AL will inform to the diverse blocks working with common information about the presence and the type of action with the data that the new block does. The AL sends a message to the AL_END of the interested entities; the format of this advice is presented in **Figure 34**.

0	8	16	32	40	48	56	64	72	80	88	96	104	112	120	128	136	144	160
0x03	Length		Seq ID	NodeId							Topic Name	Topic Action	Location (Ip Address+Port)					
T	L		V															

Figure 34: Information update packet

The diverse fields present in the packet are:

- **Type** – one byte field identified by the hexadecimal code "0x03" indicating the type of packet.
- **Length** – two bytes that include the whole length of the packet at application level.
- In the **Value** field the following information has been included:
  - **Seq ID** – this is the identifier of the request. This field is needed in order to allow the application at AL_CORE side of confirming actions related to specific packets.
  - **Node ID** – as explained above, this field includes the identification of the recently registered block.
  - **Topic Name** – one byte that identifies the data structure.
  - **Topic Action** – one byte showing the action to be done with the data type presented in the previous field.
  - **Location (IP Address+Port) –** This 6 byte field represents the IP address and port of the entity acting over the indicated topic.

The information sent must be acknowledged by the reception side. The packet used to do so is presented in **Figure 35**.

0	8	16	32	40	48	56	64	72	80	88	96
0x04	Length		Seq ID	NodeId							Topic ACK/NACK
T	L		V								

Figure 35: Update ACK packet

The scope of this packet is not only notifying about the correct reception of the update packet, but also confirming the correct processing of the information contained in it.

8.3.3 Keep Alive

It is also mandatory to periodically check the availability of the nodes connected to the AL in order to assure the validity of the data contained in the Contactable Entity DB and not providing QoSMOS entities erroneous or invalid information.

The packet used for accomplish this issue is depicted in **Figure 36**. Each block connected to the AL should send this message with a periodicity previously defined. In case of not receiving it, the AL deletes this block from the database and demands a new registration process for it, in order to include it again among the connected QoSMOS blocks.

0	8	16	32	40	48	56	64	72	80	88	96	104	112	120
0x09	Length		Seq ID	NodeId							TimeStamp			
T	L		V											

Figure 36: Keep Alive Packet

The message includes the Node ID and a TimeStamp in order to inform about the moment when it was sent. This way the AL could be aware of the status of the connection. The AL_CORE must provide a response to the nodes so as to confirm the update (see **Figure 37**).

0	8	16	32	40	48	56	64	72	80	88	96
0x0A	Length		Seq ID	NodeId							ACK
T	L		V								

Figure 37: Keep Alive confirmation

This confirmation message has the same structure as the ones previously presented and its distribution is almost equal to the one exhibited by the Keep Alive Packet. The main difference lies in the substitution of the “TimeStamp” field by an Acknowledge message that occupies one byte.

So, the fields that can be found on them both are the following:

- **Type** – one byte field indicating the type of packet. In these cases, 0x09 and 0x0A.
- **Length** – two bytes that include the whole length of the packet at application level**.**

- In the **Value** field the following information has been included:
  - **SeqID** – this is the identifier of the request. This field is needed in order to allow the application at AL_CORE side of confirming actions related to specific packets.
  - **Node ID** – this field includes the identification of the recently registered block.
  - **TimeStamp** – field in charge of noting the instant of sending the message.
  - **ACK** – in this field the confirmation message will be included.

8.3.4 Information Packet

The AL also provides the possibility of sharing information among QoSMOS blocks by using the capabilities it provides. In this case, the AL will assure all security aspects regarding communication, integrity and reliability.

	8	16	32	40	48	56	64	72	80	88	96	104	112	120	128	136	144	160	168
0x07	Length		Seq ID	SRC-NodeId							Dest IP+Port						INFO ...		
T	L		V																

Figure 38: Information Packet

The packet structure (see **Figure 38**) does not differ so much from the other ones suggested. In this case, the fields that can be found are the following:

- **Type** – one byte field identified by the hexadecimal code “0x07” indicating the type of packet.
- **Length** – two bytes that include the whole length of the packet at application level.
- In the **Value** field the following information has been included:
  - **Seq ID** – this is the identifier of the request. This field is needed in order to allow the application at AL_CORE side of confirming actions related to specific packets.
  - **SRC-Node ID** – this field includes the identification of the QoSMOS entity which is sending the information.
  - **Dest IP+Port** – this field includes the IP address and port of the destination QoSMOS entity. This information was delivered to the source in the Information Update process.
  - **INFO** – any relevant information that is desired to deliver will be included into this field of variable length

The information sent must be acknowledged by the reception side. The packet used to do so is presented in **Figure 39**.

0	8	16	32	40	48	56	64	72	80	88	96
0x08	Length		Seq ID	NodeId							ACK/NACK
T	L		V								

Figure 39: Information Packet Confirmation

The scope of this packet is to confirm the QoSMOS entity which sent the information packet that its packet is correctly delivered to the desired destination.

8.4 Preliminary performance metrics

The objective of this section is to provide the details of a set of preliminary performance metrics for cognitive radio systems that is complementary to the metrics presented in chapter 5. The following metrics and criteria are not definitive in the project as their final version is expected to appear in the next deliverable. They are under discussion in WP2 with inputs from other work-packages. These metrics have been arranged in this section according to the classification proposed by the authors in [Zhao2009].

The main feature of a cognitive radio system is the ability to sense and/or predict the situation or the current state of the network (i.e., availability of frequency resources and their radio propagation conditions), and use this information to make the best possible opportunistic decision for resource allocation and transmission adaptation so that both users and operators are satisfied in the best possible way. Therefore, a set of performance metrics can be proposed to measure the situation (context) awareness capability, the efficiency of the decision making processes, and the adaptation/transmission capabilities of the cognitive radio system [Zhao2009]. These aspects are discussed in the following subsections.

8.4.1 Situation awareness

The higher the situation awareness of the cognitive radio system then the best possible decision can be potentially made for all the network elements, frequency bands and radio resources. For this purpose the following preliminary performance metrics or criteria are proposed (some have been taken from [Zhao2009] and explained here in more detail):

8.4.1.1 Distortion of the sensed information

Distortion metrics (e.g., mean square error) can be used to indicate the accuracy of the information collected by the cognitive radio system with respect to the actual network state information. The network state information can be defined as the set of parameters that describe the instantaneous state of the network at any given time [CODIVD4.4]. Typical parameters of the network state information are the individual channel and queuing states of different nodes or user terminals in the network (see [CODIVD4.4] where the concept of network state information is used for cellular networks but which can also be used for other types of network). Some of these parameters of the network state information might be collected, estimated, sensed or predicted by the cognitive radio system. In the literature of wireless sensor networks, distortion metrics are often used to measure the accuracy of the sensed information [Behroozi2005]. Therefore, a modified version of these metrics can also be used in the context of cognitive radio systems.

8.4.1.2 Incorrect opportunity detection

The cognitive system can make some errors in detecting the available spectrum opportunities. Detection of opportunities is usually based on energy threshold detectors which define a probability of correct detection and probability of false alarm. The probability of detection is the probability of correctly detect an opportunity. The probability of false alarm is the probability of incorrectly detecting an opportunity given that such opportunity does not exist [VanT1969]. The expressions or curves of probability of detection and false alarm define the receiver operational curve (ROC) of the energy detector [VanT1969]. The ROC depends on the particular detector implementation, the type of signal being detected, and more importantly the type of channel and propagation environment.

Evaluation of these probabilities on the long term also indicates the performance of the sensing capabilities of the cognitive radio implementation.

8.4.1.3 Location accuracy and availability at various environments

An important parameter that can be used by cognitive radio systems is the geographical location of a given terminal or node. This information can be used to tune transmission parameters according to that specific position. For example, if a terminal is inside a building, a set of transmitters or systems available only to that particular location can be activated or allocated to the terminal. Furthermore, in recent years accurate positioning technologies have been developed at low costs that allow using this type of information for several applications, including cognitive radio schemes [Piras2010]. Availability is also an important aspect to be evaluated as different services or frequency bands are not available for certain locations or for certain periods of time. Therefore, a set of metrics can be used to evaluate the ability of the system to be aware of the location of network entities (user terminals) and the availability of services and network resources.

8.4.1.4 Awareness of Receiver Operation Characteristics (ROC)

A metric can be used to evaluate the ability of the cognitive radio system to be aware of the ROC of the sensing and detection mechanisms [Zhao2009]. As previously explained, the ROC determines the sensing and opportunity detection performance of any energy detector, which is the most common method used in sensors. The cognitive radio system can be aware of the ROC characteristics of the sensors so as to reduce errors in detection by adapting the energy detector thresholds [Nair2010], or eliminate potential false alarms by using filtering techniques or combining the information provided by several sensors.

8.4.1.5 Spectrum sensing time

The cognitive radio system can also sense or collect information about those portions of the spectrum to be managed in order to identify all available opportunities and the characteristics of such opportunities [Zhao2009]. This operation may take some time as the range of frequency bands targeted by a particular application might be very broad. The time needed to sense the part of the spectrum to be managed can be crucial in the operation of the system as the network state information might change rapidly, thereby affecting the efficiency of the resource allocation schemes.

8.4.1.6 Mobility and trajectory awareness

In scenarios with high mobility, information regarding the geographical location is generally not enough to adapt the transmission systems accordingly**.** Terminals can move from one part of the network to another one using well defined trajectories. Knowledge of these parameters can help in a more efficient transmission adaptation and frequency band allocation along the trajectories followed by the mobile terminals.

8.4.1.7 Radio channel condition awareness

Different parts of the network, different frequency bands and different mobile terminals can experience distinct radio channel conditions. Therefore, in order to improve the decision making process, the cognitive radio system may not only detect the occupancy of different bands, but also the channel conditions experienced by each one of them. This will help the cognitive radio system in providing a better decision and allocation of resources to the user terminals [Zhao2009].

8.4.1.8 Energy efficiency awareness

Since a cognitive radio implementation has an improved knowledge of the network state information (context information, radio channel conditions, location, etc), the network elements can make use of their transmission resources in a better way, and thus consume less power. The cognitive radio system can also be aware of the energy efficient conditions of the network and thus make decisions that help in reducing energy consumption while achieving an acceptable performance.

8.4.1.9 Context awareness

Context is all that additional information that can help the cognitive radio system decide in a better way the allocation of resources [Liu2011]. Examples of context information are previous transmission events in the network, knowledge of the conditions of other contending network elements in a given geographical area, the type of information being sent by other users, etc. Context awareness is thus related to the ability of the system to collect this additional information that might play an important role in the correct performance of the system.

8.4.1.10 Network topology awareness

Cognitive radio systems also need to know the hierarchy of the network elements or topology of the network. Topology of the network refers to the role given to different elements/nodes of the network and their functional relationships. In self-organized networks, these roles are likely to change, and thus errors can be made when the topology information is not correctly updated. For example, in an ad-hoc network where terminals relay the information of other terminals towards the destination, the connectivity between nodes and the correct assignment of roles for each one of them (router, relay, cooperative node, destination or sink) is crucial for the correct decision making process and final performance of the system. The more accurate the network topology information then the cognitive scheme becomes more efficient in the resource allocation process, routing of information, and in the potential assignment of roles for the terminals/devices under its control.

8.4.1.11 Awareness of the adaptation capabilities of other nodes or parts of the network

In some cases, the cognitive functionality or related algorithms will run in a distributed manner in different network elements or terminals (nodes). In this mode, the cognitive functionality must have some kind of knowledge of the transmission and adaptation capabilities of the other entities and thus make a better decision for the all network.

8.4.2 Adaptation capability

Once the cognitive radio system has collected all the network/context information, it proceeds to make one or several decisions regarding resource allocation for different users. The system then proceeds to make changes in the transmission parameters of the radio systems of all the nodes/terminals involved in the optimization. This adaptability of the transmission parameters in the network with respect to changes in the collected network/context information is an important feature to be evaluated in cognitive radio systems. The following metrics intend to capture this ability.

8.4.2.1 Transmission adaptability

The ability to change the transmission parameters (e.g., the antenna radiation pattern, transmit power, modulation and coding schemes, etc.) according to requests or the decisions made by the cognitive system is an essential part of the evaluation of these type of system. The success of a cognitive radio system highly relies on this feature.

8.4.2.2 Routing protocol adaptability

In advanced cognitive radio system implementations with ad-hoc features, the routing protocol will play an important role in the efficiency and the correct transmission of information across the network. Routing protocols in these systems are expected to be highly adaptive with respect to channel and queuing states of the network. The ability to change the routing protocol according to requests or changes in the network state information will determine the performance of such ad-hoc system implementations.

8.4.2.3 Topology adaptability

The network topology, i.e. the hierarchy and role of each node in the network may also be changed in environments with high mobility and self-configuration features. Cooperative and routing functionalities will be hosted by potentially different nodes as they change positions in the network. The ability of the cognitive radio system to change the role of each network element in environments with high mobility is another aspect that can be evaluated in this type of system.

8.4.2.4 Average response time to network changes.

A cognitive radio system might make use of a set of sensors or other sources to acquire accurate information about the current state of the network (frequency band occupancy, radio channel conditions, etc.). This information acquisition process is however not instantaneous, as latency of signalling channels and processing of sensors may cause delays. In addition, the cognitive system runs several operations and scheduling of several tasks that do not allow an instantaneous response to the sensed parameters of the network. The result is that the collected network state information might be slightly outdated, which will affect the efficiency of the allocation decisions made by the system. This issue is particularly critical in networks with high mobility, where users change their propagation conditions relatively fast and thus decisions should be made with very low latency figures.

8.4.3 Decision making, planning and learning

A cognitive radio system aims to implement highly advanced cognitive functionalities which include learning algorithms, planning methodologies and accurate decision making processes. A straightforward method to evaluate these functionalities is to measure the performance of the systems under their control using for example the performance metrics provided in chapter 5. However, it is also important to assess the implementation efficiency of those cognitive functionalities. For example, evaluation of how efficiently the decisions are made, how long it takes to reach a good solution, how much information is required to achieve a good/mature solution, etc. The following performance metrics intend to cover the evaluation of these features.

8.4.3.1 Reasoning capability

This aspect is related to how well the cognitive system is able to infer situations and make the most intelligent decision based on the collected network state information (e.g. the spectrum opportunities). For example, to measure this abstract performance metric, the system can be tested in different scenarios to evaluate its ability to reach different solutions for different situations that were not initially predicted in the design of the system. A set of reference scenarios for which the best solution is previously known or can be easily inferred can be used to test the system and see how well it converges to the optimum or close to the optimum solution. This procedure will allow us to test the efficiency of the learning algorithms implemented in the cognitive radio system.

8.4.3.2 Decision making algorithm convergence time

This metric refers to the amount of time the algorithm takes to reach an optimum or suboptimal solution. In order to reduce convergence times, a suboptimal solution can be preferred at the expense of some performance degradation. Therefore, this performance metric should be jointly assessed with the system level performance metrics provided in chapter 5 in order to have a better idea of the trade-off between convergence time and system level performance.

8.4.4 Performance

8.4.4.1 Reliability

Reliability is a measurement of the percentage of time any system performs in the desired way [Cai2006]. Reliability is a metric used in several types of systems to evaluate the long term performance of several functionalities. A set of target performance metrics, such as certain level of spectral efficiency, packet drop rate, etc, are fixed as reference. The system performance is then tracked over long periods of time to measure the average time the system performs above the established metrics.

8.4.4.2 Delay in response to system requests

This is a measure of how long it takes to the cognitive radio system to attend or respond a request made by the systems under its control. A cognitive radio system implementation may consist of a central module that makes the decisions over a set of nodes or network entities. The system thus needs to implement an event scheduler that allows to process in sequential/parallel manner different requests. The delay in attending different requests is a measure of how well the implemented system behaves under different loads of requests and changes in the scenarios.

8.4.5 Complexity

Complexity evaluation of any system is crucial for a techno-economical trade-off assessment. In systems with ad-hoc implementations or low power consumption terminals, this evaluation is even more critical as certain level of performance must be ensured while keeping low power and complexity processing requirements.

8.4.5.1 Signal processing requirement

This metric is related to the complexity required on hardware platforms to implement the signal processing algorithms of the cognitive radio system. The number of operations for each process of the cognitive system is a good measure of its processing requirements. Complexity is directly related to implementation cost, so it is a good indicator for further techno-economical analysis.

8.4.5.2 Signalling loads

Adaptation in wireless networks requires the acquisition of accurate parameters of the network state information (mainly channel state information) [CODIVD4.4]. In order to acquire these parameters it is necessary to deploy a network of signalling and feedback channels that transport this information from different sensors distributed in a given geographical area to the location(s) where decisions are made. The higher the adaptability of the system then the higher the bandwidth for signalling and information acquisition is required. Therefore, a good trade-off between signalling bandwidth and adaptability performance must be achieved so that the system is feasible from the economical point of view. Signalling loads figures are then also useful evaluation criteria for the efficiency of a cognitive radio system.

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