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System Architecture Consolidation, Evaluation and Guidelines

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Abstract:

This report presents a consolidated view of the QoSMOS system architecture. Details are given for the technical solutions developed within the project, which cover the various roles within the system architecture. These solutions are evaluated using selected performance metrics. The technical tools

The research leading to these results was derived from the European Community's Seventh Framework Programme (FP7) under Grant Agreement number 248454 (QoSMOS)

developed during the project, which allow for performance assessment or proof-of-concepts are also presented.

The report also considers the realisation of deployed systems. This includes a review of several business cases along with some recommended deployment guidelines. Finally, this report discusses how QoSMOS systems might be realised in hardware, including modifications to 3GPP LTE.

Keyword list:

Cognitive Radio, Opportunistic channel access, TV whitespace, Scenario, System architecture, Reference model, Standardisation, Deployment guidelines, Business case.

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Abbreviations

3GPP	Third Generation Partnership Project
ACLR	Adjacent Channel Leakage Ratio
AD	Anderson-Darling
AL	Adaptation Layer
AP	Access Point
ASN GW	Access Service Network Gateway
BDUK	Broadband Delivery UK
BLER	Block Error Rate
BS	Base Station
CAC	Cognitive Access Control
CAF	Cyclostationary Autocorrelation Function
CC	Cancellation Carriers
CD	Cyclostationary Detector
CDMA	Code-Division Multiple Access
CIR	Carrier-to-Interference Power Ratio
CM	Cognitive Manager
CMIP	Common Management Information Protocol
CM-RM	Cognitive Manager for Resource Management
CM-SM	Cognitive Manager for Spectrum Management
CN	Core Network
CP	Cyclic Prefix
CPFR	Common Portfolio Repository
CSN	Connectivity Service Network
CSS	Collaborative Spectrum Sensing
DTT	Digital Terrestrial Television
ED	Energy Detector
eNB	Evolved Node B

EWC	Equal Weight Combining
FBMC	Filter Bank Multi Carrier
FCC	Federal Communications Commission
FCME	Forward Consecutive Mean Excision
FM	Frequency Modulation
FUE	Femtocell User Equipment
GFDM	Generalised Frequency Division Multiplexing
GLRT	Generalised Likelihood Ratio Test
GoS	Grade of Service
HSS	Home Subscriber Server
IA-PFT	Interference Avoidance Transmission by Partitioned Frequency- and Time-Domain Processing
ISR	Interference-to-Signal Ratio
KPI	Key Performance Indicator
KS	Kolmogorov-Smirnov
LOC	Local Spectrum Management
LTE	3GPP Long Term Evolution
MAC	Media Access Control
MGT	Management
MME	Mobility Management Entity
NET-COORD	Network Coordination
NC-OFDM	Non-Contiguous Orthogonal Frequency-Division Multiplexing
NP	Normal Peak
OFDM	Orthogonal Frequency-Division Multiplexing
OSS	Operational Support Systems
PAPR	Peak-to-Average Power Ratio
PGW	Packet Data Network Gateway
PHY	Physical layer
PMF	Probability Mass Function

PMSE	Programme Making and Special Events
PoC	Proof-of-Concept
PSD	Power Spectral Density
QoS	Quality of Service
RAT	Radio Access Technology
RC	Resource Control
RCC	Resource Control - Centralised
RCD	Resource Control - Distributed
REP	Repository Access
RM	Resource Management
RMSE	Root Mean Squared Error
ROC	Receiver Operating Characteristic
RPDB	Regulatory and Policy Databases
RS	Reference Signal
RU	Resource Use
SAP	Service Access Point
SCTRL	Sensor Control
SEL	Spectrum Selection
SFDR	Spurious-Free Dynamic Range
SGW	Serving Gateway
SIR	Signal-to-Interference Ratio
SM	Spectrum Management
SMDP	Semi Markov Decision Process
SNMP	Simple Network Management Protocol
SNR	Signal-to-Noise Ratio
SS	Spectrum Sensing
SSC	Centralised Spectrum Sensing
SSD	Distributed Spectrum Sensing
SSL	Local Spectrum Sensing

TCP	Transmission Control Protocol
TMN	Telecommunications Management Network
TRX	Transceiver
TV	Television
TVWS	TV Whitespace
UDP	User Datagram Protocol
ULYR	Upper Layer
UMTS	Universal Mobile Telecommunication System
US	United States
WP#	Workpackage# (e.g., WP2 = workpackage 2)
WSD	Whitespace Device

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1 Executive Summary

This report presents the consolidated system architecture for QoSMOS systems. This is formed through harmonisation of the technical contributions from the workpackages across the project. These various technical contributions are evaluated against selected performance metrics. Deployment guidelines are then presented based on an evaluation of the business cases for several scenarios that have a high potential.

The technical contributions in QoSMOS are classed as either technical solutions or technical tools. The technical solutions each play a role in part of the overall system architecture, which was defined earlier in the QoSMOS project in [D23]. The technical solutions are evaluated using selected performance metrics to show a quantitative assessment of each solution's benefits and demonstrate how they advance the state-of-the-art. The technical tools provide ways to evaluate system performance in the form of performance prediction, opportunity prediction and proof-of-concepts (PoC). An overview of each system tool is provided along with its benefits for QoSMOS system development.

The consolidated system architecture is always presented with consideration for the QoSMOS scenarios:

- **Cellular extension in whitespace** – This is where an operator can use whitespace spectrum in addition to any of its own licensed spectrum for offloading, either for capacity or coverage enhancement. A special case of this is rural broadband where mobility is not required.
- **Cognitive femtocell** – Cognitive femtocells using opportunistic channel access. This includes deployments such as wireless access in the home, public hotspot coverage, and indoor-to-outdoor coverage.
- **Cognitive ad hoc network** – Ad hoc networks (typically limited in time and space) using opportunistic channel access. This includes deployments for emergency scenarios where a network must be quickly established between emergency response services and their coordination centres. Another example is for a machine-to-machine network using whitespaces.

When considering actual deployments, this report focuses on some specific realisations of these scenarios, which are:

- LTE offloading using TV whitespace (TVWS) for **capacity enhancement of an LTE network** (subset of cellular extension in whitespace)
- **Rural broadband** using TVWS (subset of cellular extension in whitespace)
- A fixed operator providing a **mobile data service using cognitive femtocells** (subset of cognitive femtocell)
- **Machine-to-machine** using TVWS (subset of cognitive ad hoc network)

A common theme for these specific scenarios is the use of TVWS. This is because the regulatory situation means that opportunistic access to the TV band could be possible in many European countries (already possible in USA) very shortly.

For the business case evaluations, assumptions and regulations are discussed in general as well as the unique details for the business case of each specific scenario. Deployment guidelines are given for each specific scenario, listing which issues must be dealt with along with a timeline suggesting how the deployment could progress. The realisation of these specific scenarios requires that equipment with QoSMOS functionality is made available on time. This report has a particular focus on the modifications required to LTE technology to include QoSMOS functionality, but also looks at the options for creating proprietary solutions for business cases that require roll-out sooner than standardisation is likely to allow. For example, the rural broadband scenario looks at starting roll-out from 2013 if TVWS are already available.

2 Introduction

This document presents a harmonised view of the technical contributions from all of the workpackages in the QoSMOS project and shows how they apply to the overall system specification defined in [D23]. The technical contributions of QoSMOS are evaluated in this deliverable using a refined set of evaluation metrics. Guidelines for the deployment of the QoSMOS scenarios are also provided based on results from an economic study.

The QoSMOS target scenarios identify those applications that have a high potential for success as real implemented systems. These scenarios were defined early in the project to give guidance to the work that followed. As the project has progressed, these scenarios have been refined to give more focus to those applications judged to have the highest potential (Earlier in the project there were six scenarios. This has since been reduced further to three (as listed below). In [D16] an overview is provided of how the scenarios have been refined during the project from the initial six listed in [D12] and [MacEtal2011]) to the three listed below.

The QoSMOS scenarios can be summarised as (more detailed descriptions of these scenarios can be found in [LehEtal2012]):

- **Cellular extension in whitespace** – This is where an operator can use whitespace spectrum in addition to any of its own licensed spectrum for offloading, either for capacity or coverage enhancement. A special case of this is rural broadband where mobility is not required.
- **Cognitive femtocell** – Cognitive femtocells using opportunistic channel access. This includes deployments such as wireless access in the home, public hotspot coverage, and indoor-to-outdoor coverage.
- **Cognitive ad hoc network** – Ad hoc networks (typically limited in time and space) using opportunistic channel access. This includes deployments for emergency scenarios where a network must be quickly established between emergency response services and their coordination centres. Another example is for a machine-to-machine network using whitespaces.

Chapters 3 to 5 describe and evaluate the solutions and tools developed during the project. These solutions and tools allow for the various functionalities of the QoSMOS system architecture to be developed for the requirements of the above scenarios.

Chapters 6 and 7 take a more detailed look at the realisation of some specific implementations of the above scenarios (More details on the business cases can be found in [D16]).

These, more specific scenarios, are summarised as:

- LTE offloading using TVWS for **capacity enhancement of an LTE network** (subset of cellular extension in whitespace)
- **Rural broadband** using TVWS (subset of cellular extension in whitespace)
- A fixed operator providing a **mobile data service using cognitive femtocells** (subset of cognitive femtocell)
- **Machine-to-machine** using TVWS (subset of cognitive ad hoc network)

One common theme of these more specific scenarios is the use of TVWS. This is because opportunistic access to the TV band is either already available (e.g. USA) or is expected to be available soon (e.g. UK) and so the business cases for this band are of great interest to the many actors involved with QoSMOS.

This chapter introduces the document and provides a brief summary of the key system architecture details from previous QoSMOS deliverables. This includes the main functional blocks within the QoSMOS reference model and how these apply the QoSMOS scenarios, cellular extension in whitespace, cognitive femtocell and cognitive ad hoc network.

Chapter 3 describes the system technical solutions that have been developed in the project. For each solution a description is given that describes how it fits into a QoSMOS system and what benefits it provides. Chapter 4 then describes some of the tools developed during the project, which can be used to evaluate system performance, including components of the QoSMOS proof-of-concepts (PoC). Chapter 5 then provides selected performance evaluation results of the system technical solutions using the refined set of evaluation metrics, in order to provide quantitative evidence of the gains and benefits derived from the solutions and show how QoSMOS has advanced the state-of-the art.

This report then considers the deployment of QoSMOS systems. Chapter 6 reviews the business case for each of the specific QoSMOS scenarios and offers some deployment guidelines. These guidelines show what barriers must be overcome and a timeline for the deployment of each scenario is suggested. Chapter 6 then continues the consideration of real deployments by describing how a QoSMOS system might be realised for a deployable system. Particular attention is given to adding QoSMOS functionality to LTE technology, which is particularly useful for the cellular extension in whitespace and cognitive femtocell scenarios.

Finally, chapter 8 presents the main conclusions of this report.

2.1 QoSMOS system - Functional Architecture and Reference Model

The QoSMOS system architecture has been designed to operate in different regulatory regimes [D22], [D23], [Cel2011], i.e., to make use of either or both geo-location databases and spectrum sensing, for example, and to be flexibly applicable to a range of diverse target scenarios [AriEtal2011]: cellular extension in whitespace (including rural access), cognitive femtocell, and cognitive ad hoc network. These have correspondingly different constraints [LehEtal2011].

Figure 2-1 illustrates the reference model functional blocks, together with their interfaces [D22] [D23], mapped onto the four topological domains [CelEtal2011], illustrated in chapter 3, which abstract together the possible application scenarios [Cel2012].

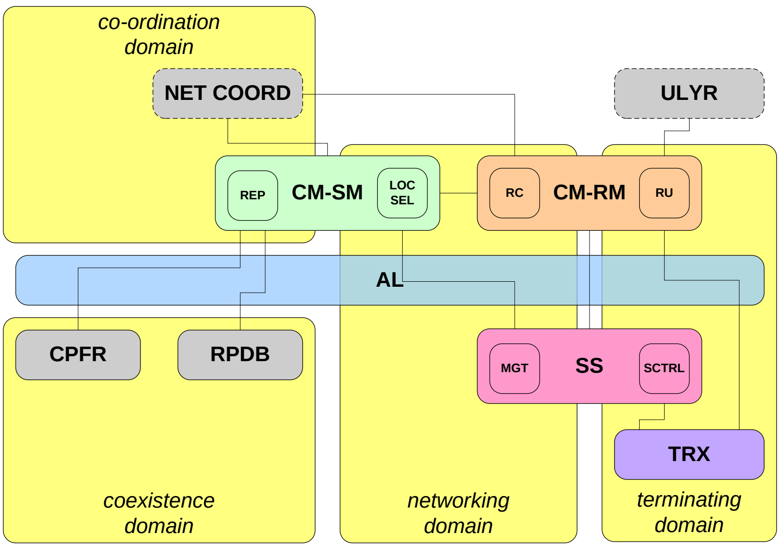

Figure 2-1 The QoSMOS reference model mapped onto the topological domains.

The main highlights about the functional blocks, the cognitive manager for spectrum management (CM-SM), the cognitive manager for resource management (CM-RM), the spectrum sensing (SS) and the transceiver (TRX) are presented in sections 3.1, 3.2, 3.3 and 3.4 respectively[1], where the focus is narrowed on portions of Figure 2-1. External blocks (network coordination, NET COORD, and upper layers, ULYR) are also shown in the figure. The acronyms used here are commonly used in the following chapters.

Flexibility is shown using the topological domains as summarised in section 3.5. The QoSMOS system architecture allows for a combination of resource control and sensing topologies to suit the intended scenario (not limited to just the QoSMOS scenarios) [D23]. The resource control can be centralised, distributed or semi-distributed while the spectrum sensing can be local, centralised (collaborative or cooperative) or distributed [D32]. The QoSMOS target scenarios (cellular extension in whitespace, including rural access, cognitive femtocell, and cognitive ad hoc network) are listed in Table 2-1 [Cel2012] together with the most reasonable [D23] combinations of resource control and spectrum sensing topologies: centralised (RCC) and distributed (RCD) resource control, and centralised (SSC), distributed (SSD), and local (SSL) spectrum sensing.

Table 2-1 The most promising QoSMOS scenarios and some of their architectural properties.

Scenario	resource control topology	spectrum sensing topology
cellular extension in whitespace	RCC	SSC
cognitive femtocell	RCC	SSC, SSL
cognitive ad hoc network	RCC, RCD	SSC, SSD, SSL

A complete mapping of the first and the last architecture options (in particular, cellular extension in whitespace with RCC/SSC topology and cognitive ad hoc network with RCD/SSL topology, respectively) are presented in [CelEtal2011].

[1] The common portfolio repository (CPFR) and the regulatory and policy databases (RPDB) are accessed by the CM-SM. The functional groups (repository access (REP), localisation and selection, ((LOC) and (SEL)), resource control RC, resource use (RU), SS management (MGT), sensor control (SCTRL)) are related to the aforementioned topology mapping. All these are discussed in the relevant sections cited in the text.

3 System Solutions

For the QoSMOS system, technical solutions have been developed in order to address, specifically, the objectives targeted. These objectives mostly consist of quality of service (QoS) management within an opportunistic system, mobility support and incumbent protection. These solutions apply to the different functional blocks of the QoSMOS reference model, recalled in the previous chapter, as well as to the interactions between them and the overall system architecture. The ordering of the sections in this chapter therefore follows the internal structure of the QoSMOS system, describing the corresponding technical solutions developed together with their benefits. The solutions are highlighted alongside the main groups of functionalities that they realise. The detailed performance evaluation of these schemes will be presented in the next chapters.

3.1 Solutions for the Cognitive Manager for Spectrum Management

3.1.1 Functional Overview

Figure 3-1 depicts the CM-SM with its two internal functional block groups together with the main other functional blocks interworking with it in the QoSMOS system, as introduced in the previous chapter.

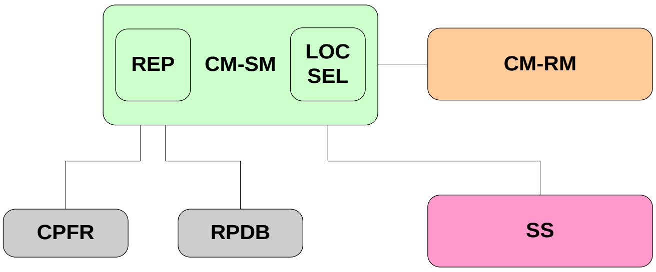

Figure 3-1 The CM-SM accesses repositories and provides CM-RM with spectrum portfolio.

3.1.2 Cognitive Spectrum Management Framework

Description

In order to make the available spectrum opportunities available to the CM-RM, the CM-SM [D62] [D65], through the repository access (REP) group managing the context at broader level, accesses the regulatory and policy databases (RPDB), providing regulatory constraints concerning the spectrum use, and the common portfolio repository (CPFR). The CPFR incorporates all the relevant information from the above repositories filtered and processed, enriched by spectrum sensing results and performance reports, gathered from the SS and the CM-RM. The latter are components of context relevant at the networking domain (for example at a base station level), also eliminating irrelevant information and adding what is meaningful only there, to enable the spectrum selection (SEL) and the following resource management.

The cognitive spectrum management framework is based on a holistic multi-disciplinary approach to spectrum management with inputs from market, technology, economics and regulation [D61]. The main objective is to increase spectrum utilisation by managing scarce spectrum resources in an intelligent way across technologies, access methods and stakeholders [D63]. This enables opportunistic operators to efficiently make decisions on the assignment of portions of the primary spectrum to the requesting entities while meeting various QoS level requirements and ensuring incumbent protection.

Benefits

Alternative approaches for the cognitive functions [D65] taking into account context filtering, aggregation and communication [D62] as well as flexibility, robustness and cognition [D64] with varying levels of complexity have been compared; this showed that the performance can be improved when applying the framework to QoSMOS scenarios [D66]. Specific realisations of the framework and their benefits are addressed in the following sections.

3.1.3 Cognitive Spectrum Management by Joint Energy and Spectrum Control

Description

This solution applied to the cognitive femtocell scenario, consists of a cognitive spectrum management functionality to enhance reliability of the spectrum management operation by investigating a joint energy and spectrum (i.e., sub–channels) utilisation for dense indoor femtocell networks. This aims not only at sharing the spectrum with the macrocell, but also at providing robust spectrum and energy resource management to the finite, random sub-channels for densely deployed femtocells.

For a given number of reserved channels not in operative use, energy control is performed at both control and data planes on every time slot. The aggregate energy usage between all of the femtocell user equipment (FUE) and the networked femtocells is addressed from the signal processing perspective. For simplicity in analysis and without loss of the generality, the worst-case interference is considered, where all the FUEs are located at the cell-edge of the femtocell and thus the resulting downlink energy usage per femtocell is the largest. This leads to an asymptotic situation where the interference caused by the femtocells results in the highest level.

Based on the mathematical treatment of the energy usage between FUEs and femtocells, the energy usage at each femtocell associated with multiple FUEs, is decomposed into energy usage at the control plane and at the data plane. The two energy terms are shown to rely on the power allocation level as well as on the number of active sub-channels for the channel feedbacks. Thus, the proposed CM-SM functionality shows that the proper management of both the power levels and the size of the subset of active sub-channels alongside the CM-RM functionality (i.e., radio resource scheduling) can improve the stability of the femtocell in terms of the outage capacity, while co-existing with the licensed macrocell receiver.

Benefits

This solution consists of interactions with the SS as well as with the CM-RM. Based on the inputs from the SS, the proposed solution intends to leverage the amount of spectrum available at the femtocells to its maximum advantage. This advantage is achievable by dynamically varying the number of active spectra as a degree of freedom. Along with the power allocation method to such active spectrum, the output of this process is transferred to the inputs to the CM-RM.

3.1.4 Distributive Self-Learning SON

Description

A Self Organising Network (SON) approach [D64] is developed and analysed, which allows distributed cognitive system nodes, i.e. the distributed Spectrum Managers, to configure, manage and optimise their many highly coupled parameter sets, such as the spectrum portfolio and the transmission power settings of the cognitive nodes. It is based on an internal prediction model, which uses self-learning to adapt itself to the particular situation for each individual cognitive node [D65].

Benefits

The distributed cognitive nodes manage to considerably improve their performance by adaptively setting their parameters individually and for each particular environment, traffic and interference situations. This SON technique is very fast, as it uses only internal mathematical calculations, without the need of any system feedback, i.e. no parameter testing is needed [D65], [D67]. This approach is a major step towards the vision, to introduce a cognitive node anywhere in any environment and then the node and the network simply adapt and optimise themselves in a self-organising manner to this complex and interacting situation [D67].

3.1.5 Portfolio optimisation

Description

Cognitive radio technology will allow for the adaptive access to licensed and unlicensed portions of spectrum. However, different parts of spectrum not only have different network (e.g. radio and load) conditions, but also different licensing and/or billing agreements. Therefore, in order for the operators to obtain the major economic return and the most efficient use of radio resources, the allocation of such spectrum resources must now target both technical and economic objective functions. This problem can be conveniently formulated as a multi-objective portfolio optimisation problem. The solution aims to adapt the concepts behind multi-objective portfolio optimisation, commonly used in the areas of economics and finance theory, to the particular case of spectrum aggregation/selection in cognitive radio, and observe the advantages and potential interactions between technical and economical approaches. A framework has been established for such coexistence and simulation results have been produced considering the Pareto optimal trade-off region obtained when using a multi-objective function based on return and risk factors per Hz of allocated spectrum. The trade-off is between the expected utility (which can be the throughput or another metric combining throughput, fairness and QoS for example) and the risk of using that spectrum portfolio (for example using free spectrum, we have a lower cost and may expect an average throughput but have fewer guarantees that it will be achieved) [SamEtal2012] , [SamEtal2013].

Benefits

The network and economic targets can be simultaneously met inside the Pareto optimal solution region under an appropriate balance between return and risk values of primary and secondary transmissions, where risk can be directly associated with the interference created to/from primary transmissions (dependent on the values used for the utility and the risk, as described above).

3.2 Solutions for the Cognitive Manager for Resource Management

The spectrum portfolio discussed in the previous section is passed to the CM-RM for its exploitation as described in the following. The work in [ManEtal2011] offers a detailed look the requirements for the CM-RM and defines the functional entities required to allow for incumbent protection, QoS optimisation and mobility.

3.2.1 Functional Overview

The CM-RM [D53] [LevEtal2012] receives a spectrum portfolio deployed by the CM-SM to provide communication services to upper layers, such as the application or transport layer. This is achieved by exploiting a flexible transceiver TRX, illustrated in the previous chapter and in detail in Figure 3-2. The CM-RM also feeds its performance reports to the CM-SM and uses SS services for incumbent protection.

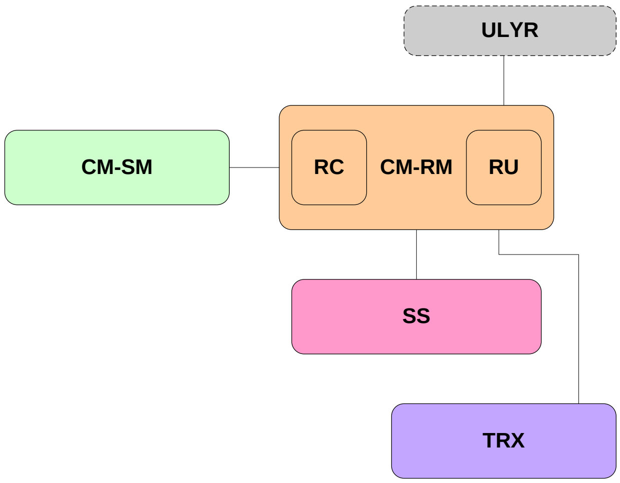

Figure 3-2 The CM-RM uses the deployed portfolio to provide service to upper layers.

One key differentiation between the CM-SM and the CM-RM is the timescale they operate on [Cel2012]: the CM-RM works closer to traffic needs and radio context changes, which are faster than the repository-based events that the CM-SM works with.

3.2.2 Flexible Architecture

The architecture of the CM-RM has been designed with the diverse scenarios, as described in the previous chapter, as target applications. Therefore, the functionalities needed to provide managed QoS and incumbent protection under physical and spectrum mobility have been organised so that the CM-RM can serve those diverse realisations.

Description

The functionalities for cognitive resource management have been identified considering the peculiar requirements [D14] [ManEtal2011]. The responsibilities of the internal functional blocks have been properly divided in two groups: Resource Control (RC) and Resource Use (RU) as shown in Figure 3-2.

The RC functional group controls access and allocates the resources to the network, whereas the RU functional group has the duty of overseeing the TRX to exploit the spectrum resources.

Benefits

This internal architecture of the CM-RM allows diverse topology mappings of the functionalities using the same architecture. This allows easy reuse of the design and for resource management services to be exploited over a range of topologies associated to the various scenarios [CelEtal2011], whilst providing QoS optimisation, mobility support and incumbent protection as needed, and with a clean interwork with the CM-SM (see also section 3.5.2).

3.2.3 Cognitive Access Control and Channel Selection

Description

An optimised access control with cognitive capabilities has been studied for an LTE network opportunistically operating over TVWS [D53].

For the cognitive femtocell scenario, admission control proceeds jointly with eviction control and bandwidth adaptation for QoS support, and is implementable in a cognitive femtocell as shown in [GuoMoe2012].

[D34] and [YuEtal2010] illustrated an adaptive scheduler and admission control protocols suitable to a distributed resource control network like [IEEE802.11e] for the QoSMOS cognitive ad hoc network scenario. Issues concerning reliable sensing information exchange for distributed admission control have been addressed in [YuEtal2011].

For the cognitive ad hoc network scenario, an algorithm [LevEtal2012] sorts active channels from best to worst (taking into account the load on active communication links as well as radio quality on these links) in order to select operating channels and identify the reserve channels to be used in case the operating channel would need to be freed.

Benefits

Network congestion can be prevented while ensuring that (a) the targeted QoS for the opportunistic users is maintained and (b) protecting the incumbent users' operations. It has been shown that the detrimental effects of incumbent appearance on connection dropping and blocking rates (CDR, CBR) are cancelled, or at least reduced, by using the optimised access control, thus providing a quality of experience comparable with that of conventional networks [D53]. Blocking and dropping probabilities of the opportunistic users are also reduced thanks to the joint algorithm for adaptive scheduling and admission control [GuoMoe2012].

In [D53] and [LevEtal2012] it is shown that the channel selection algorithm allows reliable transmission even when radio resources are intermittent due to incumbent pre-emption.

3.2.4 Transmit Power Control

Description

For the cognitive femtocell scenario, interference management is addressed by a power control scheme consisting of gradually reducing the downlink transmit power to react to the knowledge about interference caused to a macrocell [D53] [ZahEtal2011].

Radio context information can be exploited to identify a suitable power control strategy, as done for distributed power control algorithms developed for the QoSMOS cognitive ad hoc network scenario [DurEtal2010] [DurEtal2011b] [ManEtal2011]. Distributed power control can also be optimally joined to a rate allocation algorithm [RajEtal2010].

Benefits

The power control scheme for the cognitive femtocell scenario was shown to be capable of reducing the (cross-tier) interference to macrocells [D53] [ZahEtal2011].

A worst-case analysis for the distributed power control algorithm in the cognitive ad hoc network scenario showed that the QoS for the opportunistic users is satisfied while the incumbent users are protected [ManEtal2011] [RajEtal2010]. Furthermore, for this algorithm the effects of user mobility and a time-variant channel on both incumbent and opportunistic users have been studied in [DurEtal2011a] [DurEtal2012].

3.2.5 Optimised QoS Provisioning Under Spectrum Mobility

Spectrum mobility is defined in cognitive radio networks in addition to physical mobility by the process that a cognitive radio user switches its frequency of operation due to policy constraints or service requirements during the session's lifetime, leading to a new type of handover, called spectrum handover.

Description

Spectrum mobility for the cellular extension in whitespace scenario has been discussed in [LevEtal2011]. This function enables the forced handover of static/mobile users to another access point that operates in a different channel than the one pre-empted by the incumbent. This could be a neighbour cell operating in a reserve channel or another of the radio access technologies present in the user vicinity.

Optimised QoS provisioning for opportunistic users (OU) under spectrum mobility is realised by a decision-making framework for joint admission control, eviction control and bandwidth adaptation to support the QoS in cognitive radio networks. The optimal decision at each system state is derived to maximise the long-term network revenue.

Benefits

The spectrum utilisation is improved and the OU blocking probability is reduced while keeping the forced dropping probability of the OUs upper-bounded. Furthermore, this solution can adapt to the dynamic bandwidth allocation cost [D53].

3.3 Solutions for Spectrum Sensing

Both the CM-SM and the CM-RM seen above exploit for different use the services of the spectrum sensing block described here. The SS block is in charge of obtaining relevant knowledge of the surrounding radio environment. In particular, spectrum sensing identifies which portions of the spectrum may be available to the opportunistic users (i.e., spectrum holes or whitespaces). To this end, the SS block tracks frequency bands that are dynamic in both time and space, not only to identify idle frequency channels but also to detect the appearance of incumbent users in those channels being used by opportunistic users. Therefore, the SS block can play an important role in incumbent protection and allowing more spectrum opportunities to be exploited by opportunistic users.

3.3.1 Functional Overview

An important part of the radio context is acquired by the SS functional block, see Figure 3-3, which exploits measurements from sensors, which can be either located in dedicated devices or exploiting the internals of the transceiver (see also section 3.4), in order to provide the sensing decisions needed.

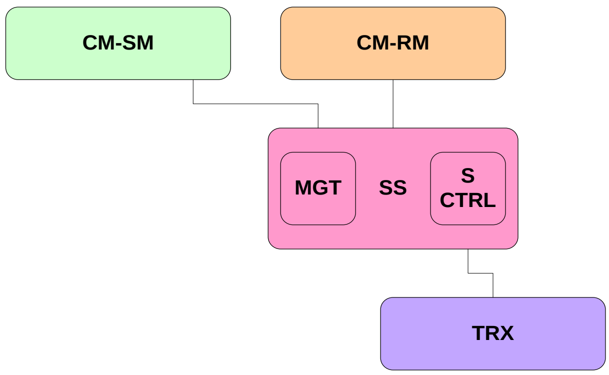

Figure 3-3 The SS exploits TRX measurements.

Sensing is used for context mapping by the CM-SM, and for incumbent detection by the CM-RM. Spectrum sensing decisions are destined primarily to the entity that requested them (CM-RM or CM-SM). However, as seen previously, they can be used also by the other entity.

3.3.2 Efficient Architecture

Description

The internals of the spectrum sensing functional block [D34] have been defined in order to efficiently interface with the rest of the QoSMOS system and to allow various spectrum sensing architectures and topologies.

The sensor control (SCTRL) controls and gathers measurements from the lower layers, such as the TRX, described later in the document, and provides sensing measurements, then collected by the spectrum sensing management (MGT) to generate a decision (e.g., Boolean), see Figure 3-3.

Benefits

This kind of internal architecture allows easy reuse of the design of spectrum sensing functionalities over diverse topologies associated to the QoSMOS scenarios. (See Table 2-1).

3.3.3 Solutions for Local Spectrum Sensing

3.3.3.1 Fast and Reliable Signal Detection with Background Process for Noise Estimation

Description

This solution considers a very reliable Energy Detector (ED) [Urk1967], [DigEtal2007] which uses a background process for noise estimation based on the statistical properties of noise [Kay1998][Poo1998][TanSah2008][TanSah2007].

Benefits

The detection probability is almost the same as for a perfect ED - which is not affected by any noise uncertainty.

3.3.3.2 Improved signal detection for PMSE

Description

Two solutions [GauEtal2010], [GauEtal2012] are proposed for detection of programme making and special events (PMSE) devices: one is based on the Teager- Kaiser detector. This detector is based on a correlator that identifies some typical characteristics of the FM signals used by PMSE devices. The second one is based on a frequency domain detector which filters out the out-band noise, thereby improving the SNR.

Benefits

Both detectors for PMSE are compared to the energy detector (ED). The advantage of the new PMSE detectors [GauEtal2010][GauEtal2012] is their better sensitivity compared to the energy detector. [GauEtal2010] [GauEtal2012].

3.3.3.3 Two-Stage Hybrid signal Detection

Description

For the OFDM and PMSE cases, a two-Stage Hybrid Detector for OFDM is composed of a Cyclostationary Detector (CD) using the Generalised Likelihood Ratio Test (GLRT) on cyclostationary peaks, and an Energy Detector (ED) An ED is characterised by a low computational complexity but has a limited detection performance. On the other hand, a CD can provide a significantly higher detection performance, but at the cost of an increased computational complexity. Therefore, both signal detection methods provide complementary characteristics that can be combined to provide an adequate design trade-off between detection performance and computational complexity.

Benefits

In both cases, the CD needs many samples for a correct decision, while ED might be affected by noise uncertainty. The Hybrid detector is a good compromise when ED noise uncertainty cannot be estimated.

3.3.3.4 Generalised Higher-Order Cyclostationary Feature Detector

Description

The generalised higher-order cyclostationary feature detector uses a cyclostationary autocorrelation function of higher order. An example has been provided for a 4^{th} order cyclostationary detector (CD4) in contrast with previous 2^{nd} order cyclostationary detector (CD2) [D33].

Benefits

CD4 may outperform CD2 only for PMSE and only when shaping functions (e.g., Root Raised Cosine) are used. It has also been shown that for OFDM transmission there is no benefit [D35].

3.3.3.5 Modified FCME algorithm

Description

The forward consecutive mean excision (FCME) signal detection method [SaaEtal2005] was modified [Var2012] to help detect malicious sensing nodes reporting 'always one' or 'always zero', because false sensing data may degrade the performance of cooperative sensing. The FCME method sets the detection thresholds using an initial set of threshold parameters. The modified FCME algorithm is run to combine binary sensing decisions, that is, consecutive sensing results from several secondary users are considered.

Benefits

The modified FCME algorithm is blind so no *a priori* information is required, and it is computationally simple. In general, it finds ‘always one’ malicious users in over 95% of the cases (P_d = 0.95) even though about 80% of the secondary users were 'always one' malicious users.

3.3.3.6 Robust spectrum sensing based on statistical tests

Description

This kind of solution is based on a novel local sensing algorithm using statistical test theory. [ArsEtal2011]. Proposed are two sensing algorithms derived from the Kolmogorov-Smirnov test (KS) sensing and Student’s test (*t*-) sensing. These algorithms are treated for the case of known noise probability, unknown noise and non-Gaussian noise. The sensing performance of these algorithms is compared with the well-known Energy Detector (ED) and with the Anderson-Darling (AD) sensing recently proposed in literature.

Benefits

The proposed *t*-sensing outperforms energy-detection ED based spectrum sensing and AD sensing, especially in low SNR regimes with less complexity. It is seen that if the noise distribution is known and Gaussian then *t*-sensing is superior in terms of detection probability, while with known non-Gaussian noise distribution KS-sensing is a better alternative.

3.3.3.7 Mobility-Tolerant Spectrum Sensing For Cognitive Radios

Description

A mobility-tolerant collaborative spectrum sensing mechanism using Neyman-Pearson’s criteria [Kay1998] [Poo1998] is considered and a framework for local spectrum sensing, in order to exploit spatio-temporal diversity due to the user mobility, is proposed.

Benefits

The obtained results demonstrate that cognitive radios can improve spectrum sensing performance if user mobility is exploited by performing multiple measurements as the sensing device moves. The suitable detector structure proposed is optimal according to the Neyman-Pearson’s criterion and the expressions for the probability of detection for spectrum sensing under user mobility are derived.

3.3.3.8 Parallel Sensing Using Smart Antennas

Description

This technique uses an antenna array and smart antenna processing to perform cyclostationary feature detection on OFDM waveforms.

Benefits

Thanks to the interference rejection capabilities of a multi-antenna system, in-band sensing can be performed by an opportunistic user without having to integrate quiet periods in its waveform. The gain in SIR (to reach a 90% probability of detection) is estimated to be -55dB by using two antennas instead of one.

3.3.3.9 CDMA Traffic Detection

Description

This technique allows for the detection of the codes used on CDMA frequency channels (UMTS/HSDPA channels). Simultaneous transmission without interfering with the incumbent users could then be possible in the code domain with codes that are orthogonal to the incumbent users' codes.

Benefits

CDMA channels are classically considered as inappropriate for CR use as they are always used by common channels. Sensing in code allows for the use of the available code resource on CDMA channels.

3.3.4 Solutions for Collaborative Spectrum Sensing

Centralised collaborative sensing is used to generate a decision at a central node exploiting the measurements from scattered sensors, all observing the same target (channel, signal, etc.) at different location and/or in different conditions (height, etc.). Collaborative sensing can therefore mitigate the hidden incumbent problem and compensate for the effects of noise, fading and shadowing, thus improving the sensing reliability.

3.3.4.1 Selective Reporting Distributed Sensing Algorithm

Description

One significant issue in collaborative sensing is the overhead required for the local sensors to transmit the information to the fusion centre. It is therefore highly convenient for energy reduction and overhead minimisation purposes to devise distributed sensing schemes that minimise the number of transmissions from the localised sensors to the fusion centre. This solution provides a method to selectively decide which sensing nodes send their sensing report to the fusion centre, thus reducing the number of sensing reports required for a certain target performance and hence reducing the energy consumption and reporting overhead.

Benefits

This allows reducing the signalling load without penalty in sensing related metrics by using censorship or silence periods.

3.3.4.2 Spectrum Sensing Based on a Beta Reputation System

Description

In the presence of malfunctioning or misbehaving users, the performance of collaborative spectrum sensing (CSS) deteriorates significantly [D35]. A proposed solution therefore is a credibility based mechanism using a beta reputation system in which the fusion centre assigns weights to each user observation based on its individual credibility score. The performance of the proposed credibility based (CF-CSS) scheme is compared with the case of equal weight combining (EWC). In EWC, the same weight is assigned to each user regardless of its credibility score.

Benefits

Compared to EWC in the presence of dubious users, the proposed CF-CSS scheme demonstrates significant improvement in reliability of aggregated information at the fusion centre in the presence of falsified users.

3.3.5 Interference Monitoring

Description

Interference monitoring is an advanced framework for incumbent protection, which combines spectrum sensing and the geo-location database approaches. The interference monitoring consists of performing measurements at monitoring nodes near an incumbent receiver to be protected in order to estimate the carrier-to-interference power ratio (CIR) of the incumbent receiver and to compensate the inaccuracy of the path loss prediction. The compensation is done by comparing the calculated root mean squared error (RMSE) to the standard deviation of the path loss estimation error. This aims at adjusting the transmission parameters (e.g., transmission power) at the operating opportunistic transmitter to adapt to a changing transmission environment.

Benefits

This authorises more optimised transmission power for the opportunistic system, in consequence, increases the number of whitespace opportunities.

3.4 Solutions for the Transceiver

The Transceiver (TRX) functional block performs synchronised data transmission, provides dedicated broadcast and multicast channels on different spectrum bands operated by the supported heterogeneous radio access technologies, and serves the SS block for its sensing decisions. It also supports the CM-RM with measurement reports and transceiver capabilities (i.e. capabilities to transmit and receive data).

3.4.1 Overview

Figure 3-4 shows the internal structure of the TRX block in the QoSMOS reference model: Physical Sensing (PHY SENS), Transmission Plane (TRX PL) and Analogue RF. The Physical Sensing deals with the integration of the physical sensing operations performed for the Cognitive Radio architecture. The Transmission Plane provides the functions required for the baseband processing of the data transmitted over the air. The Analogue RF includes the functions needed for the RF processing involved in the up-conversion and down-conversion of the baseband signals, up to the transmission part (e.g. antenna array).

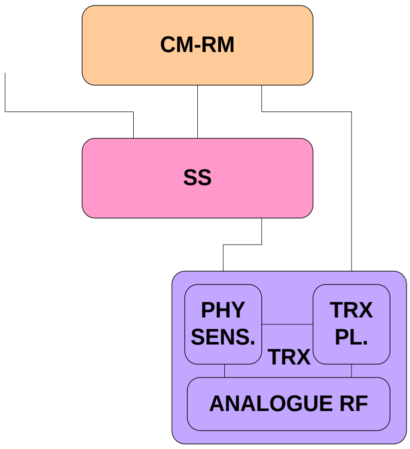

Figure 3-4 The TRX serves SS and CM-RM.

3.4.2 OFDM Windowing

Description

This solution consists in an enhancement to conventional OFDM, where the modification from a rectangular to a smooth windowing scheme allows the control of high and controlled out-of-band roll-off [D43].

Benefits

The novel windowing OFDM provides a simple and backwards compatible method for decreasing out-of-band interference and is therefore highly suitable for cognitive radio. This technique provides one more option of significant interest when simplicity and compatibility are required.

3.4.3 Interference Avoidance Transmission

Description

The solution IA-PFT (Interference Avoidance transmission by Partitioned Frequency- and Time-domain processing) is a non-contiguous OFDM transmission, which is capable of producing a notch within its transmission spectrum by using a proper combination of time windowing (TW) and cancellation carriers (CC) [D43].

The TW approach (e.g., used in IEEE 802.11a) is able to significantly reduce out-of-band emission for the centre of the notch. Alternatively, CC is known as a method to suppress the out-of-band emission at the edge of the notch. The IA-PFT is configured by a partitioned combination of CC insertion in the frequency domain and TW processing in time domain to be able to combine effect of CC and TW.

Benefits

The IA-PFT can achieve a high suppression effect for the entire band of the notch, owing to the combined effect of TW and CC. Moreover, IA-PFT realises transmission performance and PAPR performance as good as those attained by conventional interference avoidance methods.

3.4.4 GFDM and Cyclostationary Detection

Description

Generalised Frequency Division Multiplexing (GFDM) is a recent multicarrier modulation technique with extremely low out-of-band radiation that makes it an attractive choice for the PHY layer of cognitive radio [D43]. GFDM has a flexible pulse shaping technique that reduces the out-of-band leakage. It also has an innovative tail biting cyclic prefix (CP) which shows unique circular detection properties. Compared to OFDM, only the GFDM signal presents side peaks characteristics in the cyclostationary autocorrelation function (CAF). The solution uses the improved detection probability on peaks specific to cyclostationary GFDM characteristics.

Benefits

The impact of the roll-off factor on the detection result is analysed when the cyclostationary detector uses the CAF side peaks. The trade-off between the length of the CP and the roll-off factor for the detection performance is studied as well. The results show that if the roll-off factor is properly designed, it can increase the detection capability even when the CP is very low, thus allowing to transmit more useful data in the same time without decreasing the detection performance. Sensing a cognitive user’s opportunistic signal is also of importance and hence simulations have been done on sensing GFDM signals and it is found out to give better ROC curves compared to OFDM.

3.4.5 Filter Bank Multi Carrier (FBMC)

Description

FBMC [Farh2011] is a more general modulation technique providing good out-of-band radiation performance and belonging to a class of multicarrier modulations with extreme low Adjacent Channel Leakage Radio (ACLR) compared to CP-OFDM [D43], but the statistical properties of the signal such as PAPR remain the same. FBMC uses a filter bank structure, which is based on a well-designed prototype filter fulfilling the Nyquist properties. With the use of offset-QAM modulation, where the real and imaginary data are transmitted with a time offset of half a symbol duration, no data rate loss will occur compared to OFDM. Prior to transmission, the symbols are overlapped such that they can be separated at the receiver. In order to maintain orthogonality of the filter bank structure, CP cannot be used in Staggered MultiTone (SMT) systems. As a result, techniques with higher complexity must be applied in comparison to OFDM in order to combat the channel-induced inter symbol interference,

Benefits

Simulation results are shown in [D43] to compare the signal characteristics and transmission performance of the proposed scheme. Performance improvements in the ACLR can be implicitly reached without additional signal processing or data rate loss. Due to its longer symbol duration FBMC is less sensitive to timing errors as well [Kolletal2010].

3.5 Solutions for the Overall System Architecture

3.5.1 Adaptation Layer

Description

The concept of the Adaptation Layer (AL) consists of offering the necessary Service Access Points (SAPs) and data management functionalities to the different functional blocks presented earlier in the QoSMOS Reference Model. Its main scope is to enable the exchange of information and commands between the different entities involved in opportunistic spectrum access processes and in particular to dispatch spectrum sensing results to both cognitive managers, if needed [D23] [CelEtal2011]. The scheduling of messages and actions, including spectrum sensing functions, within the QoSMOS architecture have been taken into consideration when considering the AL and its interactions with other blocks. Details on this can be found in [D23].

Benefits

The heterogeneity of the different communication technologies presented in the QoSMOS system poses a challenge related to the data management and representation that can be addressed by the AL. Its functionalities enhance the overall system performance as it is monitoring the status of each entity connected to it.

3.5.2 Interface between CM-RM/CM-SM

Description

The interworking of the CM-SM and the CM-RM occurs through a direct communication interface (CM1) enabling a simple and efficient communication without the need of an AL. The split of responsibilities for spectrum and radio resource management between two cognitive managers operating, as previously seen, at different time-scales and frequency granularities adds flexibility and efficiency to the management, selection and allocation of spectral and radio resources to the QoSMOS entities. However, this requires a simple communication means for an efficient operation, which is provided by the CM1 interface. The specification of this interface includes procedures to support the reporting of spectrum usage and spectrum performance, the management of spectrum portfolio, the management of spectrum policies, and the operation of the cognitive managers. Various aspects related to this interface have been partially addressed in WP2 [D22], [D23], WP5 [D53] and WP6 [D65]. A holistic description and specification is provided in [D66] and [D67].

Benefits

The CM1 interface allows a modular architectural design with a clear split of responsibilities between the two cognitive managers while at the same time enabling a close interaction between them for a more efficient operation and improved system performance. The existence of a direct communication interface between the cognitive managers removes the need for an intermediate communication entity (i.e., the AL), which results in a simple and fast communication and therefore in a more efficient interaction and operation.

3.5.3 Topological Domains

Description

Four topological domains [CelEtal2011] [D22] are defined in order to guide the design of the cognitive functionalities. Cognitive functionalities are defined depending on the topological domain they refer to (terminating, networking, coordination, or coexistence domain) instead of assigning them directly to a specific network node, such a base station or a mobile terminal. The functional blocks defined for a topological domain are assigned to a network node only in a second step and this time depending on the topology that a specific scenario assumes.

Benefits

The cognitive system designed using these topological domains can flexibly realise diverse scenarios, such as those currently identified by QoSMOS, (as seen in section 2, they are cellular extension in whitespace, which includes rural wireless access, cognitive femtocell and cognitive ad hoc network. These scenarios are summarised in summarised Table 2-1) but more importantly, these domains can easily cope with the design of future application scenarios including those not yet clearly defined.

Regardless of the scenario and its topologies (see Figure 2-1), the RU of the CM-RM and the SCTRL of the SS stay at the terminating domain (e.g., mobile terminal or user equipment). The RC of the CM-RM, the SS MGT, and the CM-SM LOC and SEL all belong to the networking domain (e.g., at base station). CM-SM REP is at the co-ordination domain (e.g., at core network, CN), and from the CN, the NET-COORD supports the resource management (e.g., at BS). All repositories are at the coexistence domain. See [CelEtal2011] for complete mappings in relevant cases and for examples for the case of cognitive ad hoc network scenarios.

4 System Tools

This chapter gives an overview of the tools that have been developed and used within the QoSMOS project. These tools cover many aspects of protocol modelling, design, analysis and evaluation that can be used for providing reliable performance assessment and system design.

These tools are grouped as proof-of-concept (PoC), spectrum opportunity predication and system performance prediction.

4.1 Proof-of-Concept Tools

The tools described in this section contribute directly towards one or more of the PoCs carried out as part of WP7. More detail on the PoCs can be found in [D73] and [D75].

4.1.1 Scene Emulator

This tool consists of a wideband signal generator, which gives complete freedom to the user to define the emulated radio scene along the time and frequency axis. By giving these additional degrees of freedom, the system opens the door to several new testing possibilities:

- Emulating recorded/modelled radio scenes to test spectrum sensing devices
- Accurately time defined interference testing schemes
- Multi-radio & carrier aggregated advanced device testing

This scene emulator encapsulates one of the three pillars of the approach to evaluating the performance of cognitive radio systems known as “Measurement, Modelling, and Emulation”. Further details of this approach can be found in [TanEtal2012].

4.1.2 CM-SM Reference Implementation

The CM-SM reference is a C++ based implementation of the CM-SM portfolio management, which functions on top of a cognitive toolkit. The implementation provides portfolio repositories and functions for requesting, deploying and revoking portfolio. Basic functions for portfolio optimisation are provided; sophisticated portfolio optimisation functions are under development. Multiple instantiations of a CM-SM are supported to demonstrate hierarchical portfolio management. Interfaces towards CM-RMs, geo-location databases and spectrum sensors are provided on top of the toolkit’s communication framework.

The CM-SM implementation follows the QoSMOS specification of a cognitive spectrum manager. It is a unique component and also a core component of the QoSMOS concept. It is also applicable to cross-domain tasks since it incorporates interfaces for integrating wireless sensor networks for environmental sensing (beyond spectrum sensing) as well as for incident alerting, for example.

The CM-SM implementation includes a concept of Observers and Reporters into the framework. Implemented as C++ classes, Observers can capture and analyse the internal state of the CM-SM (or any client to the CM-SM if it utilises the toolkit’s functions and communication framework). Reporters interface with Observers and can format the output of an Observer into a generic log file, for an HTML5 capable Web browser or towards a MATLAB client for further online or offline evaluation and presentation. The concept is applicable to capture the KPIs of the CM-SM but requires access to the source code.

Currently only external KPIs (i.e. those that can be evaluated by observing the protocol, such as response times to a certain request) can be observed and reported. Response times for some of the basic functions (e.g. a CM-RM requesting a portfolio from a CM-SM) have been measured. Those range from below 1ms to 15ms for a single concurrent client and for simple portfolio composition that could be satisfied from the local portfolio repository of the CM-SM requested. In practice those figures are of no great relevance since more realistic scenarios will differ strongly depending on the experiment set-up.

4.1.3 TVWS Geo-Location Database

This database pre-computes tables of TV channel occupancy, with predicted signal strengths using a propagation model. The spatial resolution is typically 250 metres. A web demo, which can be found at the address: http://www.ict-qosmos.eu/project/demos.html, uses an interface to communicate with the XML-RPC server, which allows for remote queries over the internet. This database connects to a QoSMOS system via the CM-SM reference implementation described in the previous subsection.

This database is unique in terms of a non-commercial geo-location database. It allows accurate modelling of specific proposed TVWS deployments, and allows computation of country-wide statistics on channel availability.

The database would typically be assessed by three measures:

1. Agreement of predicted signal strengths with actual measurements.
2. Speed of database access – As this is currently a demo this assessment is not currently so important or informative.
3. Other database metrics such as the number of simultaneous queries supported.

4.1.4 Adaptation Layer

The demonstrator of an Adaptation Layer (AL), whose implementation has been included in [D23], aims to present the benefits of using an element in charge of centralising the distribution of notifications and information related to the events that happen in the QoSMOS system. These events cover the following situations: connection of new entities, disconnection regardless of the cause and translation of information packets between entities based on different technologies.

The demonstrator consists of two entities sharing the same kind of information, one acting as provider and the other requesting it. Since initially they are not connected and they are not aware of the presence of the other, not all requests receive a response. The first thing to do is to register them in the AL. At this point the AL creates two entries in its database and matching the information identifier of both entities detects that they can interact. Due to this, the AL sends a message to both entities informing them about the communication parameters of the other entity enabling the direct communication between them. The second part of the demonstrator shows how the AL is able to translate messages. A third entity based on CORBA with the same information identifier as the previous two is registered in the AL. In order to allow communication between the new entity and one of those already registered, based on XML-RPC, the AL translates the information message. The message includes some overhead identifying the destination entity and the message itself. The AL automatically connects both entities using the control information included in the message, enabling communication via the AL between the two entities.

The evaluation of the AL included in [D53] was based on stressing the system in different setups so as to get the values of different parameters that define the performance and limits of the AL. The key parameters evaluated are related to the impact to the system of introducing the AL, mainly latency and delay introduced by the use of the AL in the different scenarios where the AL operates.

4.1.5 QoSMOS RF Board

This is a frequency-agile RF transmitter with low out-of-band leakage, a frequency-agile RF receiver with high sensitivity and input dynamic range, and a small form factor.

The benefits of this RF board include the small form factor, covering a wide input frequency range, frequency-agility and digitally programmable RF components.

This board could be evaluated with a comparison with existing RF transceiver chips with wide input frequency range Typical KPIs would include:

- Input frequency range
- Signal bandwidth
- Out-of-band leakage, SFDR, or suppression of spurious harmonics
- Receiver sensitivity and dynamic range
- Transmitter maximum output power dynamic range

Some testing has already been carried out. [JasEtal2012] shows results on the frequency-agile filter characteristics and [NogEtal2012] shows results on the baseband and RF front-end performance.

4.1.6 QoSMOS Demonstration Board

This demonstration board has a small form factor and is a computationally powerful demonstration board. The frequency agile RF board described in the previous subsection can be plugged onto this board, which then performs the baseband operations. This demo board, along with the RF board, can be thought of as a combined PoC.

The benefits of this board include, its small form factor, plus both hardware (FPGA) and software (processor) computational capabilities.

The board could be evaluated by comparison with existing development kits. KPIs could include:

- Processing power
- Form factor
- Power consumption

A comparison of this board with existing boards is carried out in [BerEtal2012].

4.1.7 Selective Reporting Distributed Sensing

This tool consists of an implementation of a selective reporting distributed sensing platform. The platform is made-up of a set of sensors, implemented with Ettus USRP hardware and the GNURadio SDR platform, and a central Data Fusion Unit, also implemented using the GNURadio SDR platform. The sensors report the local sensing decision to the Data Fusion Unit that generates the final decision on the presence of a user in the RF channel. The solution is configurable by the user that sets the sensing parameters: RF channel, number of samples used to generate a decision, sensing interval. The solution outputs the presence of a user in the RF channel

This tool is unique to QoSMOS. The implementation proves the reduction in the sensing signalling load without penalty in the sensing related metrics.

The sensing platform can be evaluated experimentally feeding each sensor with an independently faded incumbent/opportunistic signal and measuring sensing metrics such as:

- Probability of detection
- Probability of false alarm
- The network signalling load

Initial results show that the sensing metrics are not affected by the introduction of the selective reporting and that the new algorithm achieves a 50% reduction in the signalling load.

4.2 Spectrum Opportunity Prediction Tools

These tools can be used to improve prediction of what spectrum opportunities are available and could therefore be used to increase the number of spectrum opportunities made available to secondary systems.

4.2.1 Statistical Model for Opportunity Detection Based on Long-Term User Activity Estimation

The long-term observation of ON/OFF activity of incumbents and opportunistic users may lead to the large-scale overview of a cognitive system. The observed activity duration statistic can be used to build a model to express the distribution of the length of the activity and the activity-free periods. The opportunity could be detected for a cooperative operation by using the incumbents' and the opportunistic users' channel utilisation probability distributions. A probabilistic model, based on Markov chains, has been developed from real spectrum usage and network utilisation measurements. The model uses statistics about primary user behaviour to improve performance (capacity) in the secondary system.

The opportunity detection method is intended to be used as a general tool. The required algorithms can be implemented in the CM subsystem in order to support the decision mechanisms of the resource and spectrum management system. The results can be easily adapted for different operational environments, if training data is available to parameterise the stochastic models.

The tool can be evaluated with the statistics of spectrum mal-usage (described in the following section). The effective measure of the KPI is the estimation of the probability of activity duration. Results for the detection of opportunities in IEEE 802.11 wireless access can be found in [CsuEtal2011]. Further details on this tool can be found in annex B of [D65]. This includes a description on the how the tool can be implemented into a QoSMOS system and how it could be used by networks based on the IEEE 802.22 standard. Initial results include the predicted off and on probability for different numbers of users.

Performance is evaluated through network level simulations for the use of ON/OFF incumbent user (IU) statistics in a network based on the IEEE 802.22 standard [D66] [D67]. The IEEE 802.22 network consists of a base station and a set of opportunistic users (OUs). The IUs are unregistered wireless microphones operating in the UHF channels not used by TV broadcasters, hence available for use by the IEEE 802.22 network. The OUs senses IU activity on the available channels and reports the measurements to the CM-SM, which further uses these measurements to calculate the ON/OFF statistics for each channel. If the sensed signal is above a certain threshold, the OUs switch to the vacant channel with the highest probability of being available according to the ON/OFF statistics. The IEEE 802.22 network also switches channel proactively based on the ON/OFF statistics.

4.2.2 Mal-Usage Detection and User Activity Modelling

The investigated area includes locations in a TVWS environment where the primary service is not available due to low local received signal quality, characterised by the SINR value. In this case the channel can be utilised for other purposes, e.g. for secondary usage by cognitive radios. For this case, a moving cognitive radio is studied and modelled, emphasising the role of the CM during the decision process. The efficiency of the CM operation can be qualified by the statistics of the mal-usage, like the number of erroneous channel usage that can be false positive or negative as well. See [D64] for further details.

Applying a geographical database of the SINR guaranteeing incumbents' services, the gathered location information of the opportunistic users can determine the possibility of the secondary usage of whitespaces. This method requires a periodic position update at the CM reported by the moving user. As the exact location is unknown between two consecutive reports, the opportunistic user may violate

SINR requirements of the primary system. The outcome of this model is the description of the effect of location sampling on the system conformance measured by mal-usage of the available resources.

This is a tool to detect the spectrum mal-usage for mobile cognitive radio in a TVWS system. The signal quality and the opportunity for cognitive usage are modelled by a geographical database and transmitter/receiver physical parameters. Key metrics of the performance are the ratio between the modelled and real mal-usage of the spectrum. As the real mal-usage can be measured only after a (possible) mal-usage, this continuous KPI changes during the user movement. It can be given as a probability or percentage value. Results using this tool for the detection of the opportunity in TVWS can be found in [CsuEtal2012].

4.2.3 Statistical Model for Spectrum Opportunities for Cognitive Radios

Probability and approximation theory has been used to quantify the number of spectrum opportunities. A Probability Mass Function (PMF) is derived and shown to be computationally intensive. This model therefore uses derived approximate models like, for example, the Camp-Paulson (CP) model.

From analysis and simulation, it can be seen that the proposed CP approximate model provides accurate information and better approximation about spectrum opportunities for cognitive radios and is far less computationally intensive compared to the PMF model. Further details on this tool can be found in [ArsEtal2011c].

The accuracy of this tool has been evaluated using simulations. In particular, the binary idle/busy occupancy pattern of a number of channels have been generated independently, assuming exponentially distributed period durations and considering various scenarios (all channels with a low duty cycle, all channels with a high duty cycle, and all channels with arbitrary duty cycle values with some arbitrary variance). The state of all channels is then observed at various time instants and the PMF of the number of free channels is computed based on the simulation data. Three probability distribution models (normal, Camp-Paulson and Poisson) are compared in order to determine the model that best fits the simulation data, based on the maximum absolute error (i.e., maximum absolute difference between each model and the simulation data). The computational efficiency of each model is also evaluated in terms of the required computation time.

The accuracy of the considered models have been evaluated in terms of the maximum absolute error. The obtained simulation results in Figure 4-1 indicate that the Camp-Paulson based spectrum opportunity model provides an accurate approximation (in terms of the maximum absolute error) to the real PMF of the number of free channels in a band and with less computational complexity for most of the scenarios.

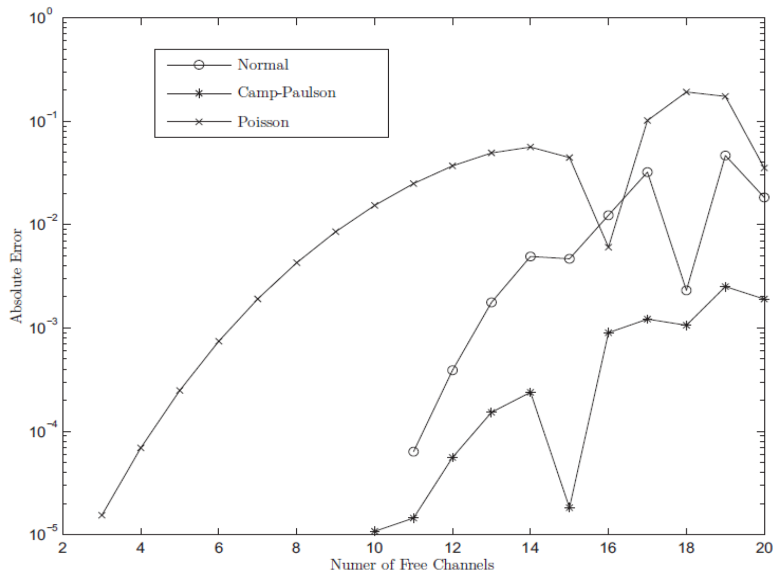

Figure 4-1 Absolute error of the considered models when the total number of channels in the band is 20 and the duty cycle of each channel is high with very low variance.

4.3 Performance Prediction Tools

These tools can be used to predict the performance of a system, based on its current settings and environment. These tools might therefore also be used in optimisation of parameters.

4.3.1 PHY Layer Abstraction

The main purpose of physical layer (PHY) abstraction is to predict link performance of the communication system based on a small number of measureable metrics. It can be applied for simplified system performance evaluation and also for dynamic adaption of the parameters in order to match the predefined performance limits. Further details can be found in [D53].

The benefit of this tool is that fast system level evaluations can be performed without the need for an exhaustive search or detailed, extremely time consuming, link-level simulations within the system-level simulator.

The PHY abstraction tool was developed for FBMC so its performance can be compared to OFDM and evaluated through this comparison. The performance can be evaluated through Monte Carlo simulations using training and evaluation sets. The task of PHY layer abstraction within the system-level simulation is to compose a simple technique that can compress a large set of parameters and predict the final BLER of the communication link. The result is a MATLAB simulation tool that is used to calculate the coefficient which can be further used to map the SINR values with a given channel profile to BLER performance.

4.3.2 Contention-Based MAC Optimisation

This tool allows for the performance of contention-based MAC layers to be optimised in terms of throughput. This can be used in saturated and non-saturated conditions. The model has been demonstrated with IEEE 802.11 and ECMA-392 systems, providing insight into the effects of different parameter settings.

A QoSMOS system is able to support multiple radio access technologies (RAT). In order to select the correct RAT to use it must be able to calculate the expected performance of each RAT and to optimise its performance. This ability to consider contention-based RATs is of particular use when sharing a channel with other contention-based users.

The typical output of this tool is to predict the throughput performance of a system. This can be evaluated by comparing the calculated performance with actual measurements or simulations. The tool also allows for a system to quickly optimise its parameters. In this case, the performance would be evaluated as the optimised throughput achieved in comparison to the throughput achieved in the non-optimised system that uses default values.

More details about this model can be found in [MacEtal2012] [D53]. Results demonstrate just how greatly contention-based throughput performance can be improved with only a small set of operating parameters. Results also show how optimising throughput not only improves throughput performance but can also reduce the level of aggregate interference caused by secondary systems contending for the channel at the same time.

4.3.3 Effects on QoS of Cognitive-Incumbent Users' Interaction

The effects on QoS due to the interaction of incumbent and opportunistic users has been investigated using a Markov chain model [D53]. This tool assesses the QoS of both incumbent and opportunistic users in the presence of inaccurate spectrum sensing. The work presents a continuous-time Markov chain-based analytical framework for analysing the performance of cognitive radio networks. The proposed model incorporates key elements such as multi-channel support, handoff capability, imperfect sensing as well as state-dependent transition rates. Extensive Monte Carlo simulations have been provided to validate the accuracy of the proposed model.

The analytical model provides a tool for evaluating performance of cognitive radio networks using the following performance metrics (described further below): (1) Incumbent user termination probability and blocking probability; (2) Opportunistic user success probability, blocking probability, as well as forced termination probability; (3) Radio resource utilisation.

The definitions for some of the performance metrics that could be used to evaluate the tool's performance include:

- Incumbent user blocking probability - This is defined as the probability that an arriving incumbent user call will be blocked because all radio channels are occupied by incumbent users.
- Incumbent user termination probability - This is the probability that an incumbent user call, which has not been blocked initially, is terminated due to collisions with opportunistic users because of misdetections.
- Opportunistic user forced termination probability - This is the probability of dropping an active opportunistic user call due to the arrival of an incumbent user to a channel occupied by an opportunistic user.
- Opportunistic user successful probability - Defined as the probability that an opportunistic user call has completed the service and normally terminated.
- Opportunistic user blocking probability - Defined as the probability that a newly arrived opportunistic user connection request cannot be accepted due to insufficient radio resources or the inability of the opportunistic user to find free channels with a certain false alarm probability.

4.3.4 System-Level Simulator

This tool is a sophisticated system-level simulator with a detailed implementation of an LTE cellular network incorporating an incumbent DTT system. The implementation of the LTE component is divided into three modules as shown in, Figure 4-2. The main module integrates general aspects such as the cellular layout/deployment, mobility and traffic models, path loss models, shadow (slow) fading models, multipath (fast) fading models and antenna radiation patterns. A downlink module integrates aspects related to the downlink of the LTE system (scheduler, link adaptation, handover and other radio resource management methods for the downlink). Finally, an uplink module integrates similar aspects related to the uplink. The incumbent DTT system is composed of a DTT transmitter at a configurable distance from the LTE network and takes into account the intended coverage area and operation conditions required by the DTT receivers. The mutual interference between the LTE network and the DTT system and its impact on the final performance of both systems is implemented as well. More details can be found in [D65] and [D66].

All of the models and simulation methods implemented in this tool have been taken from appropriate and well-known references in the existing literature, where not only the models are described but also validation results guaranteeing the realism and accuracy of such models are provided. This guarantees the realism and accuracy of the results obtained with this sophisticated simulation platform.

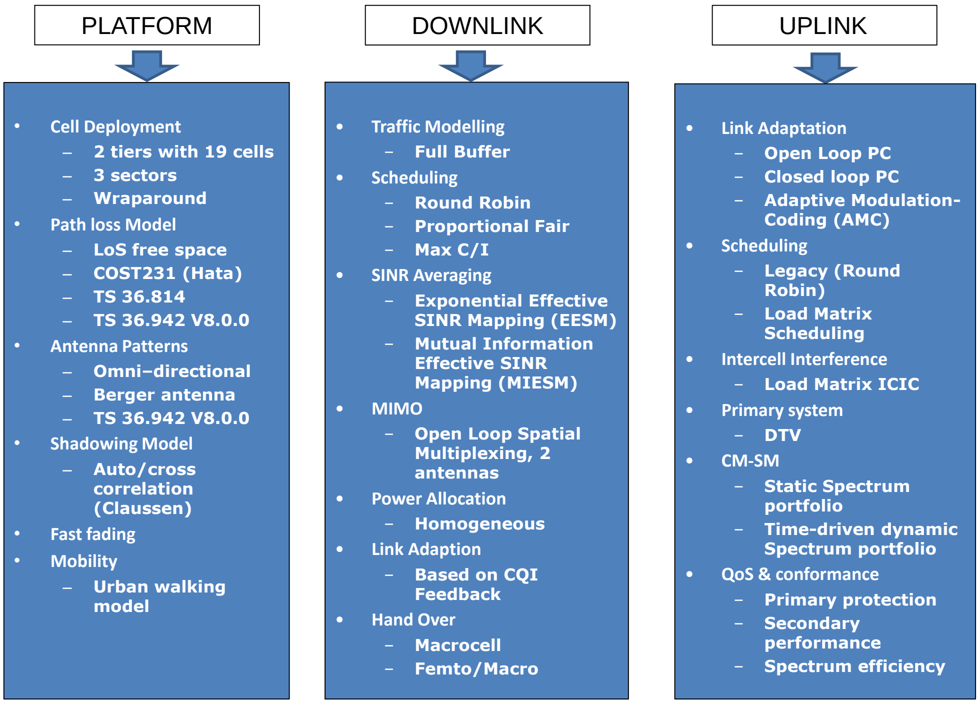

Figure 4-2 The three modules of the LTE implementation of the simulator

This tool is employed to determine, by means of system level simulations, the conditions under which the uplink component of an LTE system and a TV system can coexist in the same TV spectrum. This can provide useful conclusions and guidelines that can be exploited in spectrum management when deciding on the selection of TV bands for opportunistic operation of the LTE uplink component.

4.3.5 Model Based on Measurements

Measurements have been collected in the ISM, GSM and UMTS bands. These measurements can be used, not only to characterise the occupancy of the bands, but also to validate or tune sensing algorithms [TanEtal2012].

Occupancy results on ISM bands based on power measurements have been compared with the access point logs taken from the public access network of Oulu (panOULU) during one week. The results showed that there is a very good agreement with the actual WLAN activity logs. The slight deviation from the logs may be due to non-panOULU WLAN traffic, non-traffic beacon signals and other interference. These measurements allow for the tuning and validation of the energy detection algorithm developed. [LehEtal2012b]

Measurements were also performed on all of the E-GSM and GSM800 bands during 24hours in order to compare the spectrum occupancy (the percentage of spectrum band used) with the traffic occupancy (the amount of traffic in the bands that a UE could use at the measurement point). The difference between spectrum occupancy and traffic occupancy can be quite large (46% versus 0% during night times). This is mainly due to the broadcast channels that are always used. Frequency hopping also increases this difference. It means that the network planning used by an operator can drastically change spectrum occupancy for a fixed amount of traffic. It also highlights the fact that for some RATs, the spectrum occupancy is not the right metric to compute.

5 System Performance Evaluation

The technical solutions developed to address the QoSMOS objectives, (mostly QoS management within an opportunistic system, mobility support and incumbent protection) which were presented in chapter 3, have been evaluated in order to assess their performance and provide quantitative evidence of the gains and benefits derived from the QoSMOS solutions. This section presents the final version of the metrics used in the different workpackages to evaluate the performance of the developed solutions and provides an overview of the most representative performance results of the QoSMOS solutions. While these results offer illustrative examples, references are given, when appropriate, to show where further evaluation results can be found.

5.1 Performance Metrics

Various evaluation criteria and performance metrics have been used to assess the gains and benefits of the QoSMOS solutions investigated in the different workpackages. These criteria and metrics have been designed in such a way that the overall performance of the QoSMOS system is fairly and consistently assessed on a technical basis (the evaluation of the QoSMOS solutions with respect to costs is out of the scope of this document but a detailed analysis can be found in [D16]).

A list of performance metrics was provided in Section 5.2 of [D23], categorised into Spectrum Utilisation Metrics (SUM) and Service Performance Metrics (SPM). SUMs quantify how well and efficiently a particular solution can exploit a spectrum hole (i.e. an unused spectrum resource defined in frequency, time and space). Some examples of SUMs are (see [D23] for details):

- Spectrum efficiency.
- Overhead.
- Frequency reselection time.
- Sensing performance.
- Air interface flexibility.
- Spectrum information latency/timeliness (from sensors and/or databases).
- Operator fairness.

On the other hand, SPMs evaluate the ability of a solution to fulfil the user requirements and expectations in terms of the experienced Quality of Service (QoS) under given constraints. Some examples of SPMs are (see [D23] for details):

- User throughput.
- End-to-end delay.
- Grade of Service (GoS).
- User fairness.
- Probability of a blocked/dropped session.
- Probability of a handover failure.

In addition to the SUM/SPM classification above, and following the classification proposed in [ZhaEtal2009], a list of complementary metrics was provided in Section 8.4 of [D23]:

I. Situation (context) awareness capability.
   - Distortion of the sensed information.
   - Incorrect opportunity detection.
   - Location accuracy and availability at various environments.
   - Awareness of receiver operation characteristics.
   - Spectrum sensing time.

- Mobility and trajectory awareness.
- Radio channel condition awareness.
- Energy efficiency awareness.
- Context awareness.
- Network topology awareness.
- Awareness of the adaptation capabilities of other nodes or parts of the network.

II. Adaptation/transmission capability.
- Transmission adaptability.
- Routing protocol adaptability.
- Topology adaptability.
- Average response time to network changes.

III. Efficiency of the decision making, planning and learning processes.
- Reasoning capability.
- Decision making algorithm convergence time.

IV. Performance of the cognitive radio system.
- Reliability.
- Delay in response to system requests.

V. Complexity.
- Signal processing requirement.
- Signalling loads.

The metrics listed above provide a detailed framework for the performance evaluation of the solutions integrating the QoSMOS system. These metrics, however, may accept slightly different definitions depending on the context and particular considerations. Since a rather general definition was provided in [D23] for the presented metrics, Table 5-1 provides a precise definition for some selected metrics as used in the evaluation of the QoSMOS solutions. For each performance metric, Table 5-1 specifies the metric name, its description, a unique identifier (for future references throughout this document), the units of the metric, and the classification of the metric according to the criteria followed in [D23], as summarised above, to show how the metrics defined in WP2 are aligned with the metrics employed in workpackages WP3 to WP6. While the list in Table 5-1 is not necessarily exhaustive (i.e., a wider set of performance metrics were actually analysed when evaluating the performance of the QoSMOS solutions), the presented list provides a sufficiently comprehensive set of performance metrics capable to illustrate in a quantitative way the main merits of the QoSMOS solutions. It is also important to mention that each QoSMOS solution is aimed at improving the performance of a particular aspect of the QoSMOS system. The same aspect of the system performance can frequently be evaluated based on several metrics that provide alternative ways to quantify the performance improvement of the same particular aspect, but show a similar trend and therefore provide redundant information. For this reason, the assessment of a particular aspect of the system performance does not require the evaluation of every possible metric and, in fact, a single metric, or a reduced set of metrics, may often suffice to numerically assess the aspect under evaluation and provide quantitative evidence of the benefits obtained with the evaluated solution. Therefore, the gains and benefits of the QoSMOS solutions are illustrated based on a selected set of performance metrics, which are presented in Table 5-1. Appropriate references to other deliverables and published documents where a more detailed performance evaluation is available, including some additional metrics, are provided where applicable.

Table 5-1 List of selected metrics employed in the evaluation of the QoSMOS solutions. The classification is explained in the text

Metric ID	Metric Name	Description	Units	Classification
Thr	Throughput	Total number of bits correctly received per time unit	$bit \cdot s^{-1}$	SPM, IV
BER	Bit error rate	Quotient between the number of bits incorrectly received over a predefined time interval and the total number of bits transmitted (correctly or incorrectly) over the same predefined time interval	Dimensionless	SPM, IV
BLER	Block error rate (BLER)	Quotient between the number of data blocks incorrectly received over a predefined time interval and the total number of data blocks transmitted (correctly or incorrectly) over the same predefined time interval	Dimensionless	SPM, IV
Ret	Return	Numerical value provided by a predefined mathematical utility function used to quantify the benefit of incumbent/opportunistic transmissions	Dimensionless	SPM, IV
Ris	Risk	Variance of the return	Dimensionless	SPM, IV
NRet	Normalised return	Numerical return value divided by either the bandwidth employed for such transmission (bandwidth normalisation) or the total number of transmitted bits per time unit and bandwidth (spectrum efficiency normalisation)	Hz^{-1} or $(bit \cdot s^{-1}) \cdot Hz^{-1}$	SPM, IV
NRis	Normalised risk	Numerical risk value divided by either the bandwidth employed for such transmission (bandwidth normalisation) or the total number of transmitted bits per time unit and bandwidth (spectrum efficiency normalisation)	Hz^{-1} or $(bit \cdot s^{-1}) \cdot Hz^{-1}$	SPM, IV
CC	Computational complexity	Number of calculations	Natural number	SPM, V
CBR	Connection blocking rate	Probability/rate of new incoming connection (service request) being rejected within the system (i.e., blocked)	Dimensionless	SPM, IV
CDR	Connection dropping rate	Probability/rate of already established communications being terminated unexpectedly (i.e., interrupted prematurely), whatever the cause	Dimensionless	SPM, IV
NLoad	Normalised load	Ratio of the number of active users to the total number of supported users	Dimensionless	SUM, II
SRC	Spectrum resource consumption	Number of spectrum resources (i.e., channels) used for the transmission(s) of a predefined set of users	Natural number	SUM, II

COutC	Cell outage capacity	Capacity of a cell, expressed in terms of the total number of bits correctly transmitted per time unit and per bandwidth unit, when the number of users in outage is equal to a predefined target value	$(\text{bit}\cdot\text{s}^{-1})\cdot\text{Hz}^{-1}$	SUM, IV
OpChA	Opportunistic channel availability	Number of incumbent channels available for opportunistic transmissions	Natural number	SUM, II
PBCS	Probability of best channel selection	Probability to select from a given spectrum portfolio the best-suited channel to meet a set of particular user needs	Dimensionless	SUM, I
EComp	Energy consumption	Amount of energy consumed by a given terminal, set of terminals or other network elements	Joule	SUM, IV
ATxPow	Allowable transmit power	Maximum transmission power for an opportunistic transmission that guarantees a predefined interference target to the incumbent system	mW or dBm	SUM, II
Int	Interference	Undesired signal power from opportunistic users received at a primary receiver	mW or dBm	SUM,II
ACLR	Adjacent Channel Leakage Ratio (ACLR)	Ratio of the transmitted power to the power in the adjacent radio channel.	dB	SUM, II
PAPR	Peak-to-average power ratio (PAPR)	Ratio of the peak power of a signal to its root-mean square (RMS) value	dB	SUM, II
RMSE_Int	RMSE of interference measurement	Root-mean-square error of the measured interference with respect to the real interference	dB	SUM, I
STD_Int	Standard deviation of interference measurement error	Standard deviation of the absolute difference (error) between the measured interference and the real interference levels	dB	SUM, I
Notch	Notch depth	Difference between an original reference signal and a version of the signal attenuated over a specific range of predefined frequencies	dB	SUM, II
NSSL	Network sensing signalling load	Number of sensing reports per user and per time unit	s^{-1}	SUM, V
Pd	Probability of detection	Probability that a signal detection method declares an incumbent signal to be present in a sensed channel when it actually is present	Dimensionless	SUM, I
Pfa	Probability of false alarm	Probability that a signal detection method declares an incumbent signal to be present in a sensed channel when it is not present	Dimensionless	SUM, I
CMT	Channel move time (CMT)	Time period elapsed between the detection of an incumbent user transmission in an incumbent channel used by an opportunistic user, and the time instant when the opportunistic user vacates the channel	s	SUM, II

5.2 Performance Results

This section summarises the assessment method and metrics considered for the performance evaluation of each QoSMOS technical solution and shows several performance results illustrating the gains and benefits derived from the solutions integrating the QoSMOS system. The performance metrics analysed in each case are cited with their corresponding ID from Table 5-1 between brackets.

5.2.1 Performance of Solutions for the Cognitive Manager for Spectrum Management

5.2.1.1 Cognitive Spectrum Management by Joint Energy and Spectrum Control

Evaluation Procedure and Metrics

The maximum achievable rate in a femtocell is analytically evaluated within a given outage probability when limiting the interference at the nearest victim, caused by the networked femtocells. The main considered performance evaluation metric is the cell outage capacity (*COutC*) and the analytical results are confirmed by means of system-level simulations.

Results

Consider the cellular extension to the cognitive femtocell scenario. For simulations, a femtocell deployment is considered in a 5x5 grid layout of geographical environment such as, for example, enterprise environments. Here, both penetration and propagation losses are in line with 3GPP deployment parameters. On this layout, the co-channel deployment of femtocells is considered, where each intends to access the radio spectrum licensed to the macrocell.

It can be found in Figure 5-1 that for a given number of sub-channels, the proposed QoSMOS approach benefits from a higher outage capacity without requesting any extra energy usage in a femtocell. Particularly, it can be shown in this figure that the outage capacity is an increasing function of the number of sub-channels available. Also, it is illustrated in this figure that there are multiple discrete regions, where the outage capacity is maximised only by a subset of *n* active sub-channels. For example, when 4 sub-channels per FUE are available, activating only 2 out of 4 sub-channels improves the outage capacity by about 2.5 bit/s/Hz/cell, as compared to the case when activating 4 sub-channels.

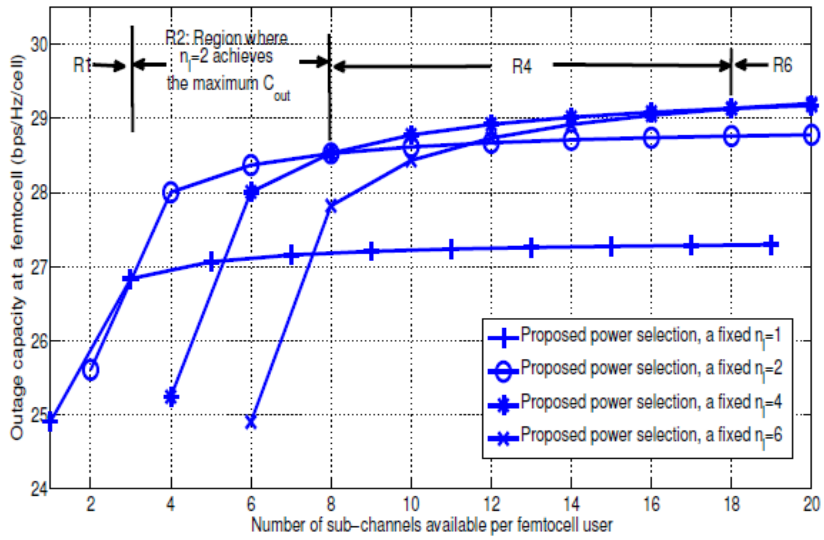

Figure 5-1 Impact of activating a subset of all sub-channels on the outage capacity

Distributive Self-Learning SON

Evaluation Procedure and Metrics

This QoSMOS solution has been evaluated via system simulation studies. The developed distributive self-learning approach has been proven and validated, its characteristics have been analysed and its performance has been assessed. The main performance metrics employed in the evaluation process are the throughput (*Thr*), the average user quality-of-service in terms of the average user data rate (*QoS*), and the energy consumption (*EComp*), which are analysed for cell areas as well as combined ones for larger local areas. Concretely, a combined metric is used as an optimisation target, which is defined based on the above mentioned metric as $Metric = Thr + QoS - EComp$. Within the SON algorithm, which compares different configuration options, all metric-contributions are normalised to prevent the SON technique from being affected by cell-specific aspects such as size or traffic load.

Results

The obtained simulation results validate this approach and indicate that it behaves and performs correctly, that the cognitive nodes adapt themselves in a self-learning way to the current situation and constraints in a very fast way by means of pure offline calculations without the need to carry out mobile measurements. This solution is a generic approach that can be transferred to all kinds of cellular networks with distributed decision-making entities and some kind of interactions or couplings. Detailed simulation results are available in [D67].

5.2.1.2 Portfolio optimisation

Evaluation Procedure and Metrics

The gains and benefits of this QoSMOS solution have been evaluated based on capacity and economic performance metrics such as risk and return. The set of metrics considered in this study include: the average throughput (*Thr*) of primary and secondary user transmissions; the average number of spectrum resources (*SRC*) allocated for primary and secondary user transmissions; the average interference from secondary to primary users (*Int*); the normalised load (*NLoad*); the average risk (*Ris*) normalised per hertz or per transmitted bit/s/Hz of spectrum in primary and/or secondary transmission; the average return (*Ret*) normalised per hertz or per transmitted bit/s/Hz of spectrum in primary and/or secondary transmission; and the average return to average risk ratio.

Results

In the testing scenario proposed with two WiMAX networks, it was observed that an optimum value of the parameter that measures the balance between return and risk in the multi-objective function can also lead to maximum throughput in the Pareto solution if one of the frequency bands (primary transmission) has a higher return and also lower risk than the other frequency bands (secondary or opportunistic transmission). This also means that despite not using realistic values of return and risk, the results obtained for this solution give an indication of the range of values that provide optimum performance of the opportunistic cognitive radio network. Further results are shown in [SamEtal2012] and [SamEtal2013].

5.2.2 Performance of Solutions for the Cognitive Manager for Resource Management

5.2.2.1 Cognitive Access Control and channel selection

Evaluation Procedure and Metrics

The performance of cognitive access control (CAC) solutions for the cellular extension scenario and the cognitive ad hoc network scenario have been evaluated by means of system-level simulations. For the cellular extension scenario, the proposed solution has been evaluated based on the implementation of an LTE system simulator model, encompassing several base stations operating in an urban area and controlling for each of them three different sectors and a set of user equipment deployed uniformly in the simulated region, moving at 5km/h according to a straight direction, randomly defined. For the cognitive ad hoc network scenario, appropriate simulation models have been implemented as well. The objective of the analysis is to characterise the impact of the incumbent apparition on the system performance and to quantify the benefits of the cognitive access control algorithm. In particular, key references are first generated by configuring the simulator to operate with no incumbent users. Then, the apparition of incumbent users is enabled and its impact on the system performance is evaluated. Finally, cognitive access control algorithms are also activated to evaluate their capacity to mitigate the impact of incumbent users. The performance of the QoSMOS cognitive access control solutions have been assessed based on the connection blocking rate (*CBR*) and the connection dropping rate (*CDR*).

The performance of channel selection algorithms have been evaluated by means of system-level simulations. Besides the system performance itself, other aspects analysed in the study include the reactivity of opportunistic networks to the apparition of incumbent users or to mutual interference of opportunistic cognitive ad hoc networks along with the verification that opportunistic cognitive ad hoc networks do not impact the performance of incumbent users. The main performance metrics analysed in the evaluation of channel selection algorithms are the probability of selecting the best operating channel in the portfolio to meet the needs of the opportunistic cognitive ad hoc network in terms of traffic demands (*PBCS*), the throughput (*Thr*) of both the opportunistic cognitive ad hoc network and the incumbent network, and the reactivity of the system, in terms of freeing and switching time of the operating channel, to the apparition of incumbent users and to mutual interference among cognitive ad hoc networks (*CMT*).

Results

For a cellular extension scenario of an LTE network, Figure 5-2 [D53] shows the connection dropping rate (*CDR*) in absence of incumbents (circle marks, blue colour) and with no cognitive access control (CAC off, triangle marks, red colour), both used as a reference. These are contrasted with the curves illustrating the performance of a cognitive access control for the cellular extension in the whitespace scenario (LTE). Two options are shown, a reactive mode (square marks, green colour) and a preventive mode (diamond marks, violet colour). The benefits of the predictive mode are visible when observing the *CDR* and the connection blocking rate (*CBR*) in time, see Figure 5-3. The effects of the prediction window size have also been investigated in [D53].

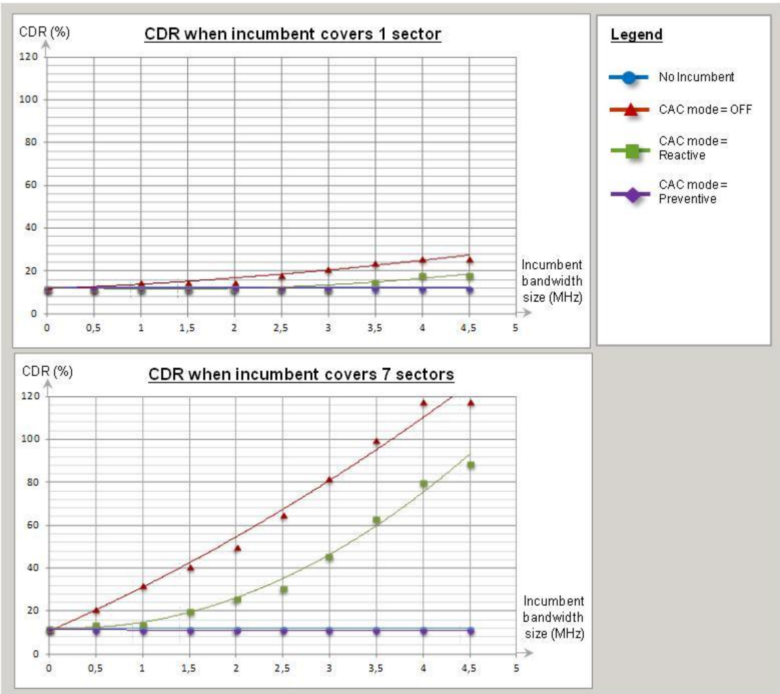

Figure 5-2 CDR vs. incumbent bandwidth size

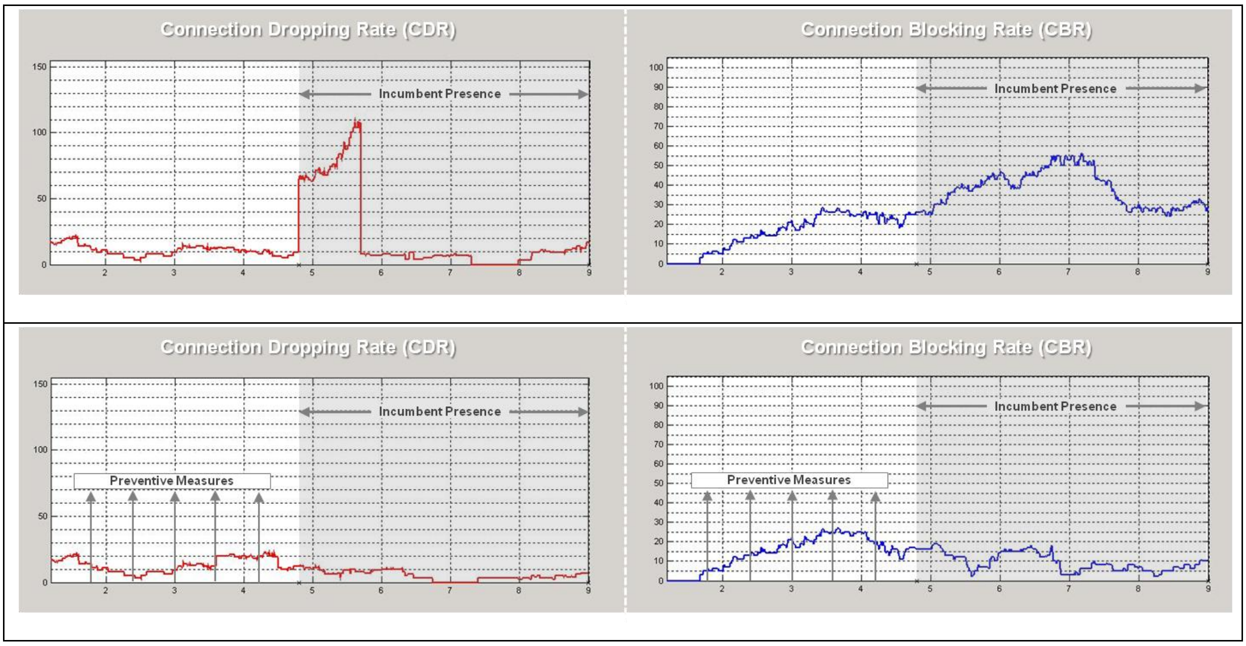

Figure 5-3 CDR/CBR vs. time, with CAC off (above) and with CAC in preventive mode (below)

For a cognitive ad hoc network scenario, Figure 5-4 shows the probability that the *k*-th channel identified by the channel selection algorithm gives the best network sum-rate for the active traffic links. The channel selection and acquisition algorithm is used in both the event of incumbent user protection and for the cognitive ad hoc network coexistence scenario. The channel selection algorithm permits the selection of the best-suited operating channel for active traffic links, while the channel acquisition protocol allows the reduction and conflict-resolution of operating channels among cognitive ad hoc networks.

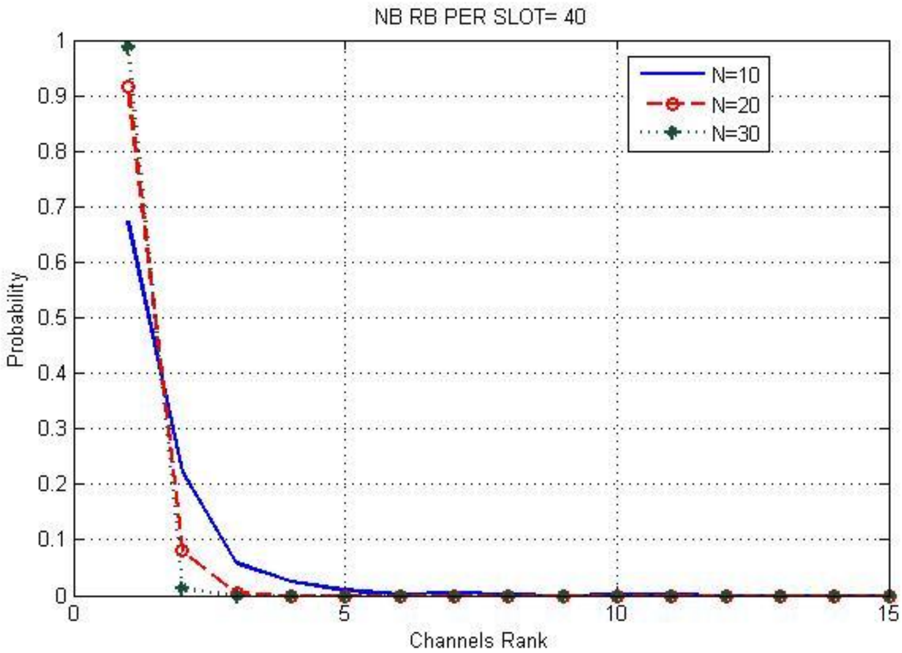

Figure 5-4 Probability of best channel selection

Figure 5-5 shows the achieved sum throughput of an incumbent and an opportunistic cognitive ad hoc network subject to temporary mutual interference. It can be observed that immediately at the beginning of the interference phase the throughput of the cognitive networks deeply decreases, while the throughput of the incumbent network remains unchanged. The decrease is because as soon as the nodes of the cognitive ad hoc network sense the presence of the incumbent users they stop transmitting data to not interfere with the incumbent network. The cognitive ad hoc network then changes the operating channel and restores the data transfers. These results show the efficiency of the incumbent user protection mechanism.

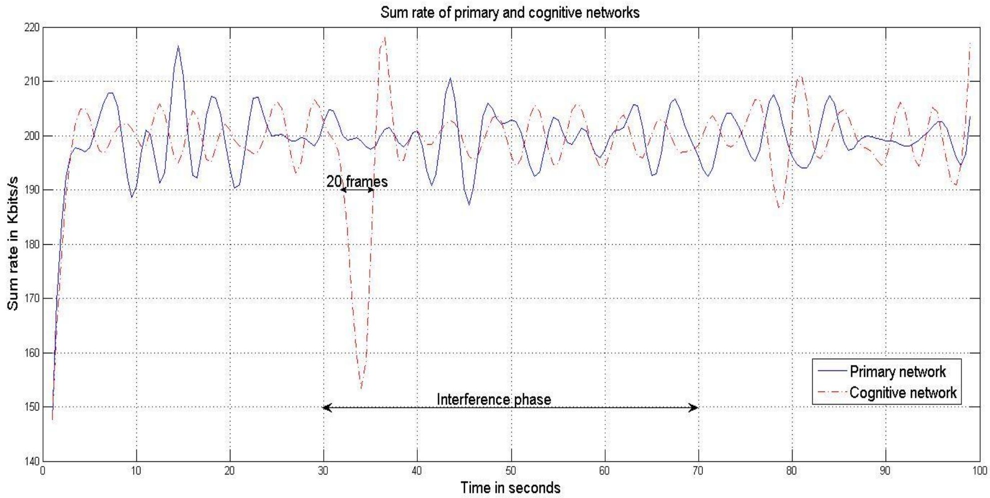

Figure 5-5 Sum throughput of incumbent and opportunistic cognitive ad hoc network.

The performance evaluation of this solution in the cellular extension in TVWS scenario showed similar trends and results. In particular, it was observed that the incumbent apparition has a major impact on the system performance (this has been highlighted with *CBR*/*CDR* observation), both on the QoS and mobility aspects. The benefits of the proposed solution were shown by reducing/cancelling the observed impacts thanks to the prediction of the incumbent apparition. Moreover, the quality of experience for access to the service is preserved in comparison to conventional networks. More detailed results for this scenario can be found in section 4.1.6 of [D53].

The proposed solution enhances the access control mechanism deployed in conventional networks with cognitive abilities in order to control the impacts of the incumbent's apparition. It has principally proved the capacity of the algorithm to cancel these impacts and to contribute to the preservation of the user mobility within the opportunistic system.

5.2.2.2 Transmit Power Control

Evaluation Procedure and Metrics

The performance of the QoSMOS transmit power control solutions have been evaluated based on simulations of the developed algorithms in various operating scenarios such as cognitive ad hoc networks, cognitive femtocells and cellular extension in TVWS. The main metrics evaluated in the analysis are the interference level to the incumbent system (*Int*) and the capacity of the opportunistic systems in terms of the supported number of opportunistic users (*NLoad*) or the allowable transmit power for the opportunistic system (*ATxPow*).

Results

The obtained results indicate that the interference threshold level at the incumbent system is never violated using the proposed distributed power control algorithms. Also, the distributed user selection mechanism selects and removes users based on their individual outage based criterion, leading to an increased number of supported users in cognitive ad hoc networks.

In cognitive femtocells, the introduction of an interference reduction capability at the micro base station using the developed power control algorithms, gradually reduces downlink transmit power from femtocell access points by reading the uni-directional downlink broadcast channel information from the micro base station. Also, the proposed resource allocation scheme outperforms the random resource allocation schemes, thus leading to a significant capacity increase in terms of the number of supported users.

Moreover, transmit power control mechanisms that compute the allowable transmit power based on interference monitoring methods are able to provide appreciable capacity improvements with respect to the computation of the allowable transmit power based on geo-location databases.

5.2.2.3 Optimised QoS Provisioning Under Spectrum Mobility

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by means of simulations, considering the spectrum utilisation or spectrum resource consumption (*SRC*) and blocking probability for opportunistic users (*CBR*), as well as revenue. The performance of the developed decision process is compared with state-of-the-art threshold-based channel reservation schemes: threshold-based channel reservation scheme without bandwidth adaptation (referred as `Threshold_maxBA`), threshold-based channel reservation scheme with bandwidth adaptation (referred as `Threshold_aBA`), and the optimal strategy based on the SMDP but without bandwidth adaptation (referred as `SMDP_maxBA`).

Results

It has been shown [D53] that the proposed strategy outperforms state-of-the-art threshold-based channel reservation schemes. Using a semi-Markov decision process [D53] to make optimal decisions for each opportunistic system maximises the long-term network revenue as a function of spectrum utilisation (Figure 5-6) and the opportunistic locking probability (Figure 5-7).

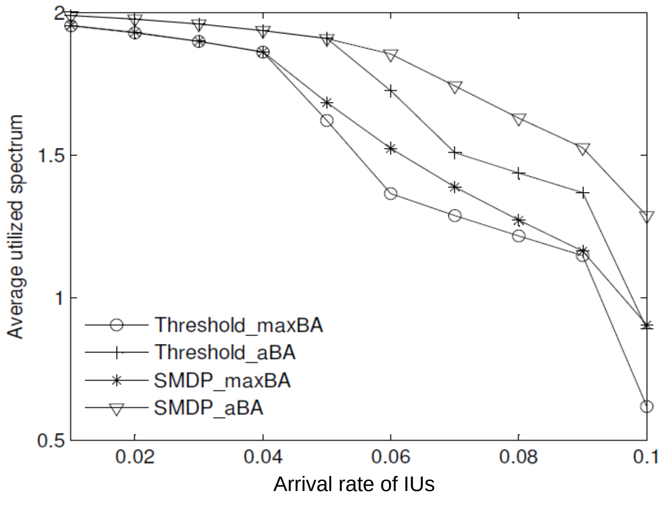

Figure 5-6 Average utilised spectrum vs. arrival rate of IUs.

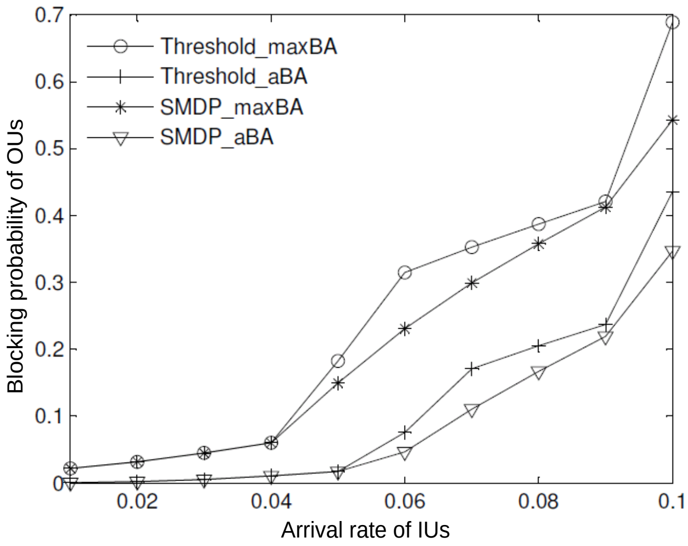

Figure 5-7 Blocking probability of OUs vs. arrival rate of IUs.

5.2.3 Performance of Solutions for Spectrum Sensing

5.2.3.1 Performance of Solutions for Local Spectrum Sensing

5.2.3.1.1 Fast and Reliable Signal Detection with Background Process for Noise Estimation

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of detection (*Pd*) as a function of the Signal-to-Noise Ratio (SNR) and comparing to that attained by the classic energy detection method.

Results

The obtained simulation results indicate that the detection probability (*Pd*) of the new sensing method is almost the same as for a perfect energy detection scenario without noise uncertainty (see Figure 5-8). More detailed results can be found in [D33] and [PanEtal2011].

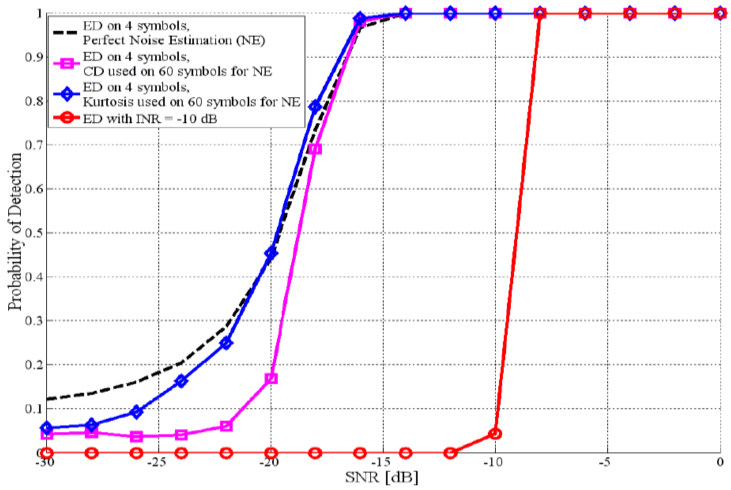

Figure 5-8 Probability of detection for the fast and reliable signal detection method with background process for noise estimation as a function of the SNR.

5.2.3.1.2 Improved Signal Detection for PMSE

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of detection as a function of the SNR and comparing to that attained by several detectors.

Results

The obtained simulation results indicate that the new spectrum sensing method is able to provide appreciable detection performance improvements with respect to other reference spectrum sensing algorithms (see **Figure 5-9**). Detailed results can be found in [GauEtal2010] and [GauEtal2012].

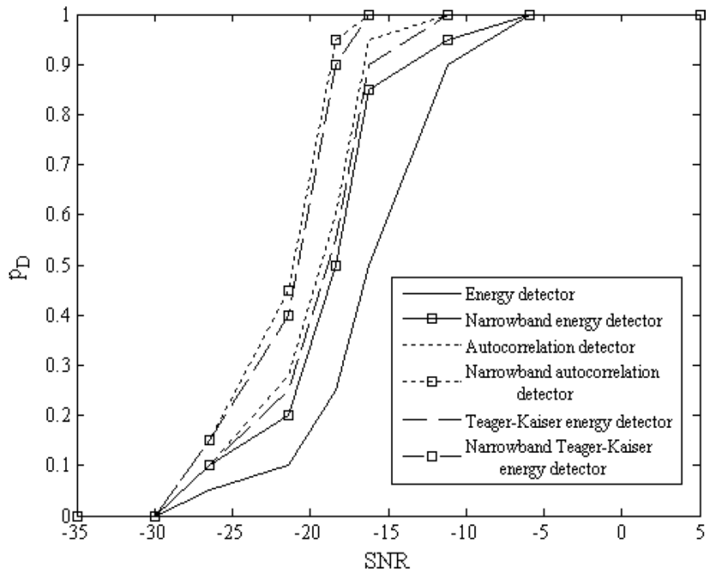

Figure 5-9 Probability of detection as a function of the SNR for the Teager-Kaiser detector and other reference detection methods.

5.2.3.1.3 Two-Stage Hybrid Signal Detection

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of detection on OFDM and PMSE signals as a function of the SNR and comparing to that attained by the classic energy detection and cyclostationary detection methods.

Results

The obtained simulation results indicate that this new hybrid sensing method results in an improved detection performance in terms of the probability of detection. Energy detection has a low sample complexity compared to cyclostationary detection (i.e., a lower number of signal samples are required for the same detection performance) but is more susceptible to noise uncertainty. The hybrid detector is a good compromise when energy detection noise uncertainty cannot be estimated. Detailed results can be found in [D33].

5.2.3.1.4 Generalised Higher-Order Cyclostationary Feature Detector

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of detection (*Pd*) as a function of the Signal-to-Noise Ratio (SNR). The evaluation also consisted in representing the Cyclostationary Autocorrelation Functions (CAF) of orders 2 and 4 (CAF2 and

CAF4, respectively) and computing the detection probability for different roll-off-factors. The detection performance of the 4th-order cyclostationary detector (CD4) versus SNR was compared to that attained by the 2nd-order cyclostationary detector (CD2) versus SNR (i.e., state of the art).

Results

The CD4 method may outperform the CD2 method only for PMSE (but not for OFDM) transmissions, and only when shaping functions (e.g., RRC) are used. Detailed results are available in [D33] and [D35].

5.2.3.1.5 Modified FCME Algorithm

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of detection (*Pd*) and false alarm (*Pfa*) of malicious users (i.e., the percentage of malicious users correctly/incorrectly detected in the system) as a function of the fraction of malicious users present in the system.

Results

The obtained simulation results indicate that the modified FCME algorithm is able to reliably detect the presence of malicious opportunistic users. For example, when there were at least 12 secondary users and at least 20 consecutive decisions, the modified FCME algorithm detected "always one" malicious users in about 95% of cases until the "always one" malicious users cover more than 80% of the secondary users (see Figure 5-10). More detailed results can be found in [Var2012].

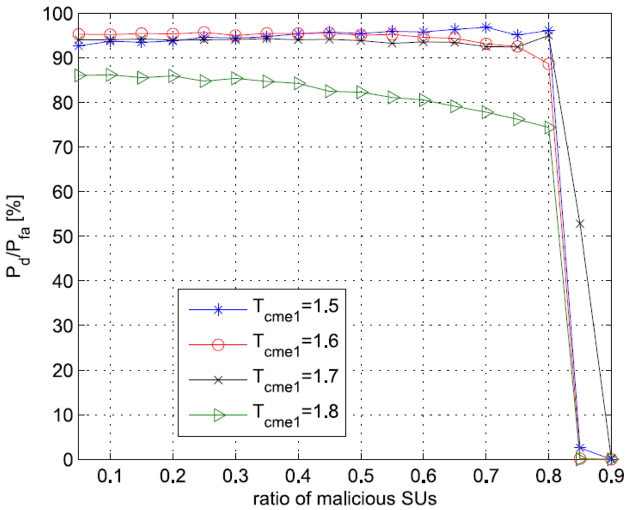

Figure 5-10 Probability of detection and false alarm of the modified FCME algorithm as a function of the ratio of malicious opportunistic users

5.2.3.1.6 Robust spectrum Sensing Based on Statistical Tests

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of detection and probability of false alarm for various operation points of the Receiver Operating Characteristic (ROC) and comparing it to the ROC of the classical energy detector and the Anderson-Darling detector recently proposed in the literature.

Results

The obtained simulation results indicated that spectrum sensing methods based on statistical tests such as the Kolmogorov-Smirnov test and the t-Student test can provide significant sensing performance improvements with respect to the classical energy detector and the Anderson-Darling sensing method as illustrated in Figure 5-11. More detailed results can be found in [ArsEtal2011].

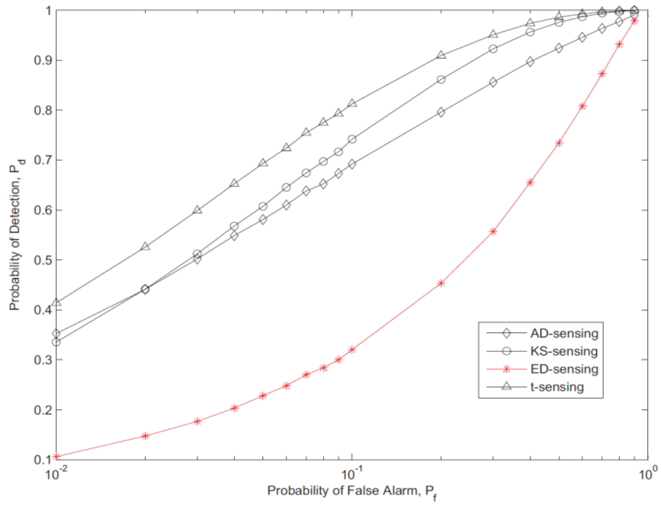

Figure 5-11 ROC for spectrum sensing methods based on statistical tests (SNR = –2dB).

5.2.3.1.7 Mobility-Tolerant Spectrum Sensing for Cognitive Radios

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of missed detection, which is the complementary probability to the probability of detection (*Pd*), for various speeds of the incumbent user.

Results

The obtained simulation results indicate that the developed mobility-tolerant spectrum sensing method is able to handle scenarios where the opportunistic sensing nodes are mobile by taking advantage of the spatial diversity of the opportunistic users to improve the detection performance of incumbent signals. An illustrative example is shown in Figure 5-12. More detailed results can be found in [ArsEtal2010].

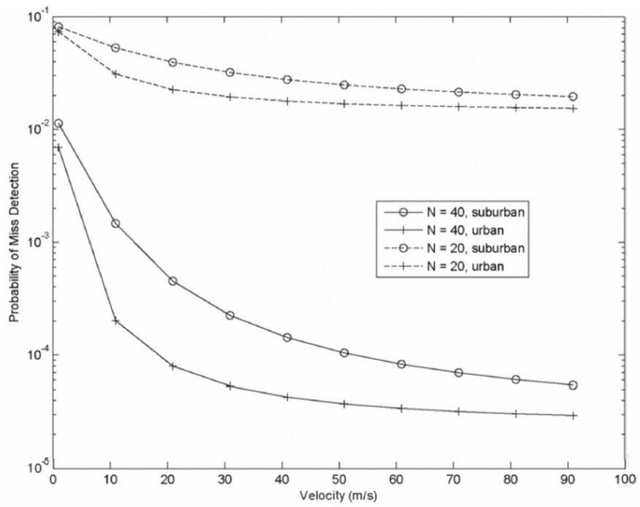

Figure 5-12 Probability of missed detection as a function of the opportunistic user speed.

5.2.3.1.8 Parallel Sensing Using Smart Antennas

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of detection as a function of the Signal-to-Interference Ratio (SIR), which provides a fair evaluation of the interference rejection capability of the algorithm, for various signal lengths and number of antennas.

Results

With two antennas, the incumbent system can be detected reliably in the presence of an opportunistic signal even if its signal level is 55dB below the opportunistic signal. (See Figure 5-13) This method can be applied for incumbent system protection. Detailed simulation results can be found in [D35] and [DepEtal2012].

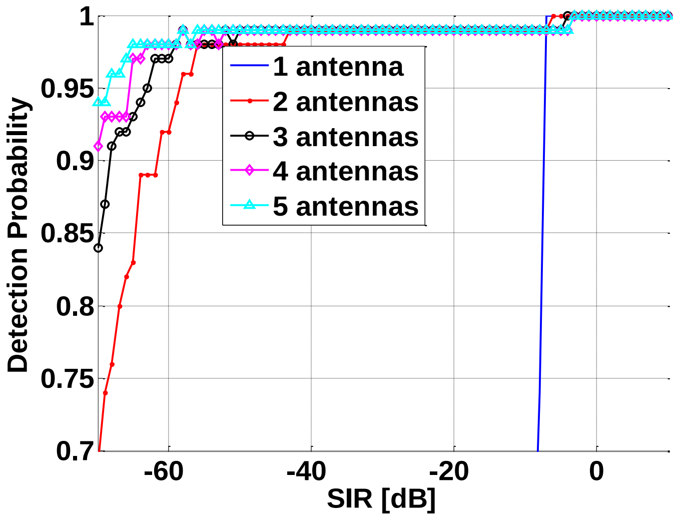

Figure 5-13 Probability of detection vs. SIR when using 1 to 5 antennas for a mono-path stationary channel.

5.2.3.1.9 CDMA Traffic Detection

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of detection as a function of the SNR.

Results

CDMA traffic detection can be a good solution to perform sensing in the code domain on UMTS or HSDPA bands using available spreading codes. In fact, there might be a potentially available resource (unused orthogonal codes) that classical sensing algorithms such as energy detection are unable to detect. Simultaneous transmission with no interference to the incumbent users could be possible in the code domain with codes that are orthogonal to the incumbent users' codes. The obtained simulation results indicate that the proposed UMTS traffic detection method is actually able to detect orthogonal UMTS codes that are used by the incumbent system with an appreciably good detection performance. Figure 5-14 shows an illustrative example of the detection performance of this solution (with and without pilot bits). More detailed results can be found in [D35].

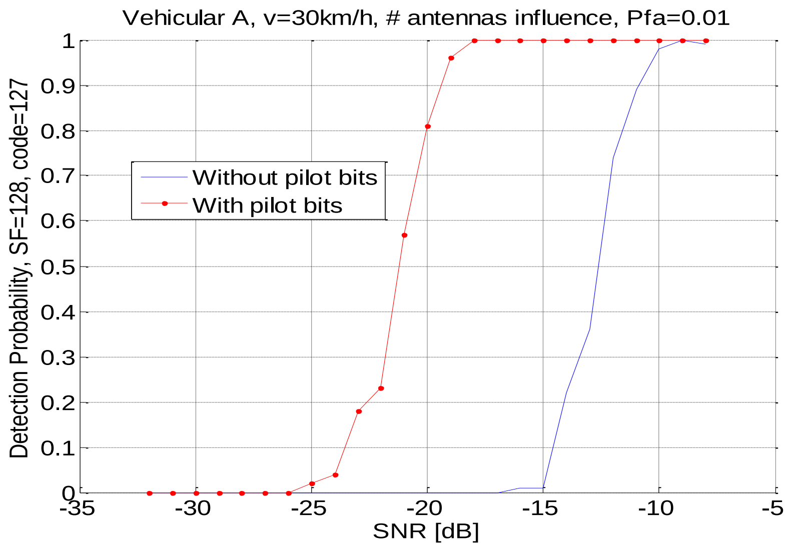

Figure 5-14 Probability of detection of a used UMTS code as a function of the SNR.

5.2.3.2 Performance of Solutions for Collaborative Spectrum Sensing

5.2.3.2.1 Selective Reporting Distributed Sensing Algorithm

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its overall probability of detection (*Pd*) and probability of false alarm (*Pfa*), as well as the network sensing signalling load (*NSSL*), and comparing the value of these performance metrics to their counterparts for the case of a non-selective sensing algorithm.

Results

The obtained simulation results indicate that the new sensing algorithm achieves a 50% reduction in the sensing signalling load (*NSSL*) without penalty in the sensing performance metrics (*Pd* and *Pfa*), which are not affected by the introduction of the selective reporting. Further details can be found in [D35].

5.2.3.2.2 Spectrum Sensing Based on Beta Reputation System

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of missed detection, which is the complementary probability to the probability of detection (*Pd*), and false alarm (*Pfa*) for various operation points of the ROC and comparing it to the ROC of a classical collaborative spectrum sensing method proposed in the existing literature.

Results

The obtained simulation results indicate that the proposed beta-reputation system relying on a credibility score-based collaborative spectrum sensing (CF-CSS) provides an appreciable detection performance improvement with respect to the case of Equal Weight Combining (EWC) as shown in Figure 5-15. More detailed results can be found in [ArsEtal2011b]

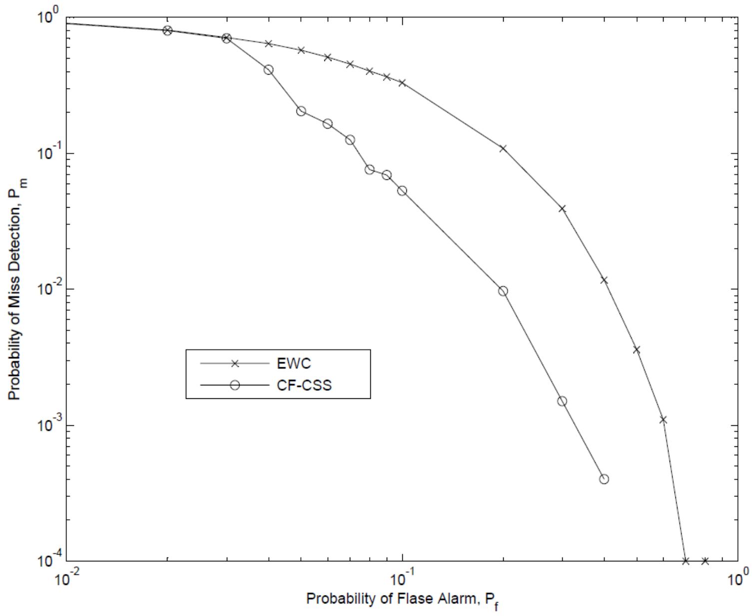

Figure 5-15 Receiver operating characteristic for collaborative spectrum sensing method based on beta reputation system.

5.2.3.3 Performance of Interference Monitoring

Evaluation Procedure and Metrics

The reliability of an interference measurement is determined by computing (over 5000 to 10,000 simulation runs) the RMSE of the interference measurement (*RMSE_Int*), which represents the standard deviation of the interference measurement error (*STD_Int*), and comparing with the standard deviation of the path loss estimation error (σ_{PL}) used in the ordinary propagation model (for example σ_{PL} = 12dB). When *RMSE_Int* < σ_{PL}, then the measurement can be trusted.

Results

Figure 5-16 shows some illustrative simulation results for a scenario without fading, depicting *RMSE_Int* and *STD_Int* as a function of the Interference-to-Signal Ratio (ISR). It can be observed that an interference monitoring method based on cell-specific reference signals (RS) provides exploitable results under low ISR conditions when the synchronisation is accurate (i.e., the cell-specific RS are known). Additional methods independent of the synchronisation using cell-specific RS will be investigated in the future and evaluated under various fading scenarios [MurEtal2011].

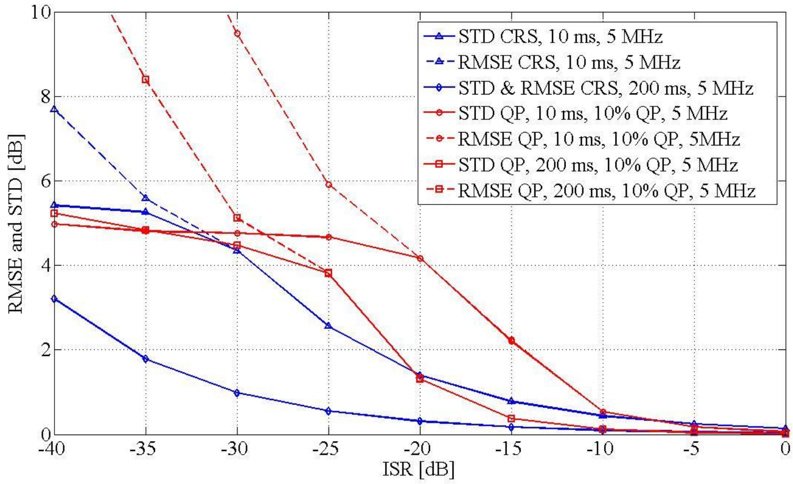

Figure 5-16 *RMSE_Int* and *STD_Int* as a function of ISR.

5.2.4 Performance of Solutions for the Transceiver

5.2.4.1 OFDM Windowing

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by means of link-level simulations based on the power spectral density, which is compared to that of the conventional OFDM scheme with a rectangular pulse and a Raised Cosine (RC) 100% pulse.

Results

The obtained simulation results indicate that a modification from a rectangular to a smooth time window allows high and controlled out-of-band roll-off compared to conventional OFDM (Figure 5-17). An improvement of 15dB relatively to conventional OFDM in the first lobe is observed, while the next lobes already achieve 55dB attenuation. These benefits come at the cost of a power penalty that is in the order of 2.8dB if one wants to keep the same bit rate.

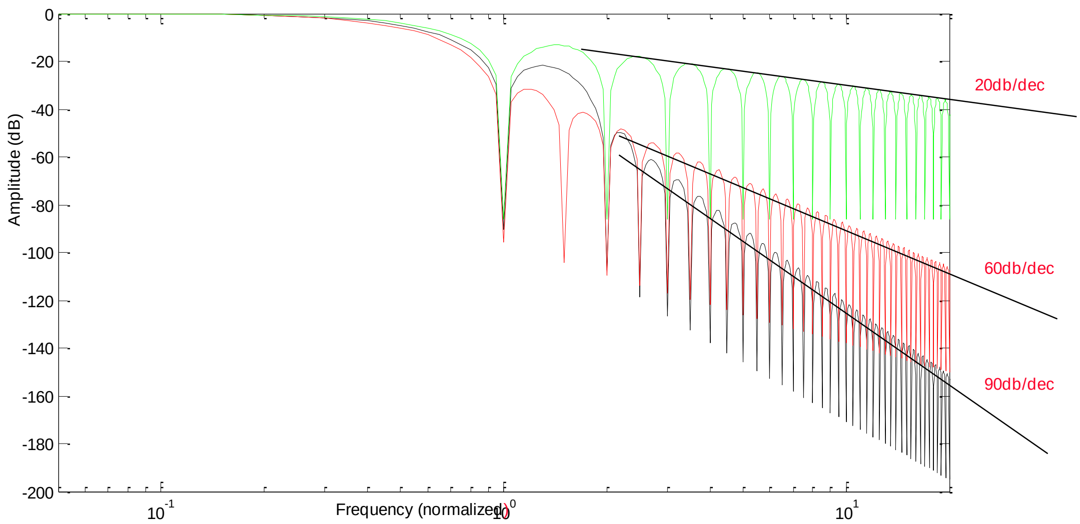

Figure 5-17 Frequency behaviour of the rectangular, RC 100% and proposed pulse.

5.2.4.2 Interference Avoidance Transmission

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by means of link level simulations where the developed Interference Avoidance transmission by Partitioned Frequency- and Time-domain processing (IA-PFT) scheme has been compared to ordinary NC-OFDM, Time-Windowed (TW) NC-OFDM, NC-OFDM with Cancellation Carriers (CC) and a serial combination of CC and TW. The comparison has been carried out in terms of the notch depth of the power spectral density (*Notch*), the BLER (*BLER*) as a function of the E_b/N_0, the PAPR (*PAPR*) and the computational complexity (*CC*).

Results

The obtained results, shown below, indicate that the developed IA-PFT solution achieves a deeper notch throughout the interference avoidance band. For example, IA-PFT improves the adjacent channel leakage ratio to about -45dB, with a 10dB improvement in suppression compared to the serial combination of CC and TW (Figure 5-18) while preserving a similar performance in terms of the BLER. This is comparable to ordinary OFDM/TW in terms of BLER (Figure 5-19) and PAPR (Figure 5-20) with a little computational complexity increase in the transmitter with respect to ordinary OFDM/TW. More detailed results are provided in [D42] and [D43].

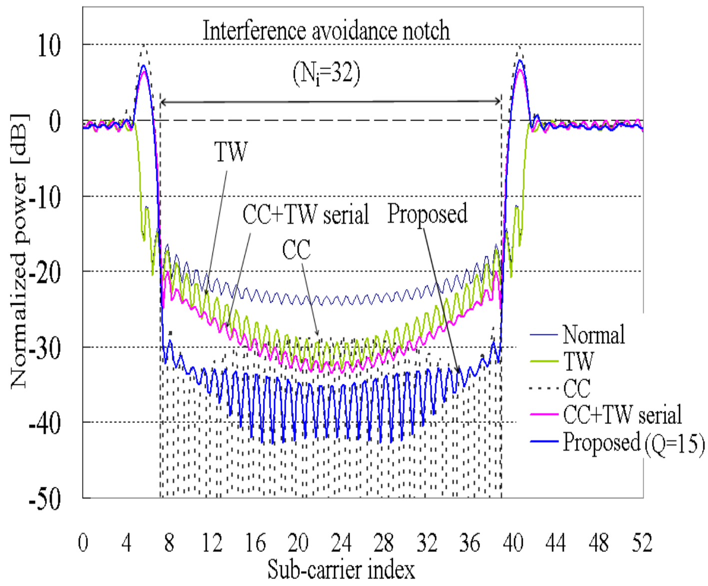

Figure 5-18 Performance evaluation of the IA-PFT solution – Transmission spectrum of notch

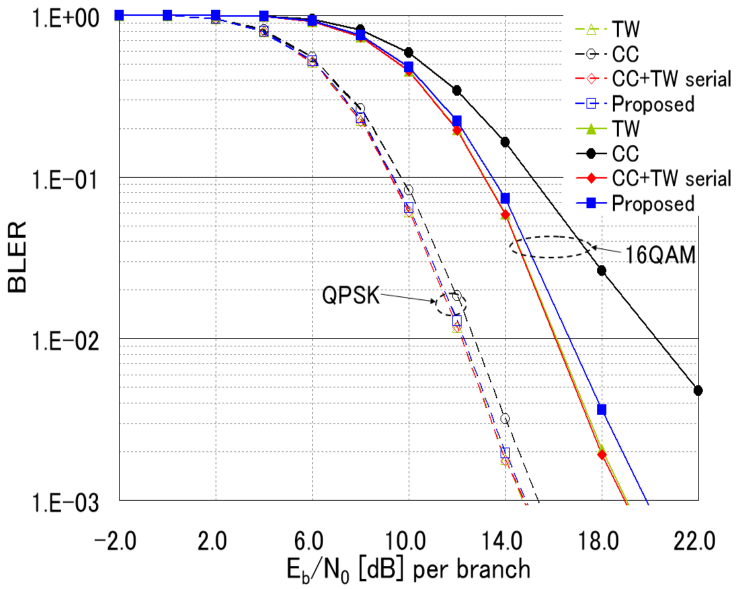

Figure 5-19 Performance evaluation of the IA-PFT solution – Transmission performance

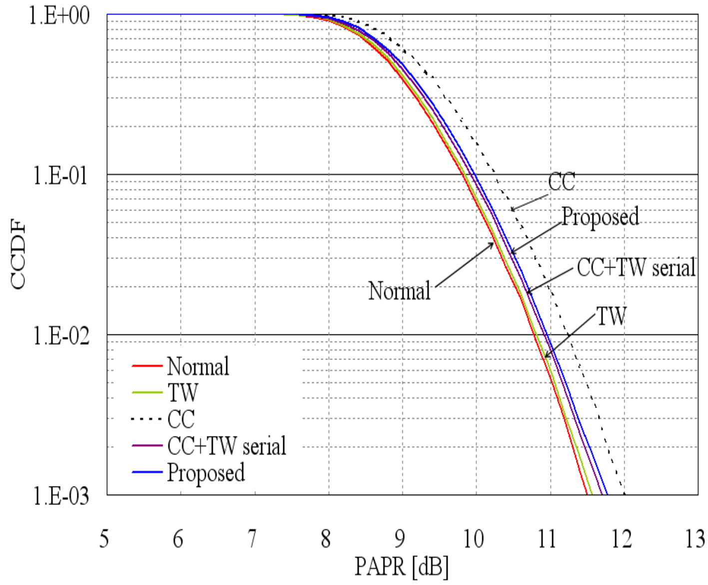

Figure 5-20 Performance evaluation of the IA-PFT solution - PAPR performance

5.2.4.3 Generalised Frequency Division Multiplexing (GFDM) and Cyclostationary Detection

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated by simulating its probability of detection (*Pd*) on peaks of the CAF specific to GFDM, as a function of the Signal-to-Noise Ratio (SNR), and comparing to that attained on peaks of the CAF resulting from cyclostationary OFDM characteristics. Both of them have been compared with the ones of OFDM waveforms having similar modulation parameters.

Results

The obtained simulation results indicate that the detection performance is improved on peaks specific to cyclostationary GFDM characteristics (see Figure 5-21). GFDM like IAPFT improves the ACLR to about -45dB. Detailed results can be found in [D33], [D35] and [PanEtal2012].

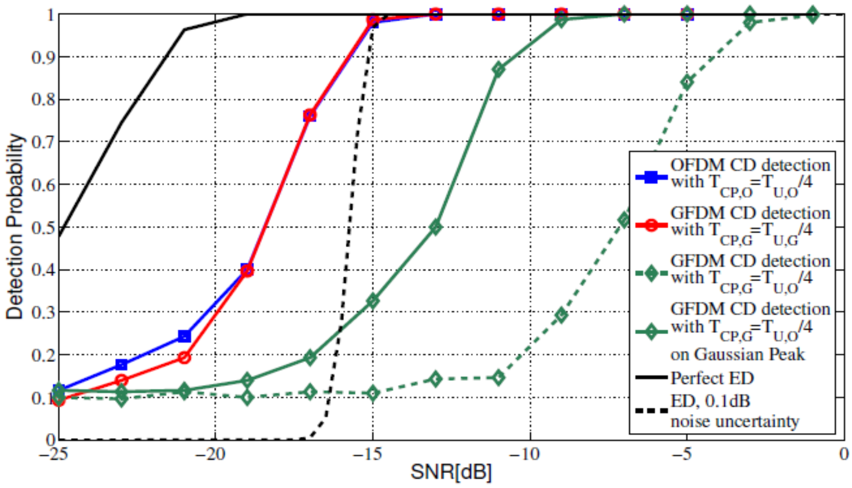

Figure 5-21 Probability of detection as a function of the SNR for energy and cyclostationary detectors on both Side Peak (SP) and Normal Peak (NP), for 10ms OFDM and GFDM signals, and different cyclic prefix lengths (*Pfa* target is 0.1)

After implementing single and double sided successive interference cancellation (SIC), the BER performance of GFDM improves and is shown in the following figure.

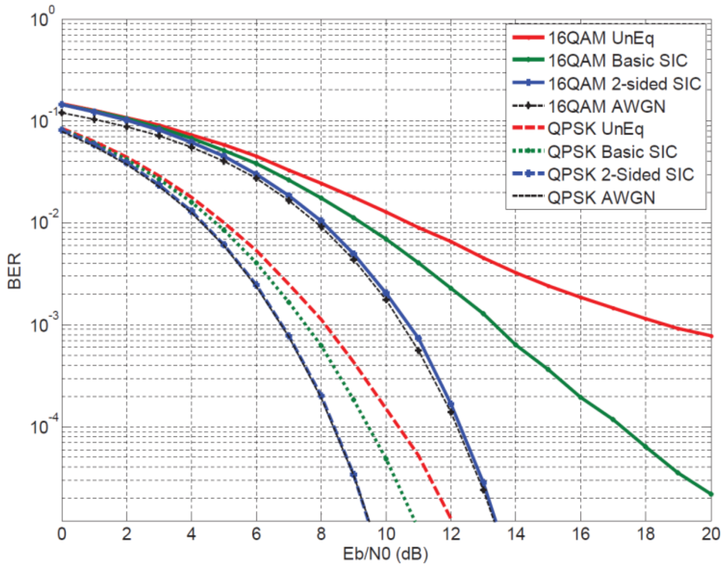

Figure 5-22 BER performance of GFDM with SIC

5.2.4.4 Filter Bank Multi Carrier (FBMC)

Evaluation Procedure and Metrics

The performance of this QoSMOS solution has been evaluated based on link level simulations. Since the main benefit of FBMC compared to OFDM is the good out-of-band radiation performance, the main performance evaluation metric is the ACLR (*ACLR*), which is evaluated based on the power spectrum density. The transmission performance is evaluated in terms of the bit and block error rates (*BER* and *BLER*, respectively). The PAPR (*PAPR*) and the computational complexity (*CC*) are also taken into account.

Results

Simulation results indicate that an ACLR below 50dB can be implicitly reached without additional signal processing or data rate loss. Detailed simulation results comparing the signal characteristics and transmission performance of the proposed scheme can be found in [D43].

6 Deployment Guidelines

This chapter, along with chapter 7, consider the realisation of deployable QoSMOS systems. This chapter focuses on providing deployment guidelines for implementing a QoSMOS system with reference to 4 specific realisations of the QoSMOS scenarios: cellular extension including offloading of LTE networks and rural broadband, cognitive femtocell, and cognitive ad hoc network for machine-to-machine (M2M) communication [Lehetal2012][D16].

6.1 Introduction

Mobile broadband traffic increases very fast in many markets and is expected to continue with an exponential growth rate doubling every year or so, on a global basis [Cisco2012]. QoSMOS cognitive radio system presents a solution to the challenge for a mobile operator to build and increase capacity in the traditional cellular networks.

Considering broadband access for rural areas the main challenge is still to establish economically feasible solutions. The gap compared to broadband capacities offered in the cities may well increase. Cognitive radio deploying television (TV) spectrum frequencies offers a viable solution to the problem and opens new business opportunities for operators.

A third trend today is the increasing atomisation with machine-to-machine communication taking place everywhere. The traffic may well be small for individual devices in the network, but in sum with a large number of devices, there is a challenge to provide the needed network capacity everywhere that it is needed. Cognitive ad hoc networks, again, using TVWS or other frequencies, are a possible and economically feasible solution.

Cognitive radio solutions are seen as particularly useful for using spectrum in an opportunistic and dynamic way as a secondary user, or a user with secondary rights, in contrast to incumbent users with primary rights. The terms and characteristics for spectrum use are defined by the ITU-R Radio Regulations [ITU-R12]. Here “stations of a secondary service

- shall not cause harmful interference to stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date;
- cannot claim protection from harmful interference from stations of a primary service to which frequencies are already assigned or may be assigned at a later date;
- can claim protection, however, from harmful interference from stations of the same or other secondary service(s) to which frequencies may be assigned at a later date.”

The QoSMOS cognitive radio system is suitably designed to operate as a secondary user. However, to get it operational the regulatory authorities must have or define a set of rules for operation.

6.2 Assumptions

The point of view taken in these deployment guidelines is for a telecom operator. The telecom operator can also be some opportunistic user deploying a cogntive ad hoc network. It is assumed that an ecosystem exists of other actors and that the general conditions for commercial operation and service delivery are present. The main assumptions following this are then:

- QoSMOS solutions should normally be part of global standards (see also chapter 7), but in lack of such, available equipment can be considered
- Regulations allowing opportunistic or shared use of frequencies on a larger scale are endorsed and effective in several markets in order to create a global momentum, leading to
- Network equipment is available off-the-shelf or at least on vendors’ roadmaps.

6.3 Alignment with Regulatory Conditions

Cellular telecommunication systems for mobile services have normally been developed with secured long-term spectrum licences for the operators. However, with the expected heavy mobile data traffic growth the concern is that the available spectrum for mobile services will not be enough. Cognitive radio systems temporarily using frequencies that are primarily allocated for other services, but not used all the time, is one interesting and promising solution. The cognitive radio system then acts as a secondary user. A set of well-defined rules must be established by the frequency regulatory authority in charge.

The idea of primary and secondary spectrum use is well established, but dynamic access on the spot when and where it is needed, is new. It is always so that the primary use shall not be affected by the secondary use. Cognitive radio has been developed to take advantage of dynamic spectrum made available locally in flexible amounts and time slots. Such a scheme requires a set of new regulatory rules that are being discussed, and some countries have taken actions partly from pressure from projects such as QoSMOS and have implemented an initial solution allowing cognitive radio in the TV spectrum.

Several regulatory authorities are aiming at implementing the set of rules necessary for spectrum sharing in a dynamic way. The main global authority is ITU-R through the radio regulations (RR), but the introduction of shared and opportunistic access does not seem to demand any major changes to the RR. Instrumental are however regional authorities like CEPT in Europe who will have to draw up the regulatory framework comprising recommended technical and operational constraints. Before cognitive radio can actually be implemented, the national regulatory authority must issue the basis or rules.

First attempts have been launched in the US ([FCC2010] and [FCC2012]) with a geo-location database system showing which frequencies are not used at a location. A service can be provided as a wireless access to the network, i.e., Internet, much the same as Wi-Fi in licence exempt bands. The mobile operator can then offload data traffic to the cognitive radio system as it is done with Wi-Fi. In the UK Ofcom has issued statements saying that licence exempt whitespace devices (WSD) will be allowed [Ofcom2011]. It is clear that the UK position is to support a common European solution, but will allow services using geo-location databases while waiting for the European solution. The European Commission (EC) has recently issued a mandate to CEN, CENELEC and ETSI to standardise “Reconfigurable Radio Systems” [EC2012]. The time-line proposed by the EC request draft harmonised standards available for trials by the end of 2013, and final harmonised standards to be listed by the end of 2014. It is unclear what the last request actually means, but it does indicate that standards and standardised solutions may be available in 2015.

The regulatory conditions are of the method to get the frequency through the system of geo-location databases, i.e., identify which frequencies are available via the database system, and then use devices with limitations to the maximum transmit power, location (such as height above terrain), and others. A couple of the FCC requirements are summarised in the next two paragraphs.

The maximum transmit power figures and power spectral densities (PSD) are listed in [FCC2012] dependent on the type of device (See Table 6-1). Here the maximum antenna gain for a fixed device is 6dBi, and for a personal/portable device 0dBi.

Table 6-1 Maximum power spectral density [FCC2012]

Type of TV bands device	Power limit (6MHz) dBm	PSD limit (100kHz) dBm	Adjacent channel limit (100kHz) dBm
Fixed	30 (1W)	12.6	-42.8
Personal/portable (adj. channel)	16 (40mW)	-1.4	-56.8
Sensing only	17 (50mW)	-0.4	-55.8
All other personal/portable	20 (100mW)	2.6	-52.8

The requirement to antenna height is divided into a maximum allowed height of 30m above ground level [FCC2010] and another to a maximum of 250m above average terrain defined in [FCC2010], and increased in [FCC2012]. Figure 6-1 illustrates the requirement to distance on the TV contours and device height above average terrain for both co-channel and adjacent channel operation.

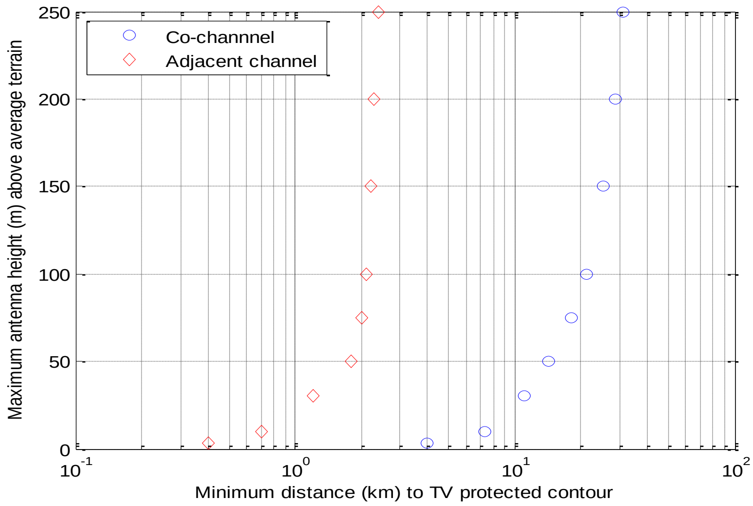

Figure 6-1 Required separation form television covered area

Regulatory authorities issuing new licences now include statements that the licensee may accept secondary opportunistic use if part of the spectrum is not used. This comes in addition to the possibility of trade and is perhaps best described as an additional feature to spectrum trading not only for the whole spectrum the licence covers but for micro-trading, dealing with smaller spectrum parts that will vary in space and time. Spectrum micro trading is the focus of [D15].

The current use of femtocells are foreseen in the licensees own spectrum and appears therefore as a frequency planning problem the operator must solve for its own cellular network. As in the cases for the cellular extension scenarios (offloading of LTE networks and rural broadband) frequencies made available for secondary and opportunistic use can be deployed by a femtocell as well. The regulatory conditions are the same as for the offloading scenario, see chapter 6.

One particular issue that concerns the rural broadband scenario is the maximum transmission power. The maximum coverage for this scenario (the example in this document targets devices from 3km up to 6km away from the base station) assumes a maximum transmission power of 36dBm (1W plus 6dBi antenna gain); in line with the maximum transmit power for fixed devices in the U.S. [FCC2012]. If regulations do not allow for power levels as high as this, then the coverage from each base station will be significantly reduced. This would necessitate more base stations, which may mean buying new base station locations. This could make the rural broadband case a significantly less attractive scenario.

6.4 Operational Support System (OSS) Integration

A network operator must plan the roll-out of a new system, such as a QoSMOS system, when it wishes to integrate the new system into its existing infrastructure. The new system, as well as being physically installed, will require integration with OSS in the operators existing networks. OSS is a wide range of systems that provides a variety of functions, which includes device configuration, system inventory, service ordering, service billing, service provisioning and fault testing.

In [Fit2004] three key business drivers for OSS are outlined which can be summarised as:

- Minimise operations cost – Lower operations costs with increased automation to support improved customer satisfaction.
- Maximise profitable revenue – Flexibility and extensibility to support quick trial setup and rapid launch of new products and services.
- Maximise the return on capital investment – The OSS should allow for the network utilisation to be optimised.

The balance, or focus, of these business drivers will adjust as the market develops. This concept is shown in Figure 6-2 [Fit2004]. When a service is first launched, the focus is on speed and flexibility to allow for rapid launch and then to increase market share quickly to bring in revenue. As the market develops the OSS focus moves more towards automation and optimisation to minimise costs. One example is the introduction of self-organising functions (SON) in the 3GPP architecture.

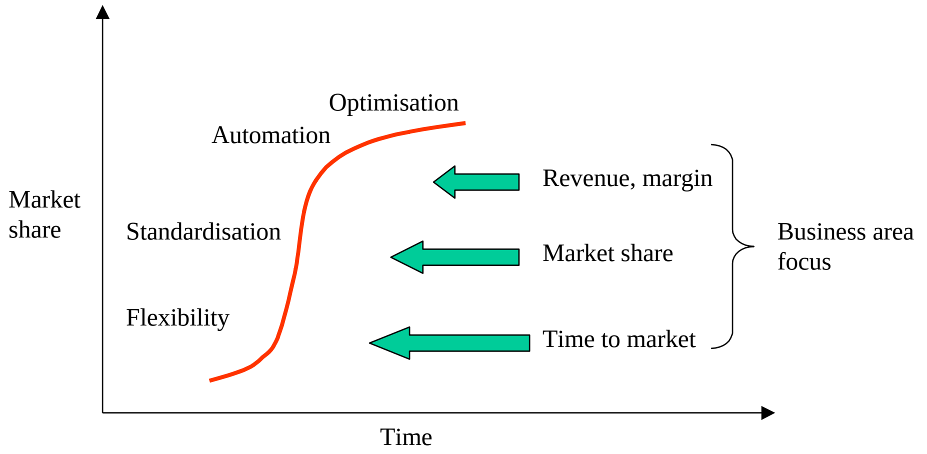

Figure 6-2 Changing business drivers for OSS as a market develops

An initial deployment of a QoSMOS system may be a simple PoC, to show that a service can be provided (QoSMOS PoCs are described in [D73]). As well as demonstrating that a service is possible this stage gives the operator the opportunity to learn what performance the system can provide in practice. A PoC may be a simple system and not a full end-to-end solution. For example, with the cellular extension scenario a QoSMOS base station may be installed on a mast to test the performance of the system in terms of capacity and coverage without actually using the QoSMOS base station to provide a service to real customers. In this case, no OSS functions for, as an example, billing would be required. Other OSS functions, such as fault finding, may be using the trial as part of its design process. More advanced trials can also be carried out which could involve deploying an end-to-end service for a small number of trial customers. The service in these more advanced trials, e.g. for rural broadband service in TVWS, might not offer any service level agreements like a real deployed rural broadband service would. What is important about these stages of deployment is that not all OSS features would be needed so it should be quick to deploy. For trial stages it is acceptable to use bespoke solutions and a high amount of manual configuration, whereas a more mature deployed system targets a highly automated and efficient OSS.

OSS is a collection of management functions, which are considered on a few separate layers. The logical layered architecture model for Telecommunications Management Network (TMN) management functions identify which management functions exist at which layers, and how the layers interact [ITU-T00]. Most OSS designs try to follow this logical architecture. There are four layers that would exist above network elements. Different management tasks are required for each layer as depicted in Figure 6-3.

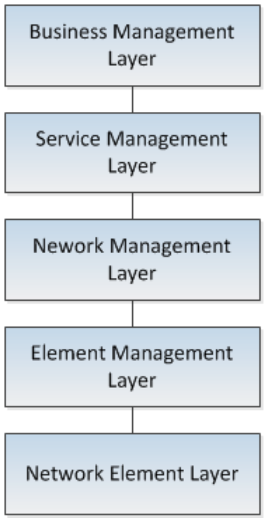

Figure 6-3 TMN Logical Layered Architecture

A summary of the various functionalities of these management layers is as follows:

- Business Management Layer – This layer has responsibility for an entire enterprise. Its functionality is less operational than the lower layers and focuses more on high-level business decision-making. This includes settings targets; making investment decisions; and supporting operational, administration and maintenance budgets and manpower.
- Service Management Layer – This layer will interact with service providers or end users and maintains service statistical data (e.g. QoS). Being the customer-facing layer it deals with functions such as contract agreements, provision/ending of service, accounts, fault reporting etc.
- Network Management Layer – This layer is responsible for the networking of various network elements in its domain and supporting services demanded from the service management layer. It controls and coordinates the network, providing service and keeping data logs on the network performance.
- Element Management Layer – this layer manages the individual network elements (These could be the QoSMOS components). This layer often controls vendor specific functions of the network elements and is therefore typically provided by the vendor. The element manager then provides the interaction between the network management layer and the network elements. Functions include control and coordination of network elements and keeping data logs for the elements that it controls.

Simple Network Management Protocol (SNMP) is widely used for communication by the element management layer. As its name suggests it is simple (only a limited set of instructions). It runs over User Datagram Protocol (UDP), so it is not reliable. It uses polling and is therefore also not scalable. SNMP is therefore a suitable protocol for this low layer interaction in the TMN Logical Layered Architecture, but not for the higher layers. Common Management Information Protocol (CMIP) is typically used for these higher layer interactions. CMIP has a larger set of services and uses TCP for reliability. CMIP does however consume more resources; this is one of the reasons that it is not used at the element management layer.

Before the new system can be deployed it is important to identify two types of OSS requirements: (a) what new systems need to be created? (b) what changes need to be made to any existing OSS systems? Once the new requirements for OSS are identified, the operator must get the changes made to the existing systems and order/develop the new systems that are required.

The OSS would interact with a new QoSMOS system via element managers, which the vendor would provide. These would be the part of the network coordination functional entity that communicates with the QoSMOS system via the adaptation layer. The southbound interfaces of the element manager will talk directly to the QoSMOS system components (via the adaptation layers in each component). The northbound interfaces will allow the operator and its customers to talk to the element manager to access certain QoSMOS functions. In [D23] it is shown how the coordination domain and the networking domain of a QoSMOS system will use interfaces QS1a and QS1b respectively to communicate with the network coordination functional block. This network coordination functional block would include the OSS network management layer and element management layer functions. This QS1b interface is also shown in the system overview diagrams for system realisations in chapter 7.

The aim for a well-designed OSS is that the interaction between itself and a QoSMOS system should allow for a new service to be quickly, easily and effectively deployed. Once OSS integration is planned and all OSS modifications built, a system can be rolled out and a service offered to customers. As the number of customers grows the focus moves towards increased OSS automation and optimisation.

6.5 Offloading of LTE Networks

6.5.1 Cellular Capacity "Shortage" and Available "Whitespace Offloading"

The scenario "Offloading of LTE networks" addresses the mobile cellular capacity shortage expected from the heavy exponential growth of mobile data traffic. QoSMOS Deliverable D1.2 [D12] describes the scenario in more detail. The basic principle is that the cognitive radio systems operating at the "whitespace" frequencies, e.g., in the 470 – 790MHz bands, offer services in much the same way as Wi-Fi systems operating in the licence exempt bands. The Digital Terrestrial Television (DTT) frequencies may well have a larger coverage than the mobile system and wholly or partly cover the cellular area or at least a number of sectors, as sketched in Figure 6-4. The mobile cellular operator can then offload the traffic to the cognitive radio system, which uses available whitespaces at the times and in the locations needed. The operational mechanisms follow regulations issued by the relevant authority and a positive business is foreseeable.

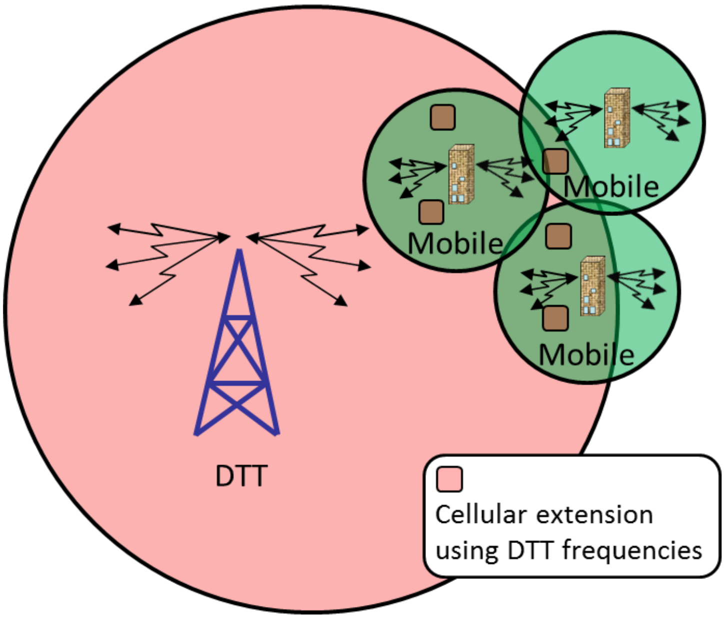

Figure 6-4 Offloading of LTE networks with cognitive radio dynamically operating at non-used (temporarily and spatially) digital terrestrial spectrum

6.5.2 Review Business Case

This business case for this scenario considers a mobile operator that has been operating a LTE network in a European city for some years, but has reached a point where there start to be capacity problems. The main reason for the capacity problems are increased traffic generated by each subscriber and possibly also an increase in the number of subscribers.

The approach taken for this business case is to compare the new cognitive radio based approach to increase the capacity in cellular networks to the traditional approach of increasing the capacity by buying more spectrum.

The business case is calculated for a mobile network operator that needs to increase its LTE capacity as can be realised as shown in chapter 7. The operator is assumed to be one of the three or four major mobile network operators in the studied area/country. It has an extensive infrastructure in the area consisting of base station sites and backhaul connections to these. In addition, it has an existing organisation for sales, marketing, technology and operation. This business case is based solely on the reuse of existing sites (i.e. no new sites will be needed).

The business case is calculated for a hypothetical western European city with 1 million inhabitants covering an area of 200km^2. The city has a downtown area which covers 50km^2 with 0.5 million inhabitants and an urban/suburban area which covers 150km^2 also with 0.5 million inhabitants.

The study period is from 2015 to 2020. The starting year has been chosen based on when it is expected that the concept is sufficiently mature both with respect to technology and business aspects. According to [Cisco2012] the monthly mobile data traffic is expected to increase 5-fold from 2012 to 2015, and this will pose a major challenge for mobile operators.

In D1.6 [D16], a simulation study shows that the downlink cognitive LTE capacity depends on what level of external interference the user terminals receive. An inter-site distance (ISD) of 750 meters is typical for macro BS deployments in urban areas. It is assumed that the cognitive LTE system is using TVWS frequencies (470-790MHz) between DVB-T single frequency networks (SFN) using the same frequency as the LTE network. A detailed description of this reference environment and the resulting whitespace LTE performance is given in Appendix 2 of D1.6 [D16]. Simulations of the capacity in one 8MHz TV channel for the cognitive LTE system in this deployment shows that 50% of the whitespace area achieves a site capacity higher than 11.7 Mbit/s, and 90% of the area have a capacity higher than 5.7 Mbit/s. This makes both the development of a business case and a roll-out plan interesting. The business case study has identified the additional functional blocks needed for the deployment of a cognitive LTE addition (see chapter 7 and [D16]):

- Upgrade existing macro eNodeBs with TVWS cognitive LTE capability, e.g. new antenna, new radio module and installation.
- CM-SM is responsible for building the spectrum portfolio based on the external constraints (regulatory policies, operator policies, etc.) and on spectrum sensing results, consisting of a server and functionality implemented in software.
- CM-RM efficiently supporting QoS and mobility for wireless networks with intermittently available spectrum resources assumed to be part of future software releases.
- AL enabling the collection of information from different radio access technologies (RATs) through medium specific interfaces and providing a single media independent interface, assumed to be implemented as a central server with routing capabilities in addition to AL functionality in the different network elements.
- “Cognitive LTE” capable terminals. Both software and hardware must be added to the user terminals in order to make it capable of cognitive radio operation.
- Spectrum (geo-location) database access.

The business case study in D1.6 gives the cost assumptions used for these.

6.5.3 Develop Detailed Roll-Out Plan

A mobile network provider wishes to extend the LTE network capacity using QoSMOS technology. As sketched in Figure 6-5 the television (TV) tower transmit in the (larger) area, but are not using all the spectrum at a given location and time. The unused TVWS spectrum is deployed by the eNodeB present in the area where both the base station can deploy this part of the spectrum with cognitive radio technology as well as the user terminals. This particular cellular system uses the 800MHz band as its normal spectrum, and then the TVWS spectrum allows extension for both capacity to terminals that are in reach of the 800MHz band and the TV band, or capacity to terminals only covered by the TV band that can be added to the cellular service provided.

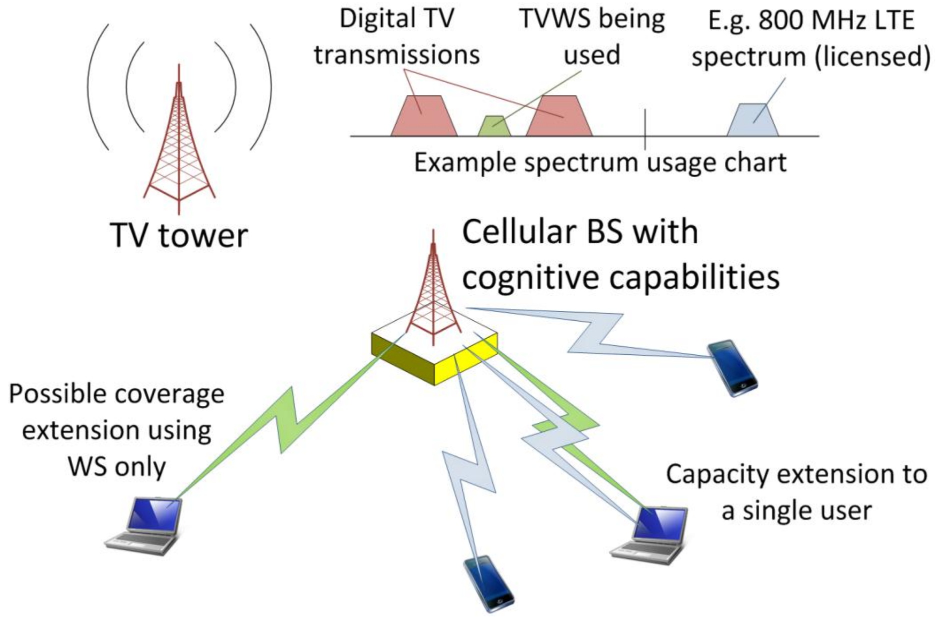

Figure 6-5 Example of cellular extension based on available “whitespace” spectrum and a base station with cognitive capabilities

In order to provide services the following must be considered and dealt with:

- Whitespace spectrum resources - The cellular network operator must first check with the national regulatory authority that cognitive radio systems are allowed in the identified and wanted spectrum. Then it is also important to estimate whether there will be sufficient WS spectrum available, i.e., spectrum that is not used (temporarily and spatially) by the primary users that have a licence.
- Geo-location database - Access to a certain part of the radio spectrum will be granted for a certain time by using a geo-location database system with all necessary information for primary spectrum utilisation and wanted secondary utilisation. The network operator must establish a contract with a geo-location database operator or become a database operator, such that WS spectrum can be acquired at the locations and times wanted. Details on the implementation of a QoSMOS TVWS database can be found in [D66].
- Availability of equipment - Clearly, there must be equipment when the operator wishes to roll-out the service based on WS spectrum, The vendor industry must offer base station equipment with cognitive radio capabilities, as indicated in Figure 6-5, or new WS access points (such as super Wi-Fi [FCC2010]) must be available in the market. Similarly, at the user end, terminals with cognitive capabilities or super Wi-Fi dongles must be available in the market. As mentioned earlier, products based on regional or global standards are preferred in order to provide economies of scale. In lack of such solutions, the relevant vendor industry and operator may well form an alliance to promote and ensure that interoperable technical solutions become available in sufficient quantity.
- Users - The mobile network operator must inform and promote the new solutions and point both at the improved user experience made available through cognitive solutions. Possibly some incentives must be established to motivate users to acquire the updated terminal allowing access to cognitive WS spectrum.

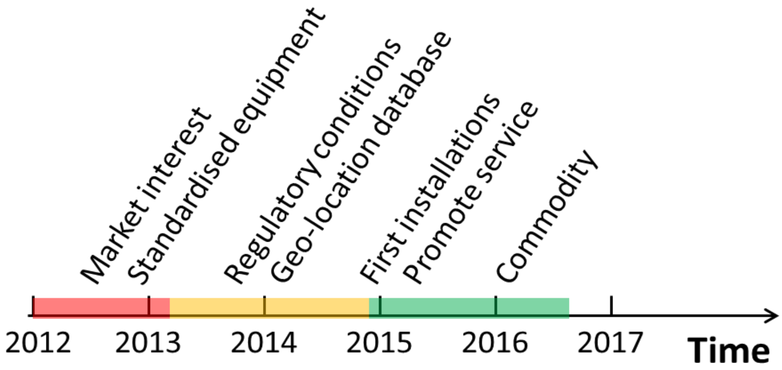

Figure 6-6 Offloading of LTE networks timeline

A timeline for offloading LTE networks is suggested in Figure 6-6 showing a 3-year period from early concluded market interest in 2012 to an offered service in 2015.

6.6 Rural Broadband

6.6.1 Rural Broadband "Shortage" and Possibilities from Using "Whitespace Frequencies"

Across the globe, broadband speeds and coverage are on the increase. The availability of broadband tends to be much greater in urban areas, while many rural areas remain underserved. In order to narrow the "digital divide" operators are extending coverage and speeds wherever economically viable; but, even in the most developed countries, there are still some areas that remain underserved. These underserved areas can be referred to as "not-spots". Not-spots are defined as locations where an adequate broadband service (in this work at least 2Mbit/s is required at peak times) is not already provided. In general these not-spots are small rural populations where it is not economically feasible to upgrade the fixed-line connections by, for example, deploying fibre-to-the-cabinet. The rural broadband scenario is where fixed-line operators provide broadband connectivity to not-spots via TVWS links. TVWS are seen as a possible solution for rural not-spot coverage due to their low spectrum cost and favourable propagation characteristics. Base stations can then be deployed at locations that are already equipped with power and backhaul capabilities, which can connect to homes that are typically from 3km up to 6km away. The antenna at the home would be installed on roof tops, pointing towards the base station. The service will have a high demand for QoS and capacity, but there are no mobility requirements. A more detailed description for this rural broadband scenario, depicted in Figure 6-7, can be found in [D12].

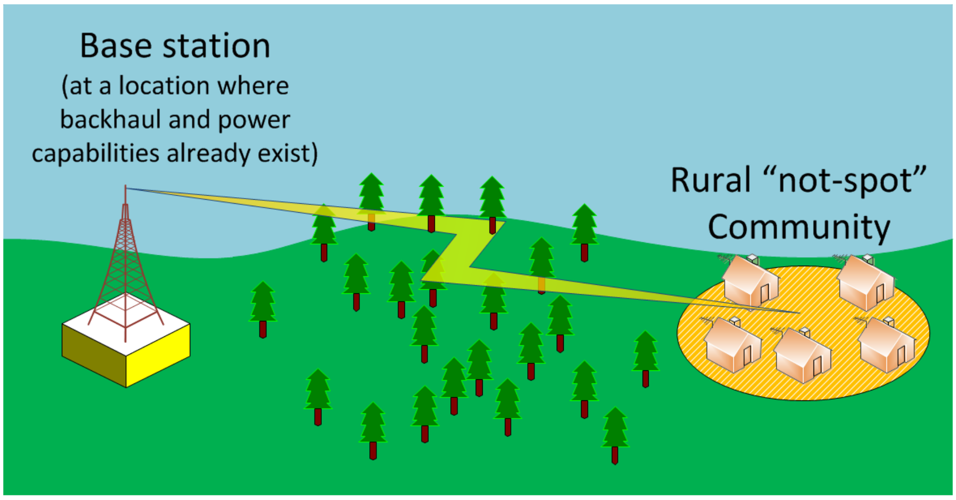

Figure 6-7 Deployment example for rural broadband scenario

6.6.2 Review Business Case

This business case scenario considers a hypothetical fixed line network operator using TVWS to provide broadband to rural not-spot locations. The business case assumes a base value of 1 million customers for rural broadband, using the UK as an example.

In order to keep costs as low as possible base stations are only deployed at locations where power and backhaul capabilities are already available. The distance between these base station locations and the customers is why the TVWS propagation characteristics are so important.

A detailed look at this business case is provided in [D16]. This shows that around 9500 base stations are required to cover close to 100% of the target not-spots with sufficient broadband capacity at peak times.

One of the objetives of the UK governement's Broadband Delivery UK (BDUK) programme is to deliver broadband with at least 2Mb/s to virtually all UK communities by May 2015 [BDUK2011]. Similar targets are set for other European countries. In order for this solution to meet such deadlines, deployment must start within the next couple of years. Within the timeframe it is unlikely that QoSMOS technology will be sufficiently mature (e.g. standardised and certified products available from vendors) in time for necessary infrastructure roll-out. This scenario only requires some of the QoSMOS functionalities, specifically functions are required QoS over whitespaces but there is no requirement for mobility. Hence a proprietary solution, implementing the necessary QoSMOS functionalities would be a suitable way to acquire equipment within the required timescale. The QoSMOS features required are:

- Base station equipment (with CM-SM, CM-RM and AL). The SS and TRX functionality, as explained in section 7.3, might be based on an existing technology or a new QoSMOS physical layer technology.
- Customer Premises Equipment (with CM-RM and AL) with compatible physical layer to the base station equipment.
- QoSMOS core network. This would include the CM-SM and AL. Further core network components depend on the technology deployed. In section 7.3 the example shown is if the QoSMOS functionality is implemented in a modified WiMAX system.
- Spectrum (geo-location) database access.

6.6.3 Develop Detailed Roll-Out Plan

In order to provide services the following must be considered and dealt with:

- Phased roll-out - Customers can only subscribe to the rural broadband service once the base station is deployed to serve their area. For the UK example, the majority of the infrastructure should be deployed by mid-2015 to meet the BDUK target [BDUK2011]. A phased deployment over a few years allows for customers to subscribe as soon as possible, while minimising initial investment. The evaluation in [D16] assumed a three year roll-out, where 40%, 80% and 100% of the bases stations were deployed by the end of the first, second and third year respectively.
- The core network - This must available and deployed at the start of roll-out.
- Availability of equipment - As mentioned in the previous section, a proprietary solution would probably be the way to acquire the correct equipment within the required timescale. The network operator would have to engage with potential suppliers as soon as possible to ensure that equipment will be available in time.
- Whitespace spectrum resources - The network operator must check with the national (or local as appropriate) regulatory authority that cognitive radio systems are allowed in the identified and wanted spectrum. An investigation of the actual spectrum primary utilisation is needed for the frequency bands in question. For this scenario it is important to confirm that the maximum EIRP are sufficiently high (36dBm has been considered for this example) otherwise the necessary coverage might not be achievable without significantly more base stations.
- Geo-location database - Access to a certain part of the radio spectrum will be granted for a certain time by using a geo-location database system with all necessary information for primary spectrum utilisation and wanted secondary utilisation. The network operator must establish a contract with a geo-location database operator or become a database operator, such that WS spectrum can be acquired at the locations and times wanted.

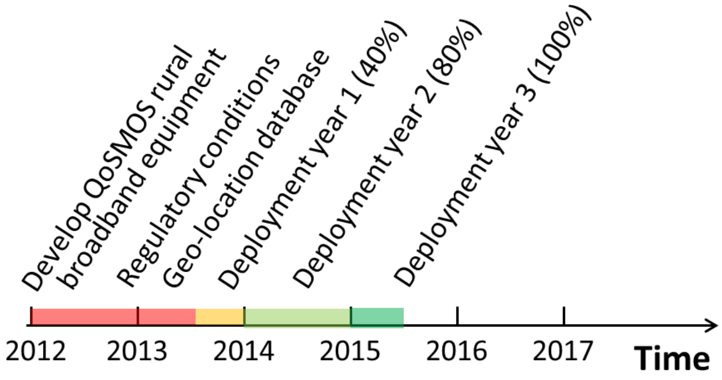

Figure 6-8 Roll-out timeline for rural broadband

Figure 6-8 shows a timeline for the rural broadband deployment. While regulatory conditions are finalised (including the production of the geo-location database) parallel work can be carried out for a QoSMOS solution (likely to be a proprietary solution given the time scale). Deployment could then begin as early as 2013. A phased deployment aims to get 100% coverage in time for mid-2015.

6.7 Cognitive Femtocell

6.7.1 Cellular Capacity "Shortage" and Available "Whitespace Spectrum" for Femtocells

Femtocell technology allows mobile operators to use other networks such as fixed cable solutions, for most or all traffic when the terminal is connected. It is similar to Wi-Fi hotspots in this respect, but it uses the macro cell mobile spectrum for user access. Cognitive radio solutions enable the use of other spectrum that may be available locally and temporarily to effectively reduce the pressure on the cellular spectrum. The scenario in Figure 6-9 depicts a case with two neighbouring residential houses using whitespace frequencies available. In this particular case the allocation of spectrum for femtocells is easily controlled using the cognitive radio system such that these femtocell sites will not cause interference to each other. QoSMOS Deliverable D1.2 [D12] describes and discusses the scenario in more detail.

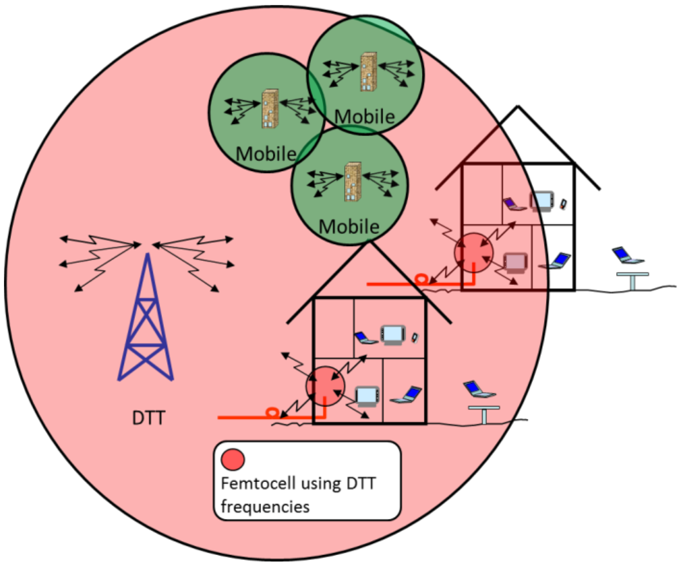

Figure 6-9 Cognitive femtocell dynamically operating at non-used (temporarily and spatially) digital terrestrial spectrum

6.7.2 Review Business Case

The business case for this scenario considers a fixed network operator who wants to exploit the fixed network infrastructure for a mobile service and to base the mobile service on cognitive femtocells. The cognitive femtocells are small LTE base stations giving coverage in a small area around the home or office where it is placed.

The fixed operator is assumed to have an existing infrastructure in the city (i.e. fibre, cable, ADSL or fixed wireless), and it will use this infrastructure in combination with cognitive femtocells to offer its customers mobile broadband at home. That is, the customers signing up for the mobile service will be given a cognitive femtocell, which they mount in their home or office.

In order to provide coverage to its customers outside the home, it will establish roaming agreements with traditional mobile broadband operators. In addition, customers can also use other customers' femtocells when they are within coverage of one or more of these.

The business case will be calculated for a fixed network operator who is the leading fixed network operators in the studied area/country. It has a large market share in fixed broadband based on e.g. DSL and FTTH solutions. It has an extensive cable, transport and switching infrastructure and an existing organisation for sales, marketing, technology and operation.

The operator will use TVWS (i.e. vacant spectrum in the frequency range 470-790MHz) in a cognitive way to extend its business to include also mobile (voice and) broadband services.

The business case is calculated for a hypothetical western European city with 1 million inhabitants covering an area of 200km^2. The city has a downtown area which covers 50km^2 with 0.5 million inhabitants and an urban/suburban area which covers 150km^2 also with 0.5 million inhabitants.

The study period is from 2015 to 2020. The starting year has been chosen based on when it is expected that the concept is sufficiently mature both with respect to technology and business aspects.

In D1.6 [D16], the results from a simulation study shows that that 99% outdoor coverage can be achieved for about 13,500 femtocells in the downtown and 28,400 femtocells in the suburban area. 90% coverage is achieved by 6,750 femtocells in downtown and 14,200 femtocells in the suburban area.

This makes both the development of a business case and a roll-out plan interesting. The business case study has identified the additional functional blocks needed for the deployment of cognitive femtocells:

- Cognitive femtocell equipment. Installation is considered to be done by the user, assuming that the operator will use self-installable cognitive femtocells.
- Mobile core network availability. Main components will be the Serving Gateway (SGW), the Packet Data Network Gateway (PGW), Mobility Management Entity (MME) and Home Subscriber Server (HSS).
- The addition of QoSMOS cognitive functions in the mobile core, including the CM-SM, CM-RM and AL.
- "Cognitive LTE" capable terminals. Both software and hardware must be added to the user terminals in order to make it capable of cognitive radio operation.
- Spectrum (geo-location) database access.

6.7.3 Develop Detailed Roll-Out Plan

A fixed network operator wishes to extend its service offering cognitive radio solutions deploying TVWS spectrum and femtocell technology, as sketched in Figure 6-10, for users to access the mobile network. For the particular area there may or may not be cellular coverage provided over the mobile licensed frequency bands.

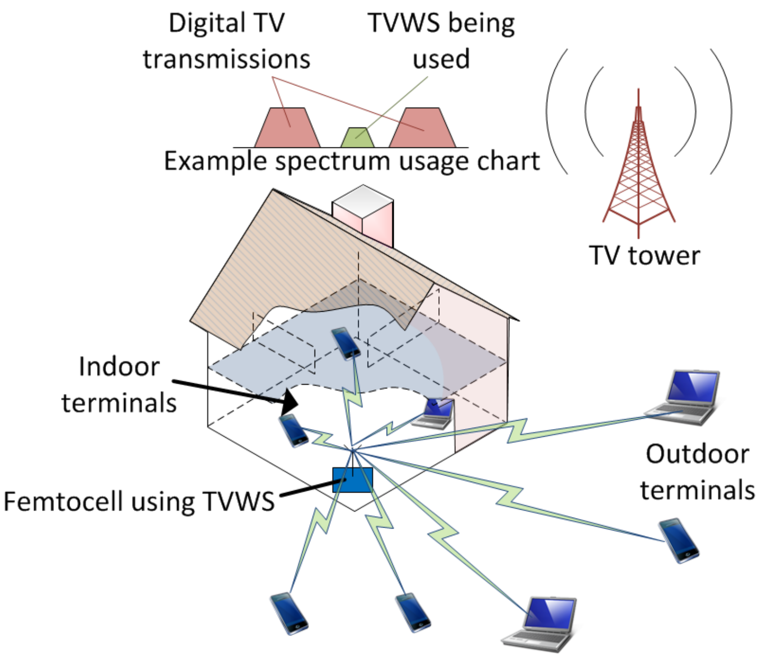

Figure 6-10 Example cognitive femtocell deployed at a residential site

In order to provide services the following must be considered and dealt with:

- Roaming - In the case of a fixed network operator providing connection to the femtocell roaming deals must be established with mobile network operators.
- Mobile core network - The operator must establish a mobile core network to manage the femtocell and handle the traffic and mobility aspects. The mobile core can either be owned or operated by the fixed network operator or other business models for this part can be implemented.
- Whitespace spectrum resources - The network operator must first check with the national (or local as appropriate) regulatory authority that cognitive radio systems are allowed in the identified and wanted spectrum. An investigation of the actual spectrum primary utilisation is needed for the frequency bands in question.
- Geo-location database - Access to a certain part of the radio spectrum will be granted for a certain time by using a geo-location database system with all necessary information for primary spectrum utilisation and wanted secondary utilisation. The network operator must establish a contract with a geo-location database operator or become a database operator, such that whitespace spectrum can be acquired at the locations and times wanted.
- Availability of equipment - Both access points such as femtocell base stations and user terminals must be available as whitespace devices WSD. The vendor industry must offer home base station equipment (femtocells) with cognitive radio capabilities, or new WS access points (such as super Wi-Fi [FCC2010]) must be available in the market. Similarly, at the user end, terminals with cognitive capabilities or super Wi-Fi dongles must be available in the market.
- Users - The network operator must inform and promote the new solutions and point to the benefits for the user of installing a cognitive femtocell or WS enabled AP. Possible some incentives must be established to motivate users to do this and also acquire the updated terminal allowing access to cognitive WS spectrum.

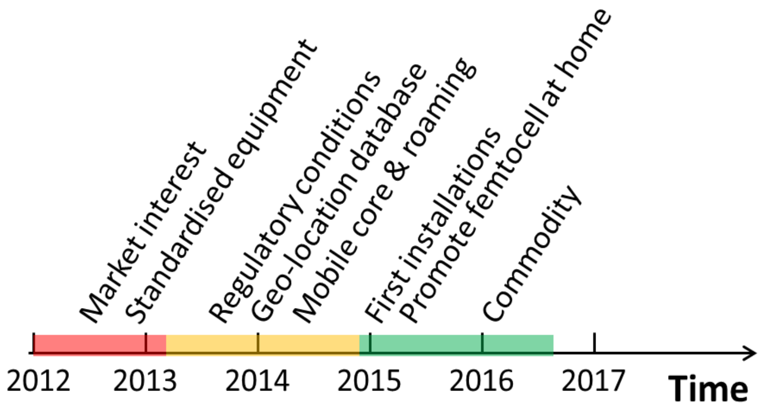

Figure 6-11 Roll-out timeline for cognitive femtocell

Figure 6-11 sketches a possible timeline for the cognitive femtocell case from being brought to standardised equipment in 2012 and early 2013 to commercial deployment from 2015.

6.8 Machine-to-Machine Network

6.8.1 Opportunity for Machine-to-Machine Using "Whitespace Spectrum"

A form of cognitive ad hoc network that has received a lot of attention recently is machine-to-machine (M2M) networking. M2M is typically used in infrastructure mode, where portable devices connect to the nearest base station. This is "ad hoc" in the sense that devices are portable and hence can appear anywhere and connect to the most appropriate base station (see illustration in Figure 6-12). The devices themselves will apply to a huge range of applications including, health care, utilities, transportation, smart device, etc. With forecasts such as more than 50 billion connected devices by 2020 [Eri2011] there is clearly a demand to provide access for these devices. TVWS is a suitable candidate for providing this access due to the low cost and good propagation characteristics, which can allow for good coverage with fewer base stations.

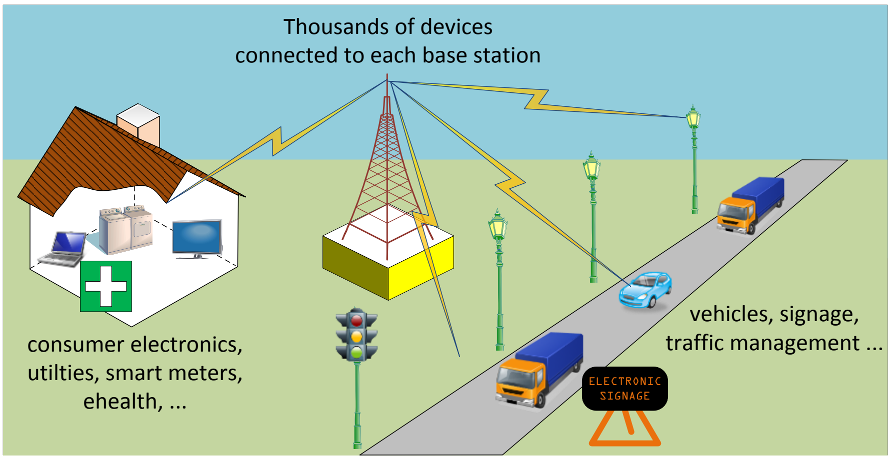

Figure 6-12 Example scenario for M2M

6.8.2 Review Business Case

This business case scenario considers an operator that will deploy a network of base stations to provide wireless access for M2M devices. TVWS will be used. The business case uses the UK as an example, where it is assumed there will be 50 million devices by 2020.

In order to keep costs as low as possible base stations are only deployed at locations where power and backhaul capabilities are already available. Approximately 5000 of these are required to provide coverage across the UK. Further details on this business case can be found in [D16].

For the number of M2M devices to grow by such forecast magnitude, the network infrastructure must be available as soon as possible. For this reason it is unlikely that QoSMOS technology will be sufficiently mature (e.g. standardised and certified products available from vendors) in time for necessary infrastructure roll-out. This solution only requires some of the QoSMOS functionalities, specifically functions are required for QoS over whitespaces but there is no requirement for mobility (similar situation to that of the rural broadband business case). Hence a proprietary solution, implementing the necessary QoSMOS functionalities would also be a suitable way to acquire equipment within the required timescale. The QoSMOS features required are:

- Base station equipment (with CM-SM, CM-RM and adaptation layer (AL)). The SS and TRX functionality, as explained in Section 7.3 might be based on an existing technology or a new QoSMOS physical layer technology.
- End user equipment (with CM-RM and AL) with compatible physical layer to the base station equipment. The range of applications for M2M is vast. A common chipset or set of chipsets would allow for these devices to connect to the same network. This chipset must therefore be available as soon as possible in order for M2M devices to incorporate this functionality. In some cases devices could be updated at a later date using a QoSMOS compatible USB dongle for example.
- QoSMOS core network. This would include the CM-SM and AL. Further core network components depend on the technology deployed. In section 7.3 the example is shown if the QoSMOS functionality is implemented in a modified WiMAX system.
- Spectrum (geo-location) database access.

6.8.3 Develop Detailed Roll-Out Plan

In order to provide services the following must be considered and dealt with:

- Phased roll-out - The predicted growth in the number of M2M devices will be restricted until base stations are available for connectivity; the greater the network coverage, the more the operator can attract various M2M applications. A phased deployment over a few years, starting in areas where more M2M demand is foreseen, allows for the operator to bring in revenue as quickly as possible while minimising the initial investment. The evaluation in [D16] assumed a four year roll-out, where 35%, 75%, 95% and 100% of the bases stations were deployed by the end of the first, second, third and fourth year respectively.
- The core network - This must available and deployed at the start of roll-out.
- Availability of equipment - As mentioned in the previous section, a proprietary solution would probably be the way to acquire the correct equipment within the required timescale. The network operator would have to engage with potential suppliers as soon as possible to ensure that equipment will be available in time. This applies to both base station equipment and chipsets for the end user devices.
- Whitespace spectrum resources - The network operator must check with the national (or local as appropriate) regulatory authority that cognitive radio systems are allowed in the identified and wanted spectrum. An investigation of the actual spectrum primary utilisation is needed for the frequency bands in question.
- Geo-location database - Access to a certain part of the radio spectrum will be granted for a certain time by using a geo-location database system with all necessary information for primary spectrum utilisation and wanted secondary utilisation. The network operator must establish a contract with a geo-location database operator or become a database operator, such that WS spectrum can be acquired at the locations and times wanted.

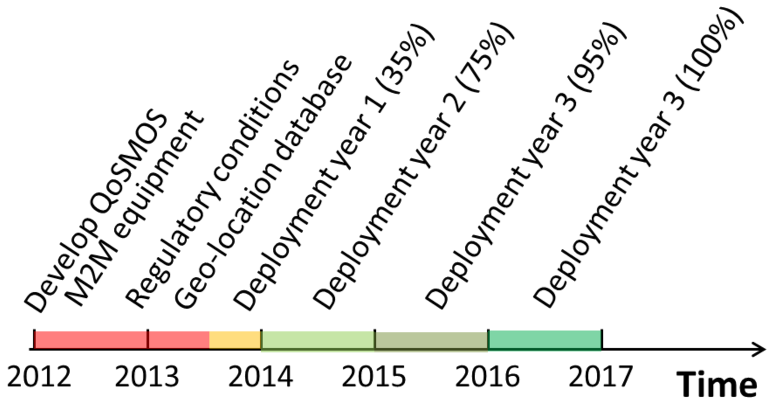

Figure 6-13 Roll-out timeline for M2M

Figure 6-13 shows a timeline for the M2M deployment. Regulatory conditions would be finalised (including the production of the geo-location database) in parallel to developing a QoSMOS solution (likely to be a proprietary solution given the time scale). Deployment could then begin as early as 2013. A phased deployment aims to get 100% coverage in time for 2017.

7 System Realisation

This chapter considers how a QoSMOS system might be realised for some of the QoSMOS scenarios. Particular attention is paid to how QoSMOS functionality might be included in LTE technology. Although the primary focus is for the realisation of the cellular extension for offloading of LTE networks scenario, it can be applied quite well to other QoSMOS scenarios that could use LTE, in particular the cognitive femtocell scenario. This chapter also looks at how the rural broadband scenario could be realised using proprietary solutions. Again, this discussion can be applied to other QoSMOS scenarios with similar system architectures, in particular the machine-to-machine realisation of a cognitive ad hoc network.

7.1 Introduction

The realisation of a QoSMOS system relies on vendors to produce this equipment. However, there is an ecosystem of entities that may be involved to make this happen. There is demand from network operators who wish to deploy this equipment, regulatory approval from regulators (further discussion on regulation can be found in section 6.3), chipset manufacture, etc. If a product needs to be standardised and certified, then there are further delays and entities that must contribute to these processes. For the various QoSMOS scenarios, different forms of realisation are required. The business cases for these scenarios were discussed in chapter 6.

For the cellular extension for offloading of LTE networks scenario, QoSMOS functionality is required in LTE equipment. The following section of this chapter evaluates what amendments might be needed to LTE in order for the equipment to allow this functionality to be added. The physical layer used in whitespaces could be modified LTE or it could use one of the QoSMOS TRX solutions, as summarised in section 3.4. The following section considers the cellular extension for offloading LTE scenario, but in general, the same modifications could be used for the cognitive femtocell scenario.

For the rural broadband scenario, deployment would be required soon. The timeline for the realisation of this scenario, which was discussed in detail in chapter 6, requires the availability of equipment in less time than standardisation would allow. For this reason, proprietary solutions may be used for this scenario. Only the QoSMOS functions that allow for opportunistic access are required (i.e. mobility functionality is not required); this functionality could then be added to a suitable existing technology. This chapter looks briefly at how a rural broadband system might be realised. While LTE has already been discussed, WiMAX is also given consideration. For the machine-to-machine realisation of a cognitive ad hoc network scenario, proprietary systems could be developed in a similar ways by making similar modifications to existing technologies suitable for the scenario.

7.2 Cellular Extension for Offloading of LTE

As described in [D12], the QoSMOS system enables a cellular operator to utilise the whitespace spectrum in addition to its own licensed spectrum, with the objective to improve the capacity of its network, and/or to enhance its coverage in areas where a macro base station is not available.

This section is focused on the cellular extension scenario, where the opportunistic resource is used to improve the capacity of the network cells. More specifically, this analysis will address essentially the LTE technology specified by the 3GPP standardisation group.

7.2.1 Deployment Assumptions

The additional whitespace spectrum should produce supplementary bandwidth for the benefit of the operator’s users. As depicted in [LehEtal2012], a device can operate in the licensed band, but also in the TVWS: this should improve the access to the operator’s services especially during a high-loaded period, or should boost the capacity of a user’s connection in case of simultaneous data transfer on both bands.

This scenario implies the availability of user devices with the capability to operate on both licensed and TVWS bands, or on a licensed band only. It is not expected that the system supports TVWS-only devices.

However, for the base stations, several assumptions can be envisaged, as depicted in Figure 7-1:

- The deployment of TVWS-only base stations in areas where no licensed cell is present (but assumption needed for coverage extension only).
- The co-localisation of TVWS base stations with the licensed ones (LTE evolved NodeBs, eNodeBs). This has the benefit to reuse the geographical sites and cancel the integration risk of CR functionalities with legacy components.
- The utilisation of re-configurable eNodeBs/base stations which have the capacity to select the band where to operate depending on the environment observation: as an example, reconfiguring the radio to operate in TVWS may be useful for small cells which experience high interferences from a macro cell.
- The replacement of current eNodeBs with base stations capable of transmitting data on both bands simultaneously and to exploit the flexibility offered by joint management of the licensed and opportunistic radio resources.

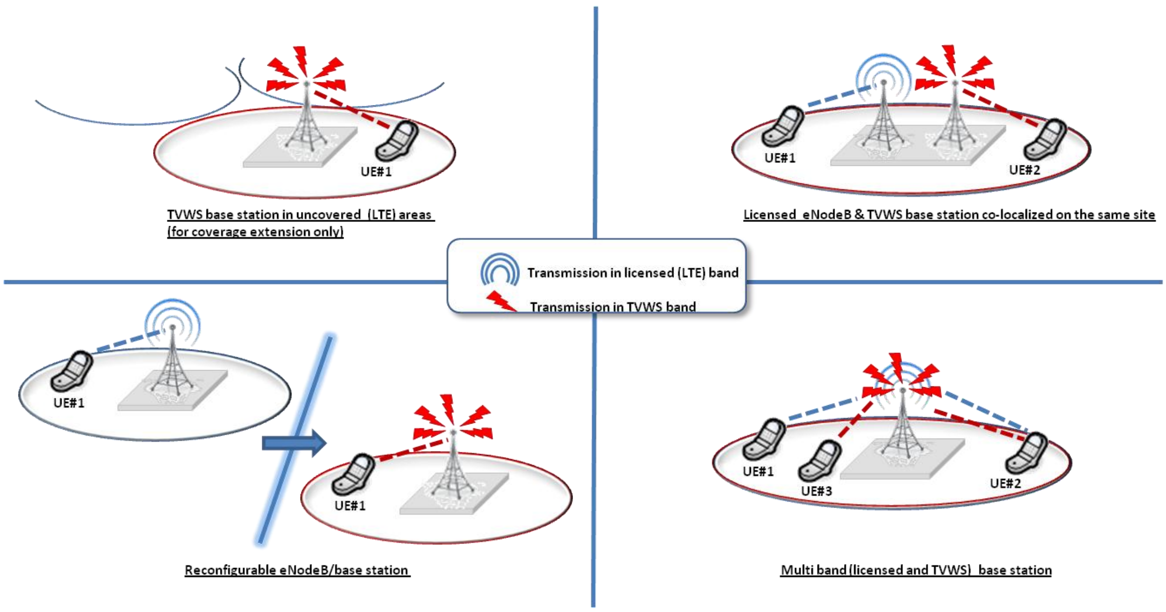

Figure 7-1 Deployment assumptions for offloading of LTE

The different assumptions for capacity extension of the LTE case are explored with more details in subsequent sections.

7.2.2 Mission Statements for LTE Network Equipment

The following tables present the mission statements already defined by the 3GPP standardisation group for each element of the network's equipment in both Radio Access Network (RAN) and Core Network (CN). These tables include the amendments needed by the QoSMOS system, when applicable, and also identifies where new mission statements are needed to enable opportunistic transmissions in the TVWS band, as defined in the QoSMOS system. The network elements addressed in this section are depicted in Figure 7-4 in the following section, giving an overview of a QoSMOS system realisation for the LTE extension scenario.

Table 7-1 Mission statements for the UE

User Element in RAN	
Mission statements (as defined by 3GPP 36.106)	**Amendments (in blue text)**
Select & reselect cell.	A new strategy for the cell selection may be required to handle the presence of "opportunistic" cells.
Receive and decode System Information.	New data (i.e. relative to the sensing measurements) has to be decoded.
Support PLMN selection and registration.	---
Decode paging data.	---
Perform / report mobility measurements.	---
Support location registration / update	---
Establish / release / reconfigure radio bearers	New QoS classes' definition may be required for applications executed in the opportunistic system.
Support interworking with legacy 3GPP networks	---
Support interworking with trusted non 3GPP networks	---
Support LTE Layer 1 & Layer 2 air interface	UE may have to support a new Physical Layer.
Execute intra & inter-system handover	---
Support security procedures (authentication, identification, integrity …).	---
New Mission statements from QoSMOS system definition	
Perform / report sensing measurements.	New mission statement

Table 7-2 Mission statements for the eNodeB

eNodeB in RAN	The eNodeB supports the LTE air interface and includes functions for radio resource control, user plane ciphering and Packet Data Convergence Protocol.
Mission statements (as defined by 3GPP 36.100)	**Amendments (in blue text)**
Schedule transmission of paging messages	---
Broadcast System Information.	New data (i.e. relative to the sensing measurements) have to be broadcast.
Transfer NAS messages to MME	---
Rout user plane data towards S-GW	---
Perform IP header compression and encryption	---
Establish / modify / release Radio bearer	---
Schedule mobility measurements and reporting configuration	---
Perform eNodeB handover through X2 and S1 interface	This includes spectrum mobility, but no modifications are expected.
Support inter-RAT handovers procedure for 3GPP interworking	---
Configure L1 and L2 procedures (modulation, coding scheme, ARQ, HARQ …) to fulfil QoS objective	This configuration should take into account decisions coming from the cognitive managers.
Select MME at UE attachment and following load rebalancing procedure	---
Allocate radio resources to UEs depending on negotiated QoS	This allocation shall consider the specificities of the operations in an opportunistic band.
Support LTE Layer 1 & Layer 2 air interface	eNodeB may have to support a new Physical Layer.
eNodeB reconfiguration	Used in case of back-up channel selection.

Control of the network access	This management should take in account decisions coming from the cognitive managers.
New Mission statements from QoSMOS system definition	
Configure spectrum sensing measurements (including scheduling).	New mission statement.
Perform spectrum sensing measurements.	New mission statement.
Analyse spectrum sensing results and detect incumbents.	New mission statement.
Select operating channel from the portfolio.	New mission statement.
Establish connection with external QoSMOS entities.	New mission statement.
Report context information observations.	New mission statement.
Enable incumbent protection by taking suitable eviction decisions.	New mission statement.

Table 7-3 Mission statements for the MME

MME in CN	The Mobility Management Entity(MME) is in charge of all the control plane functions related to subscriber and session management. From that perspective, the MME supports security procedures, terminal-to-network session handling and idle terminal location management.
Mission statements (as defined by 3GPP 23.002)	**Amendments (in blue text)**
Manage NAS signalling with the UE.	---
Support network (de)registration.	---
Control the idle state mobility	---
Distribute paging messages to eNBs	---
Establish the secure link with UE authentication, identification	---
Provide bearer management functions	---
Select the gateway entities (S-GW and P-GW) for user plane data	---
S1 handover between eNodeBs	---
Select MME for handovers with MME change	---
Support Inter-RAT (2G, 3G) handover and inter-system change	---
Provide roaming procedure	---

Table 7-4 Mission statements for the S-GW

S-GW in CN	The Serving Gateway routes and forwards user data packets. It also acts as the mobility anchor for the user plane during inter-eNB handovers and for mobility between LTE and other 3GPP technologies
Mission statements (as defined by 3GPP 23.002)	**Amendments (in blue text)**
Perform packet routing and forwarding.	---
Switch the user plane for inter-eNodeB mobility	---
Switch the user plane for inter-3GPP mobility	---
Manage accounting on user and QCI granularity for inter-operator charging	---
Perform E-UTRAN idle mode downlink packet buffering and initiation of network triggered service request procedure	---

Table 7-5 Mission statements for the P-GW

P-GW in CN	The Packet Data Network Gateway provides connectivity to the UE to external networks by being the point of exit and entry of traffic for the UE.
Mission statements (as defined by 3GPP 23.002)	**Amendments (in blue text)**
Allocate IP address to UE.	---
Constitute the anchor for mobility between 3GPP access systems and non-3GPP access systems.	---
Support policy enforcement	---
Perform per-user based packet filtering	---
Provide charging support	---

Table 7-6 Mission statements for the HSS

HSS in CN	The Home Subscriber Server supports the network control layer with subscription and session handling and provides authentication and authorization functions in Evolved Packet Core network
Mission statements (as defined by 3GPP 23.002)	**Amendments (in blue text)**
User security.	---
User identification handling	---
Access authorization	Manage access to opportunistic cells
Service authorization	Some service many not be authorized on opportunistic band.
Subscribed QoS profile	New QoS profile if needed

Table 7-7 Mission statements for the PCRF

PCRF in CN	The Policy and Charging Rules Function (PCRF) enables the network to dynamically control resources with real-time policy decisions to determine what services are delivered and how they are delivered
Mission statements (as defined by 3GPP 23.002)	**Amendments (in blue text)**
Handle network access aware of device and subscribers.	To be enhanced to support QoSMOS-capable UE.
Control the bearer establishment (Accept / Reject QoS control).	New QoS profile if needed

7.2.3 Mapping of QoSMOS Entities onto LTE Network Equipment

The network equipment involved in the QoSMOS cellular extension for offloading LTE scenario needs to support the architecture options specified by the RCC-SSC topology, as defined in [D23] and summarised in chapter 2. This section provides a more detailed mapping of two key pieces of QoSMOS equipment, namely User Element and Access Point, corresponding to the eNodeB in the LTE case. This analysis aims at elaborating recommendations for a functional integration of QoSMOS-specific features within legacy mechanisms.

Figure 7-2 depicts a functional view of a multi-RAT User Element capable of operating on the licensed bands deployed by the operator, such as LTE, 2G and 3G, but also able to establish an opportunistic communication over a TVWS channel by using QoSMOS technology. In this example, the LTE Access Stratum is shared between the 3GPP and the QoSMOS protocol stacks and provides standardised procedures to access the network. Cognitive capacities are then supplied by the CM-RM block. The role of the CM-RM is nevertheless limited to the generation of QoSMOS specific L2/L3 messages to be sent by using the LTE Access Stratum stack and the QoSMOS Physical layer.

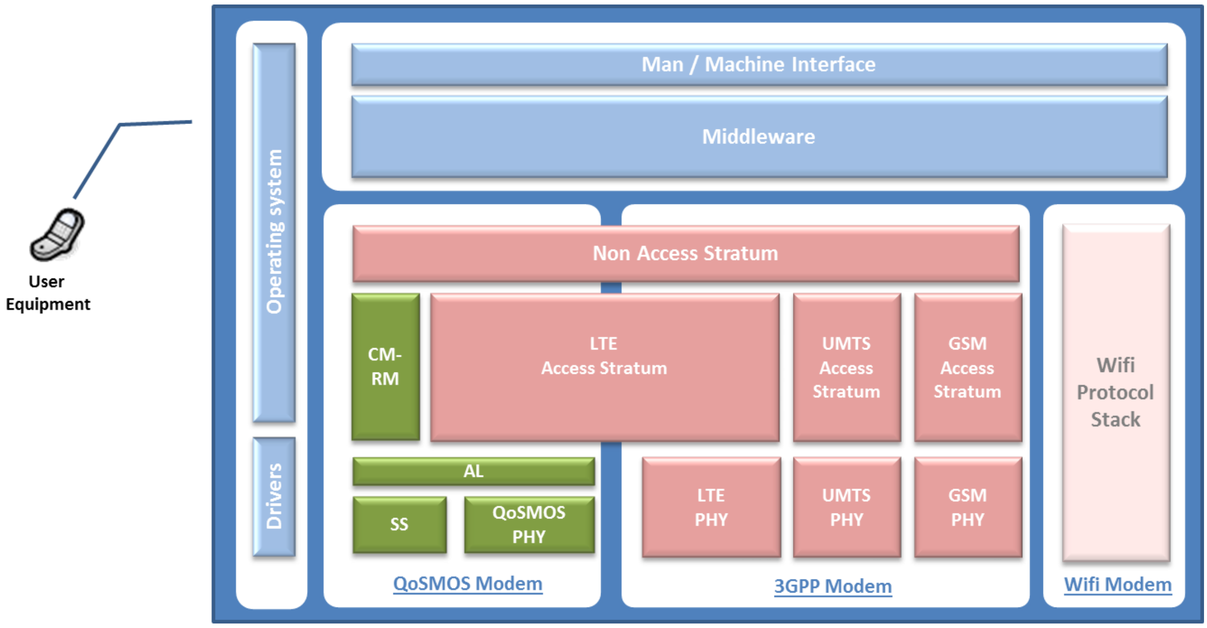

Figure 7-2 Functional view of LTE UE with QoSMOS capacities

Figure 7-3 depicts the functional view of a LTE eNodeB, which has been enhanced in a QoSMOS system realisation to extend the capacity of the cellular network. The communication technology is based on the LTE protocol stack represented in this view by the "LTE access stratum" block. Nevertheless, the traffic can be transferred on both legacy and opportunistic bands and the adaptation layer is used in the latter case to interconnect the QoSMOS front-end to the standardised protocol stack. In addition, decisions triggered by the cognitive managers (CM-RM & CM-SM) may have to interact with the legacy Radio Resource Management (RRM) functions (see Table 7-8): this is done through the adaptation layer, which adapts the format of the actions to the manufacturer's interfaces. This module is also used by the CM-SM gateway to connect to its corresponding instance present in the core network.

Table 7-8 Description of legacy RRM functions implemented in a LTE eNodeB

3GPP LTE Legacy component [3GPP 36.410] [3GPP 36. 420]	**Description**	**Interactions with**
Radio Bearer Control (RBC)	This component is charged to establish, maintain and release the radio bearers. When setting up a radio bearer for a service, the RBC takes into account the overall resource situation in the eNodeB and the QoS requirements for this new service. It is also concerned with the maintenance of radio bearers at the change of the radio resource situation due to mobility and is involved in the release of radio resources associated with the radio bearers at session termination, handover or at other occasions.	---
Radio Admission Control (RAC)	This component is responsible to admit or reject the establishment requests for new radio bearers. It takes into account the overall resource situation in the eNodeB, the QoS requirements, the priority levels and the provided QoS of the new radio bearer request. The goal of RAC is to ensure high radio resource utilization (by accepting radio bearer requests as long as radio resources available) and at the same time to ensure proper QoS for in-progress sessions (by rejecting radio bearer requests when they cannot be accommodated).	CM-RM AC entity

Connection Mobility Control (CMC)	This component is concerned with mobility. In idle mode, the cell reselection algorithms are controlled by setting parameters (thresholds and hysteresis values) that define the best cell and/or determine when the UE should select a new cell. Also, the eNodeB broadcasts parameters that configure the UE measurements and reporting procedures. In connected mode, the mobility of radio connections has to be supported. Handover decisions may be based on UE and eNodeB measurements. In addition, handover decisions may take into account other inputs, such as neighbour cell load, traffic distribution, transport and hardware resources and Operator defined policies.	CM-RM MC entity
Dynamic Resource Allocation (DRA):	The objective of this component is to allocate and de-allocate resources to the user. DRA typically takes into account the QoS requirements associated with the radio bearers, the channel quality information for UEs, buffer status, interference situation, etc.	CM-RM RA entity
Inter-Cell Interference Coordination (ICIC)	Inter-cell interference coordination has the task to manage radio resources such that inter-cell interference is kept under control. ICIC is inherently a multi-cell RRM function that needs to take into account information (e.g. the resource usage status and traffic load situation) from multiple cells.	CM-RM RA entity
Inter-RAT	This component is primarily concerned with the management of radio resources in connection with inter-RAT mobility. At inter-RAT handover, the handover decision may take into account the involved RATs resource situation as well as UE capabilities and Operator policies.	---

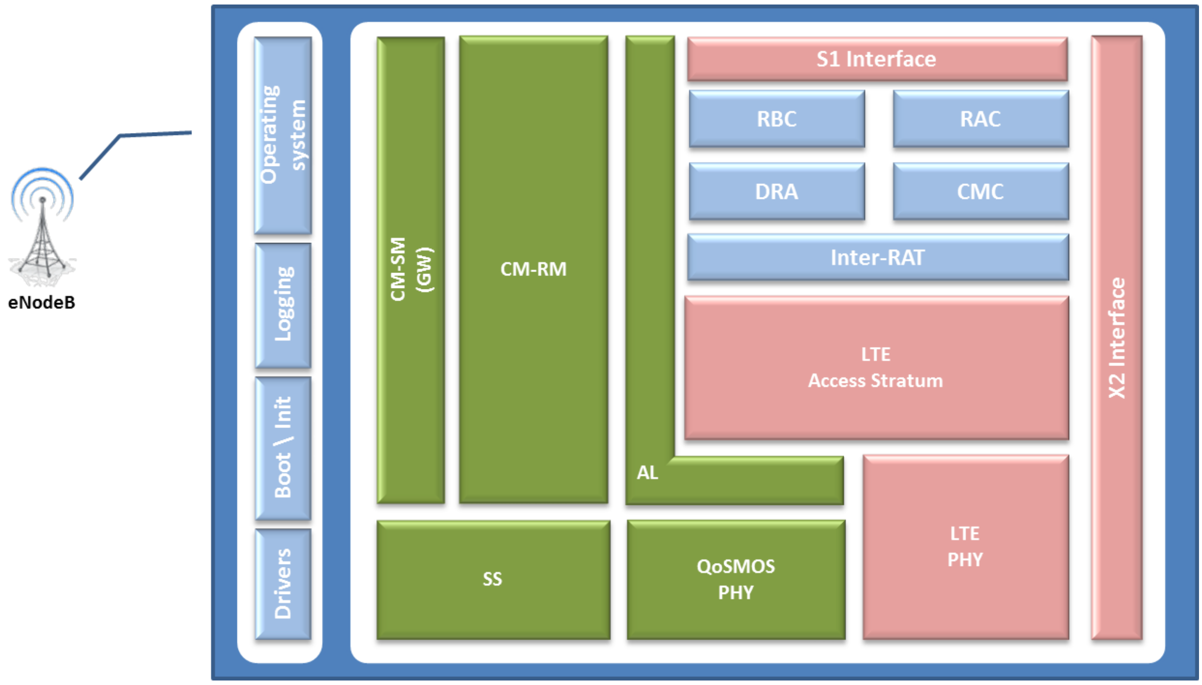

Figure 7-3 Functional view of LTE eNodeB enhanced with QoSMOS capabilities

7.2.4 QoSMOS System Realisation Overview for the Offloading of LTE Networks Scenario

Figure 7-4 presents a possible realisation of a QoSMOS system within a LTE network, providing eNodeBs operating in both legacy and opportunistic bands. These enhanced eNodeBs are connected to new equipment named in this figure. The Spectrum Manager is charged to elaborate the spectrum portfolio according to the information provided by the global databases localised in the Internet

Figure 7-4 contains interfaces between the system elements, which are the legacy ones as defined by 3GPP LTE as well as the ones defined by the QoSMOS system [D23]. All these system interfaces are referenced and described in more detailed in Table 7-9.

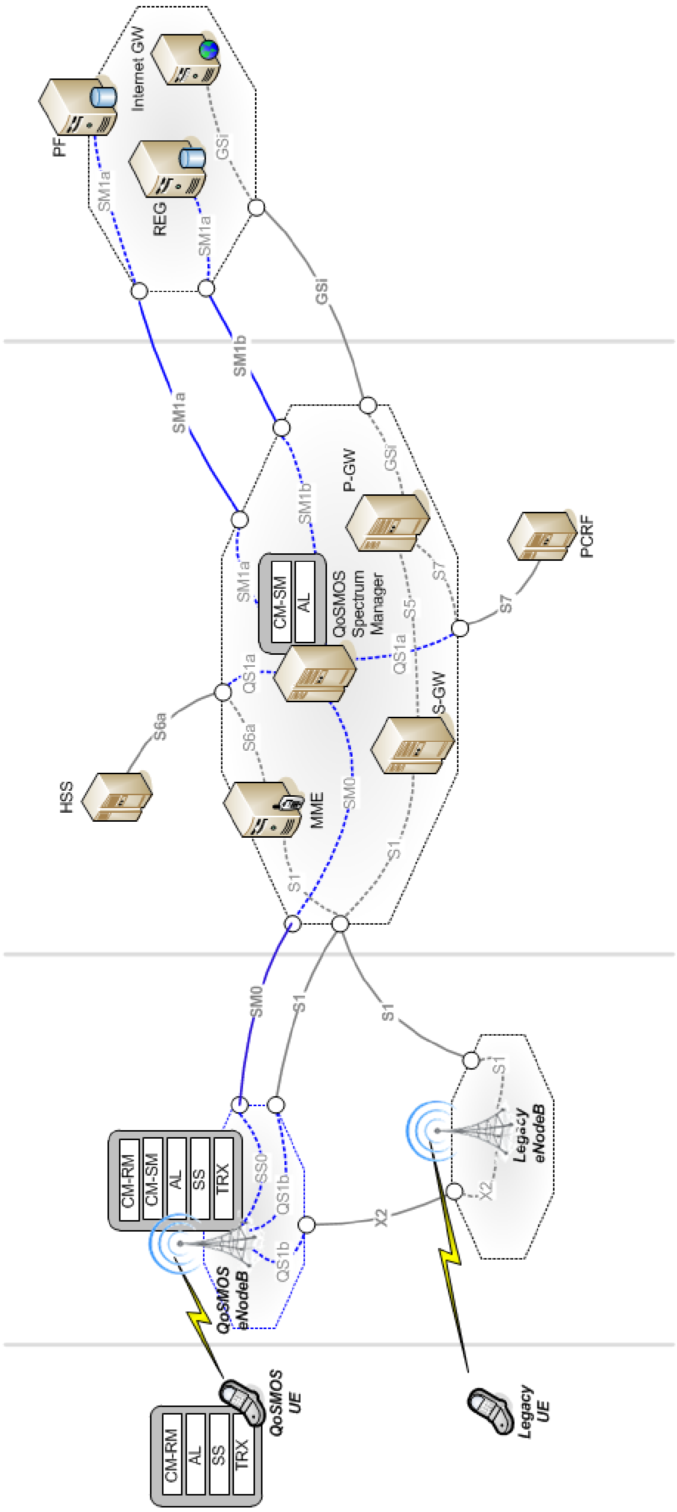

Figure 7-4 System overview for the offloading of LTE

Table 7-9 System interfaces mapped within the LTE network architecture

Interface name	Network Entities		Description
3GPP [3GPP 23.002]			
X2	eNodeB	eNodeB	This interface interconnects eNodeBs with each other in order to support radio interface mobility of UEs between eNodeBs, load management and inter-cell interference coordination.
S1	eNodeB	MME S-GW	This interface provides an access to E-UTRAN radio resources for both user-plane and control plane data traffic. Two types of interfaces are then defined to rout signalling data to the MME and user data to the GW.
S2	S-GW	non 3GPP network	Route the user plane data and provide mobility support between trusted & un-trusted non-3GPP IP access and the Gateway.
S5	S-GW	P-GW	Provide user plane tunnelling and tunnel management. It is used for S-GW relocation due to UE mobility and if the S-GW needs to connect to a non-collocated P-GW for the required PDN connectivity.
S6a	MME	HSS	Enable transfer of subscription and authentication data for authenticating/ authorising user access to the system between MME and HSS.
S7	P-GW	PCRF	Provide transfer of (QoS) policy and charging rules in the P-GW.
S11	MME	S-GW	Serve as a reference point between MME and Serving GW.
GSi	P-GW	IP network	It is the reference point between the access gateway and the IP-services network.
QoSMOS [D23]			
SM0	QoSMOS enhanced eNodeB	Spectrum Manager	This interface is used to exchange data between the spectrum manager and the local instance of CM-SM localised in the eNodeB.
QS1a	Spectrum Manager	PCRF HSS	QS1a interface is used to transfer data from the spectrum manager to external entities within the core network. It is then mapped onto the S6a interface to access the HSS and the S7 interface to interact with the PCRF.
QS1b	QoSMOS enhanced eNodeB	eNodeB MME S-GW	QS1b interface is used to transfer data from the QoSMOS eNodeB to other eNodeB through the X2 interface or to the core network (MME or S-GW) via S1 interface.
SM1a	Spectrum Manager	Common Portfolio repository	This interface is used for exchanging common portfolio, including operating policies.
SM1b	Spectrum Manager	Regulatory databases	This interface is used for exchanging regulatory constraints relative to the used channels.

7.2.5 Recommendations for Guaranteeing Emergency Service in QoSMOS System Realisation for LTE

In the 3GPP standard [3GPP 25.304], emergency service is provided by voice calls established in priority within the network. This service shall be available at any moment:

- When UE is successfully attached on a network: in that case, UE is camped on a suitable cell and is registered to the network in NORMAL SERVICE.
- When UE is not yet attached on a network, when the attach procedure has been rejected or when the SIM card is not available: in these cases, UE is camped on an acceptable cell and is registered in LIMITED SERVICE. In this state only emergency calls are authorised.

In a cell operating in an opportunistic band, this service availability cannot be guaranteed as the radio resources may be pre-empted at any time by an incumbent. The options to bypass this issue depend then on the deployment cases:

- For eNodeBs operating simultaneously in both legacy and opportunistic bands, it is the responsibility of the internal scheduler to identify the emergency communications and to allocate resources in the legacy band to avoid any pre-emption by the incumbent.
- For eNodeBs operating in the opportunistic band only, it is then up to the operator to determine if the area, where the opportunistic cell is deployed, is covered by another technology, such as 2G or 3G. It has to configure the cell's parameters to force the emergency call to be established on another radio access technology:
    - In order to force UEs in idle mode to select in priority the cells with emergency capacities, the network may broadcast within the opportunistic cells a system information message (SYSINFO#2) with the parameter "*imsEmergencySupportIndicator*" set to FALSE [3GPP 36.331] .
    - In addition, for UEs already connected to the opportunistic cells and wanting to originate an emergency call, the circuit-switched fallback function defined in 3GPP Release-9 [3GPP 23.869] can be applied. The mobile terminal sends a circuit-switched fallback service request message to the MME which initiates a handover procedure with another RAT, which provides in a QoSMOS context, more guaranteed radio resources.
- For eNodeBs operating in the opportunistic band with no other available RAT in the area, it is the access control responsibility to take the eviction measures (block incoming connection, drop low priority connections, force handover to neighbour cells …) to ensure radio resources to the emergency call even in presence of the incumbent.

7.2.6 Recommendations for Sensing Measurements Integration in QoSMOS System Realisation for LTE

As specified, in [D34], the integration of the QoSMOS sensing operation within an LTE system should be achieved without defining a separate protocol stack and require the enhancement of the RRC layer [3GPP 36.331] for two functions: the sensing measurement configuration and the sensing measurement reporting.

In connected mode, the eNodeB may command a UE to perform periodic measurements for enabling physical mobility management. This control is sent by the RRC layer within the "*RRC Connection Reconfiguration*" message in the "*MeasConfig*" information element [3GPP 36.331].

The "*MeasConfig*" information element defines measurements to be performed by the UE, and covers intra-frequency, inter-frequency and inter-RAT mobility as well as configuration of measurement gaps. The parameters of this information element should then be extended to support measurements for sensing and signal classification, as proposed in the following table:

Table 7-10 Parameters extension for 3GPP *"MeasConfig"*

Parameter type [3GPP 36.331]	**Description**	**Extension**
Measurement identity	This is used to identify a measurement configuration, i.e., linking of a measurement object and a reporting configuration.	---
Measurement object	Notify the type of measurements and the associated parameters.	"Sensing" and "Signal classification" object

Reporting configuration	This specifies criteria for triggering of a measurement reporting event.	Create a new object to define the sensing measurements reporting.
Quantity config	This specifies the measurement quantities.	---
Measurement gap config	This specifies the measurement gap configuration and controls setup/release of measurement gaps	No need to modify this parameter as explained in [D34]

The measurement results are reported in the "*MeasResult*" information element of the RRC "*Measurement Report*" message [3GPP 36.331]. It is therefore proposed to amend the definition of this information element as described in the following table:

Table 7-11 Parameters extension for 3GPP "*MeasResult*"

Parameter type [3GPP 36.331]	**Description**	**Extension**
Measurement identity	Identifies the measurement identity for which the reporting is being performed.	---
Measurement result PCell	Measured result of the Primary Cell.	---
Measurement result neighbour cells	Measured result for neighbour cells	---
Sensing result	Measured sensing results for required frequencies	Add information as defined in [D34]
Signal classification results	Measured signal classification results for required frequencies	Add information as defined in [D34]

7.3 Rural Broadband

This section is focused on the rural broadband scenario, where the opportunistic resource is used to provide broadband to rural not-spots. In this work a location is considered as a not-spot if it cannot get at least 2Mbit/s download speeds at peak-times. The realisation of this scenario is not specific to a particular standard. For example, it could be implemented using LTE or WiMAX with the necessary modifications to allow for opportunistic access to TVWS.

7.3.1 Deployment Assumptions

As described in [D12], the QoSMOS scenario for rural broadband involves a fixed-line operator providing wireless links to homes who cannot achieve broadband (at least 2Mbit/s) using fixed line solutions.

There are several assumptions made about this scenario. The first assumptions determine the targeted end users. These should be those homes that are considered as not-spots which are in a location where it is unlikely that the fixed-line infrastructure will be upgraded (e.g. fibre roll-out) soon. In general these locations are in rural areas. The client devices would be installed at roof top heights on homes. The base stations could be installed at the operators existing locations, which already have the capability to satisfy a base station's power and backhaul requirements.

TVWS are the considered frequencies for this service, due to its low cost and favourable propagation characteristics. The deployed system could use a new QoSMOS transceiver (if manufactured in time) or could be standardised equipment that is modified to be QoSMOS capable (e.g. WiMAX or LTE with QoSMOS capabilities). Given that the business case evaluation for rural broadband (details in chapter 6) recommends roll-out of equipment very soon, the system used would likely be a proprietary one.

7.3.2 Mapping of QoSMOS Entities onto Standardised Network Equipment

If LTE is used for this scenario then modifications from the previous section could be used. However, this solution could remove any QoSMOS functionalities related to mobility as these are not needed for this scenario. This might make equipment available sooner. An alternative realisation could be, for example, WiMAX operating in TVWS.

In [D22] it is described how modules for the functional blocks of the QoSMOS system architecture could be mapped into the IEEE 802.11 reference model. Here the same process is applied for the possible realisation within IEEE 802.16 systems using the 802.16 reference model. Figure 7-5 shows a generic model for an 802.16 base station and Figure 7-6 shows the same model with only the blocks required for user equipment. Further details on the notation used for these models can be found in [D22]. For a proprietary solution to be available quickly this solution could implement only the QoSMOS features necessary for opportunistic access of TVWS (i.e. no mobility) by modifying an existing firmware build. By modifying an existing firmware build a vendor could allow for the required QoSMOS functionality to be implemented with some existing chipsets.

For further understanding, the details in [D22] and [D23] give a more thorough explanation of the QoSMOS reference model and its mapping to various scenarios.

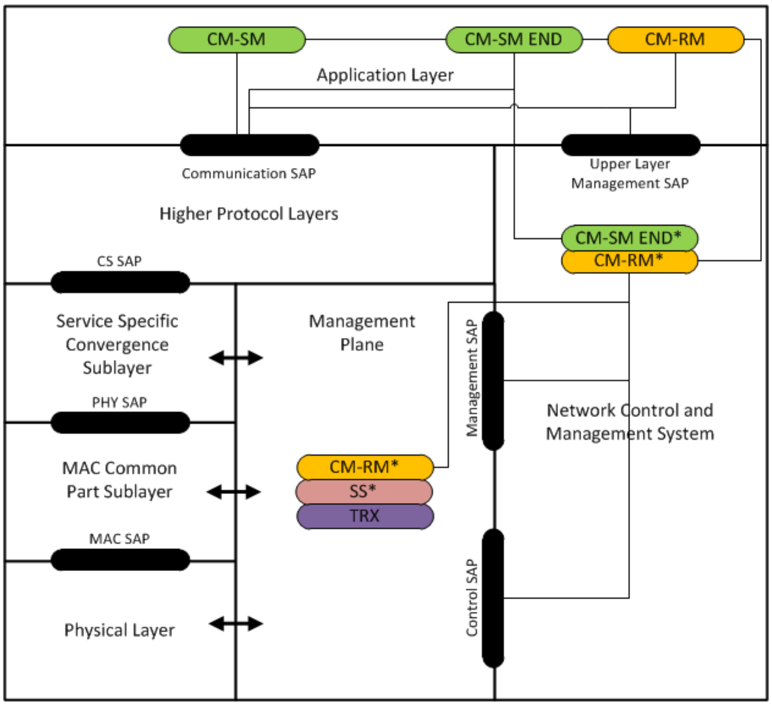

Figure 7-5 Topological view for an IEEE 802.16 base station with QoSMOS functionality

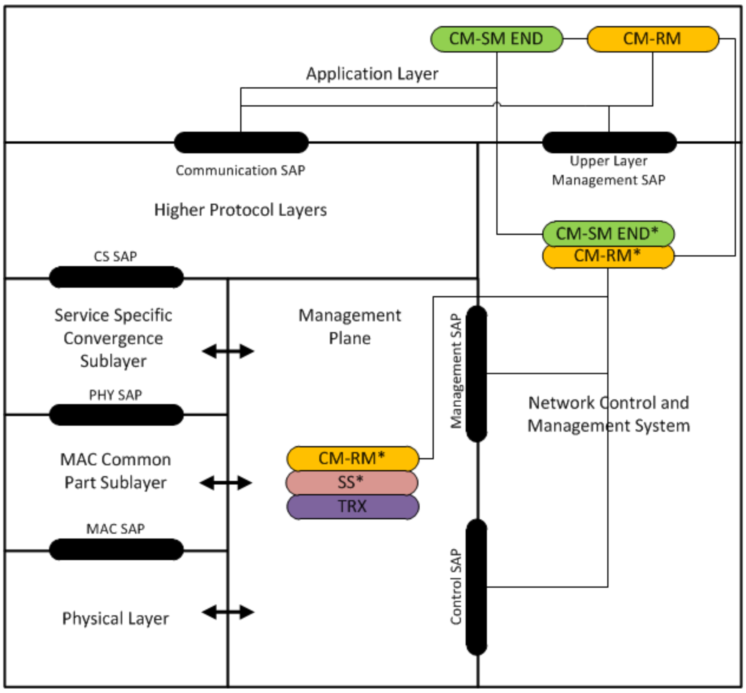

Figure 7-6 Topological view for an IEEE 802.16 user equipment station with QoSMOS functionality

7.3.3 System Overview for the Rural Broadband Scenario

For rural broadband to be deployed, a complete mobile core is not required (as mobility is not a requirement of this scenario) unless it is a necessity of the standard chosen. For example, if LTE is chosen a mobile core might be required. However, even in this example a mobile core might not be a necessity as a vendor may offer LTE base stations that include additional functionality that means a mobile core is not required. The decision for technology may depend on a network operators' existing network and also on the availability and cost of candidate technologies. If an LTE system is used as in section 7.2.4, the system overview could be the similar to the cellular extension for offloading LTE scenario as described earlier in the chapter. Figure 7-7 shows a possible deployment of a non-LTE rural broadband system. The newly defined QoSMOS interfaces remain, while the LTE interfaces are no longer shown. This example shows the components required for a WiMAX realisation of rural broadband where the link to the Internet would be from a base station through an Access Service Network Gateway (ASN GW) and then a Connectivity Service Network (CSN) using reference point interfaces R6 and R3 respectively.

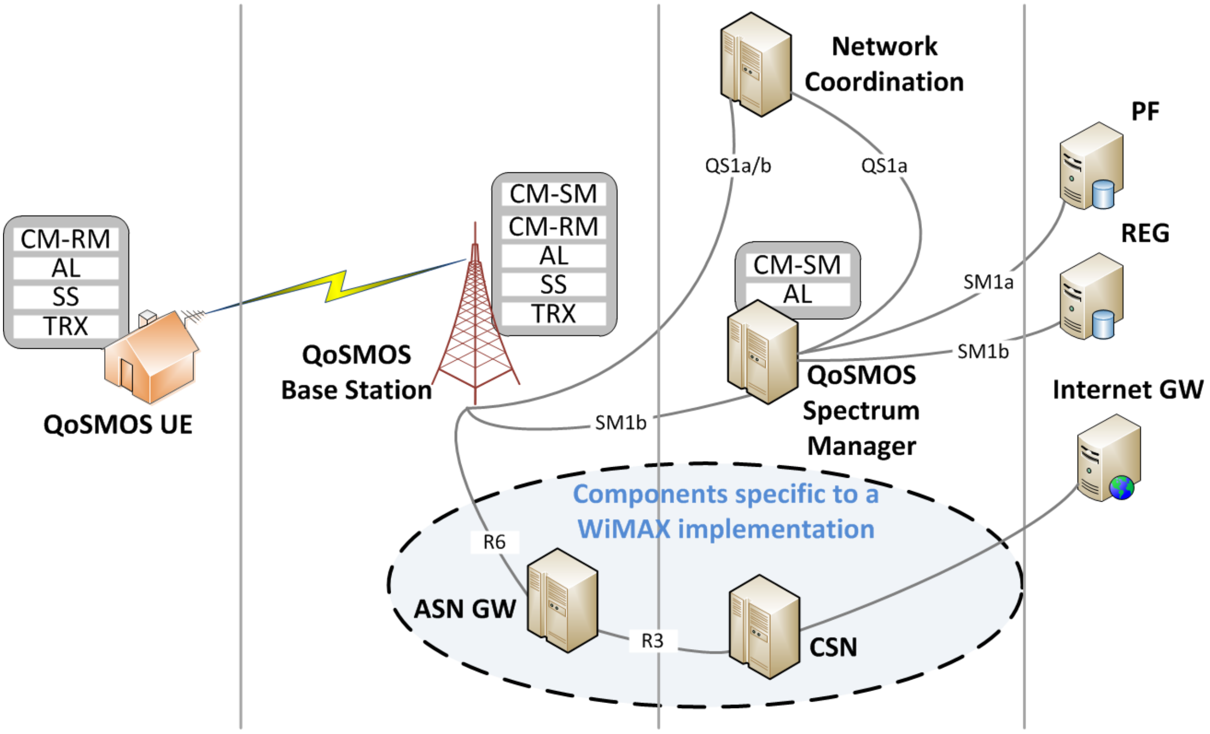

Figure 7-7 System overview for the rural broadband scenario

8 Conclusions

This document has presented a consolidated view of the QoSMOS system architecture, already defined in [D23]. This document has given details of how the various technical solutions created as part of the QoSMOS project are included as part of this system architecture. As well as technical solutions, tools were also developed during the project. These tools have been used as part of the QoSMOS proof-of-concepts or as assessment tools for the various parts of the QoSMOS system. Each technical solution and tool has been accompanied with a description of what it does and what benefits this can allow a QoSMOS system to offer. In addition, the technical solutions have been evaluated using selected performance metrics, which give a quantitative assessment of each solution's benefits and demonstrate how they advance the state-of-the-art.

This document brought together the information on the new technical solutions and tools developed across the entire project so that an appreciation can be gained of the role that each part has in an overall QoSMOS system. The solutions and tools are described whilst considering the various architectural options required for the QoSMOS scenarios:

- **Cellular extension in whitespace**
- **Cognitive femtocell**
- **Cognitive ad hoc network**

Proposals for time-ready deployment of QoSMOS systems have also been considered in this report. This was done for specific realisations of the QoSMOS scenarios closely harmonised with the business case evaluations. These specific scenarios include:

- LTE offloading using TVWS for **capacity enhancement of an LTE network** (subset of cellular extension in whitespace)
- **Rural broadband** using TVWS (subset of cellular extension in whitespace)
- A fixed operator providing a **mobile data service using cognitive femtocells** (subset of cognitive femtocell)
- **Machine-to-machine** using TVWS (subset of cognitive ad hoc network)

For the business case evaluations, assumptions and regulations are discussed in general as well as the unique details for the business case of each specific scenario. Finally, deployment guidelines are given for each specific scenario, listing which issues must be dealt with and a timeline suggesting how the deployment could progress.

The realisation of these specific scenarios requires that equipment with QoSMOS functionality is made available on time. This report has a particular focus on the modifications required to LTE technology to include QoSMOS functionality. Attention is also given to the option for proprietary solutions if the business case demands roll-out sooner than standardisation would allow.

9 References

[D12] R. MacKenzie, P. H. Lehne, U. Celentano, M. Ariyoshi, B. Cendón, A. Medela, "QoSMOS consolidated scenarios", QoSMOS D1.2, Dec 2010.

[D14] P. H. Lehne, U. Celentano, J. Lehtomäki, D. Noguet, R. Datta, P. Delahaye, R. Wansch, V. Berg, P. Grønsund, "QoSMOS consolidated system requirements", QoSMOS D1.4, Mar 2011.

[D15] P. Grønsund, R. MacKenzie, P. H. Lehne, K. Briggs, "Spectrum micro-trading analysis", QoSMOS D1.5, Jun 2012

[D16] "Economic benefits of a QoSMOS system. Preliminary analysis", QoSMOS D1.6, Dec 2012.

[D22] S. Leveil, C. Le Martret, O. Grøndalen, B. Bochow, C. Rosik, V. Mérat, B. Cendón, J. Herrero, A. Medela, U. Celentano, R. Datta, F. Noack, C. Lange, J. Gebert, K. Moessner, H.Sugahara, K. Muraoka, M. Ariyoshi, "System architecture options for the QoSMOS system", QoSMOS D2.2, Dec 2010.

[D23] G. Mange, P. Horváth, V. Berg, B. Bochow, R. Robles, M. Ariyoshi, C. Rosik, O. Grøndalen, P. H. Lehne, J. Rico, A. Medela, R. Datta, U. Celentano, "System specification and evaluation criteria", QoSMOS D2.3, Nov 2011.

[D32] U. Celentano, J. Lehtomäki, J. Vartiainen, F. Kemeth, M. Schühler, K. Arshad, X. Yu, P. Navaratnam, K. Moessner, M. Gautier, M. Ariyoshi, K. Muraoka, P. Delahaye, L. Gonçalves, "Reference protocol stack for QoSMOS radio environment mapping and sensing", QoSMOS D3.2, Oct 2010.

[D33] K. Muraoka, H. Sugahara, M. Ariyoshi, D. Depierre, M. Gautier, D. Noguet, J. Vartiainen, J. Lehtomäki, K. Arshad, D. Panaitopol, L. Gonçalves, A. Gameiro, "Radio Context Acquisition algorithms – Preliminary Version", QoSMOS D3.3, Feb 2011.

[D34] U. Celentano, K. Muraoka, M. Ariyoshi, A. Bagayoko, D. Panaitopol, P. Delahaye, X. Yu, P. Navaratnam, K. Moessner, A. Gameiro, F. Kemeth, R. Wansch, D. Noguet, V. Berg, "Reference protocol stack for QoSMOS", QoSMOS D3.4, Apr 2012.

[D35] K. Muraoka, H. Sugahara, M. Ariyoshi, D. Depierre, M. Gautier, D. Noguet, J. Vartiainen, J. Lehtomäki, K. Arshad, O. Durowoju, D. Panaitopol, L. Gonçalves, A. Gameiro, "Radio Context Acquisition algorithms – Final Version", QoSMOS D3.5, Nov 2012.

[D42] R. Datta, V. Berg, D. Noguet, A. Gameiro, M. Ariyoshi, Y. Futatsugi, M. Schühler, Z. Kollár, P. Horváth, "Flexible PHY concepts for white spaces – Intermediate Report", QoSMOS D4.2, Jan 2012.

[D43] V. Berg, D. Noguet, A. Gameiro, M. Ariyoshi, Y. Futatsugi, M. Schühler, Z. Kollár, P. Horváth, R. Datta, "Flexible PHY concepts for white spaces – Final Report", QoSMOS D4.3, Jul 2012.

[D53] H. Anouar, P. Bakki, J. Bitó, K. Briggs, U. Celentano, O. Durowoju, M. Fuentevilla, T. Guo, P. Horváth, I. Karla, Z. Kollár, S. Leveil, M. López-Benítez, R. MacKenzie, G. Mange, A. Medela, J. Rico, C. Rosik, I. Suliman, J. Vartiainen, "Final description and specification of cognitive manager and corresponding QoS support mechanisms with performance evaluation", QoSMOS D5.3, Jul 2012.

[D62] F. Noack, C. Lange, S. Kawade, B. Bochow, A. Gameiro, H. Sugahara, K. Muraoka, T. Nakamura, M. Ariyoshi, P. Grønsund, K. Moessner, U. Celentano, J. Vartiainen, J. Lehtomäki, "Description of context filtering, aggregation and communication functions of the spectrum management framework", QoSMOS D6.2, Apr 2011.

[D64] L. Csurgai-Horváth, J. Vartiainen, J. Lehtomäki, S. Kawade, B. Bochow, I. Karla, Y. Ko, "Flexibility, robustness and cognition", QoSMOS D6.4, May 2012.

[D65] B. Bochow, I. Karla, P. Bakki, L. Csurgai-Horváth, R. S. Robles, P. Grønsund, Y. Ko, M. López-Benítez, "Specification of cognitive and opportunistic functions of the spectrum management framework", QoSMOS D6.5, Apr 2012.

[D66] "Spectrum management framework integration and implementation report", QoSMOS D6.6, Dec 2012.

[D67] "Integrated final functional specification of spectrum management framework and procedures", QoSMOS D6.7, Dec 2012.

[D73] D. Noguet, V. Berg, X. Popon, M. Laugeois, J. Duplicy, M. Zelenak, D. Tandur, A. Medela, J. Rico, M. Fuentevilla, C. Ribeiro, J. Quaresma, M. Tessema, M. Schuehler, P. Delahaye, "QoSMOS Prototype – version 1", QoSMOS D7.3, Jul 2012.

[D74] "QoSMOS Prototype – version 2", QoSMOS D7.4, Mar 2013.

[D75] "Analysis of demonstration results and conclusions", QoSMOS D7.5, Mar 2013.

[3GPP 23.002] 3GPP Technical Specification 23.002, "Network architecture", v. 11.0.0, Sept 2011

[3GPP 23.869] 3GPP Technical Specification 23.869, "Support for Internet Protocol (IP) based IP Multimedia Subsystem (IMS) Emergency calls over General Packet Radio Service (GPRS) and Evolved Packet Service (EPS) v. 9.0.0, Mar 2009

[3GPP 25.304]] 3GPP Technical Specification 25.304, "User Equipment (UE) procedures in idle mode and procedures for cell reselection in connected mode", v 10.0.0, Mar 2011

[3GPP 36.300] 3GPP Technical Specification 36.300, "Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2", v. 11.0.0, Dec 2011

[3GPP 36.306] 3GPP Technical Specification 36.306, "Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities", v. 11.0.0, Jul 2012

[3GPP 36.331] 3GPP Technical Specification 36.331, "Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification", v. 11.0.0, Jul 2012

[3GPP 36.410] 3GPP Technical Specification 36.410, "Evolved Universal Terrestrial Radio Access Network (E-UTRAN) S1 general aspects and principles", v. 10.0.0, Dec 2010

[3GPP 36.420] 3GPP Technical Specification 36.420, "Evolved Universal Terrestrial Radio Access Network (E-UTRAN), X2 general aspects and principles", v. 10.0.0, Dec 2010

[AriEtal2011] M. Ariyoshi, R. MacKenzie, P. H. Lehne, U. Celentano, "Application and deployment of cognitive radio networks: High potential scenario examples", IEICE Technical Committee of Software Radio, Tokyo, Japan, 26-28 Oct 2011.

[ArsEtal2010] K. Arshad, K. Moessner, "Mobility driven energy detection based Spectrum Sensing framework of a Cognitive Radio", Proc. UKIWCS 2010, Dec 2010

[ArsEtal2011] K. Arshad, K. Briggs, K. Moessner, "Robust Spectrum Sensing for Cognitive Radio based on Statistical Tests", Proc. CogART 2011, Oct 2011.

[ArsEtal2011b] K. Arshad, K. Moessner, "Robust Collaborative Spectrum Sensing based on Beta Reputation System", Proc. FuNeMS 2011, Jun 2011.

[ArsEtal2011c] K. Arshad, K. Moessner "Statistical Models for Spectrum Opportunities for Cognitive Radio", Proc. PIMRC 2011, Sep 2011

[BDUK2011] "Broadband delivery programme: delivery model", Broadband Delivery UK, Version 1.01, Sept 2011.

[BerEtal2012] V. Berg, D. Noguet, X. Popon, "A Flexible Hardware Platform for Mobile Cognitive Radio Applications", EUROMICRO DSD, Sep 2012.

[Cel2012] U. Celentano, "QoSMOS system architecture and reference model", IEICE Technical Committee on Software Radio, Workshop on QoS & mobility in cognitive communications, Oct 2012.

[CelEtal2011] U. Celentano, B. Bochow, C. Lange, F. Noack, J. Herrero, B. Cendón, O. Grøndalen, V. Mérat, C. Rosik, "Flexible architecture for spectrum and resource management in the whitespace", Proc. Int. Symp. Wireless Personal Multimedia Commun. (WPMC 2011), Oct 2011.

[Cisco2012] "Cisco Visual Networking Index: Forecast and Methodology, 2011–2016", Cisco White Paper, May 2012.

[CsuEtal2011] L. Csurgai-Horvath, J. Bito, "Primary and secondary user activity models for cognitive wireless network", Proc. ConTEL 2011, pp. 301-306, Jun 2011.

[CsuEtal2012] L. Csurgai-Horvath, J. Bito, P. Bakki, G. Goldschmidt, "Mobility control in cognitive radio system", Proc. Future Network & Mobile Summit 2012, Jul 2012.

[DepEtal2012] D. Depierre, F. Pipon, D. Noguet, "Multi-Antenna Cyclostationarity Feature Detection for Parallel Sensing in Cognitive Radio", Proc. Future Network & Mobile Summit (FutureNetw), Jul 2012.

[DigEtal2007] F. F. Digham, M.-S. Alouini, M. K. Simon, "On the energy detection of unknown signals over fading channels," IEEE Transactions on Communications, vol. 55, no. 1, pp. 21–24, Jan. 2007.

[DurEtal2010] O. Durowoju, K. Arshad, K. Moessner, "Distributed power control for cognitive radios with primary protection via spectrum sensing", *IEEE VTC 2010 Fall*, Sept 2010.

[DurEtal2011a] O. Durowoju, K. Arshad K. Moessner, "Cognitive time variant power control in slow fading mobile channels", *IEEE VTC 2011-Spring*, May 2011.

[DurEtal2011b] O. Durowoju, K. Arshad, K. Moessner, "Distributed power control for cognitive radio networks, based on incumbent outage information", *IEEE ICC 2011*, Jun 2011.

[DurEtal2012] O. Durowoju, K. Arshad, K. Moessner, "Distributed power control algorithm for cognitive radios with primary protection via spectrum sensing under user mobility", *Elsevier Journal of Ad Hoc Networks*, Special Issue: CRAHNs, 2012.

[EC2012] European Commission. "Standardisation Mandate to CEN, CENELEC and ETSI for Reconfigurable Radio Systems", Ref. Ares(2012)1359338 – 19/11/2012. Nov 2012.

[Eri2011] "More than 50 billion connected devices", Ericsson White paper, Feb 2011.

[Farh2011] B. Farhang-Boroujeny, "OFDM versus filter bank multicarrier," IEEE Signal Processing Magazine, vol. 28, no. 3, pp. 92–112, 2011.

[FCC2010] "Second memorandum of order" in the Matter of "Unlicensed Operation in the TV Broadcast bands" and "Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band", FCC 10-174, Federal Communications Commission, USA, Sep 2010.

[FCC2012] "Third memorandum of order" in the Matter of "Unlicensed Operation in the TV Broadcast bands" and "Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band", FCC 12-36, Federal Communications Commission, USA, Apr 2012.

[Fit2004] M. Fitch, "OSS for Satellite Systems", PhD thesis, 2004

[GauEtal2010] M. Gautier, M. Laugeois, D. Noguet, "Teager-Kaiser energy detector for narrowband wireless microphone spectrum sensing", Proc. CROWNCOM 2010, Jun 2010.

[GauEtal2012] M. Gautier, V. Berg, D. Noguet, "Wideband frequency domain detection using Teager-Kaiser energy operator", Proc. CROWNCOM 2012, Jun 2012.

[GuoMoe2012] T. Guo, K. Moessner, "Optimal strategy for QoS provision under spectrum mobility in cognitive radio networks, *VTC2012*, Sept 2011.

[ITU-R12] "Radio Regulations", International Telecommunication Union, Geneva, Radiocommunications sector (ITU-R), Nov 2012.

[ITU-T00] "Principles for a telecommunications management network", International telecommunication Union, Telecommunication sector (ITU-T), Recommendation M.3010, 2000

[JasEtal2012] A. Jaschke, M. Schuehler, M. Tessema, R. Wansch, "Digitally Tunable Bandpass Filter for Cognitive Radio Applications," IEEE CAMAD 2012, Sept 2012

[Kolletal2010] Z. Kollár and P. Horváth, “Modulation schemes for cognitive radio in white spaces,” Radioengineering, vol. 19, no. 4, pp. 511–517, 2010.

[Kay1998] S. M. Kay, Fundamentals of statistical signal processing: detection theory. Prentice Hall, 1998, vol. 2.

[LehEtal2011] P. H. Lehne, D. Noguet, R. Datta, U. Celentano, G. Fettweis, “Requirements for a CR-system - Challenges compared to conventional wireless technology”, Proc. Wireless Innovation Forum Eur. Conf. Commun. Technol. Software Defined Radio (WInnComm), Jun 2011.

[LehEtal2012] P. H. Lehne, R. MacKenzie, O. Grøndalen, P. Grønsund, K. Briggs, “Business opportunities and scenarios for cognitive radio systems”, QoSMOS white paper, April 2012.

[LehEtal2012b] J. J. Lehtomäki, R. Vuohtoniemi, K. Umebayashi, J.-P. Mäkelä (2012). “Energy Detection Based Estimation of Channel Occupancy Rate With Adaptive Noise Estimation”, *IEICE Transactions on Communications* E95-B: 04. 1076-1084 April 2012

[LevEtal2012] S. Leveil, C. J. Le Martret, H. Anouar, K. Arshad, T. Zahir, J. Bito, U. Celentano, G. Mange, J, Rico, A. Medela, “Resource management of centrally controlled cognitive radio networks”, Proc. Future Network & Mobile Summit (FuNeMS 2012), Jun 2012.

[MacEtal2011] R. MacKenzie, P. H. Lehne, U. Celentano, M. Ariyoshi, “Identifying scenarios with high potential for future cogntivie radio networks”, Proc. Future Network & Mobile Summit (FuNeMS 2011), Jun 2011.

[MacEtal2012] R. Mackenzie, K. Briggs, “Comparison of contention-based protocols for secondary access in TV whitespaces”, Proc. WinnComm-Europe, Jun 2012.

[ManEtal2011] G. Mange, C. Rosik, S. Leveil, U. Celentano, O. Durowoju, K. Arshad, “Cognitive resource management for QoS support in mobile opportunistic communications”, Proc. Future Network & Mobile Summit (FuNeMS 2011), Jun 2011.

[MurEtal2011] K. Muraoka, H. Sugahara, M. Ariyoshi, “Monitoring-Based Interference Management for Expanding Opportunities of White Space Utilization”, in Proceedings of the IEEE DySPAN 2011, May 2011.

[NogEtal2012] D. Noguet, V. Berg, X. Popon, M. Schuehler, M. Tessema, “T-Flex: A mobile SDR platform for TVWS flexible operation,” IEICE 2012, Oct 2012.

[Ofcom2011] “Implementing Geolocation. Summary of consultation responses and next steps”, Ofcom Statement, UK, Sep 2011.

[PanEtal2011] D. Panaitopol, A. Bagayoko, P. Delahaye, L. Rakotoharison, “Fast and Reliable Sensing Using a Background Process for Noise Estimation”, Proc. CROWNCOM 2011, Jun 2011.

[PanEtal2012] D. Panaitopol, R. Datta, G. Fettweis , “Cyclostationary Detection of Cognitive Radio Systems using GFDM Modulation”, Proc. WCNC 2012, Apr 2012.

[Poo1998] H. V. Poor, An introduction to signal detection and estimation, 2nd ed. Springer, 1998, vol. 2.

[RajEtal2010] U. Rajeskaran, K. Arshad, K. Moessner, "Joint rate and power optimisation using distributed power control algorithms in cognitive radio networks", *SDR 2010*, Dec 2010.

[SaaEtal2005] H. Saarnisaari, P. Henttu M. Juntti, "Iterative multidimensional impulse detectors for communications based on the classical diagnostic methods". *IEEE Transactions on Communications* 53(3): 395–398, 2005.

[SamEtal2012] R. Samano, A. Gameiro, "'Joint Spectrum Selection and Radio Resource Management for Cognitive Radio based on Multi-objective Portfolio Optimization' accepted in the Future Generation Communication technology (FGCT), London, Dec 2012.

[SamEtal2013] R. Samano, A. Gameiro, "Joint spectrum selection and radio resource management for distributed antenna systems with cognitive radio and space division multiplexing", to appear in WSA 2013, March 2013.

[TanEtal2012] D. Tandur, J. Duplicy, K. Arshad, D. Depierre, K. Moessner, J. Lehtomaki, K. Briggs, L. Goncalves, A. Gameiro, "Cognitive Radio Systems Evaluation: Measurement, Modeling, and Emulation Approach," *Vehicular Technology Magazine, IEEE* , vol.7, no.2, pp.77-84, Jun 2012.

[TanSah2007] R. Tandra, A. Sahai, "SNR walls for feature detectors," in Proceedings of the 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN 2007), Apr. 2007, pp. 559–570.

[TanSah2008] R. Tandra, A. Sahai, "SNR walls for signal detection," IEEE Journal of Selected Topics in Signal Processing, vol. 2, no. 1, pp. 4–17, Feb. 2008.

[Urk1967] H. Urkowitz, "Energy detection of unknown deterministic signals," Proceedings of the IEEE, vol. 55, no. 4, pp. 523–531, Apr. 1967.

[Var2010] J. Vartiainen, "Concentrated signal extraction using consecutive mean excision algortihms", PhD thesis, University of Oulu, 2010. Available from: http://herkules.oulu.fi/isbn9789514263491/isbn9789514263491.pdf [December 2012]

[Var2012] J. Vartiainen, "Always one/zero malicious user detection in cooperative sensing using the FCME method", Proc. CrownCom 2012, Jun 2012.

[VarEtal2012] J. Vartiainen, J. Lehtomäki and R. Vuohtoniemi, "The LAD Methods in WLAN Indoor Multipath Channels", Crowncom 2012.

[YuEtal2010] X. Yu, P. Navaratnam, K. Moessner, "Distributed resource reservation mechanism for IEEE 802.11e-based networks", *IEEE VTC 2010 Fall*, Sept 2010.

[YuEtal2011] X. Yu, P. Navaratnam, K. Moessner , "Distributed resource reservation for real time sessions in multi-hop wireless networks", *7th International Wireless Communications and Mobile Computing Conference* (IWCMC 2011), Jul 2011.

[ZahEtal2011] T. Zahir, K. Arshad, K. Youngwook, K. Moessner, "A downlink power control scheme for interference avoidance in femtocells", *7th International Wireless Communications and Mobile Computing Conference* (IWCMC), Jul 2011.

[ZhaEtal2009] Y. Zhao, S. Mao, J. O. Neel and J.H. Reed, “Performance evaluation of cognitive radios: metrics, utility functions, and methodologies” Proceedings of the IEEE, vol. 97, no. 4, Apr 2009.