# Flexible and Spectrum Aware Radio Access through Measurements and Modelling in Cognitive Radio Systems

## FARAMIR

## Document Number D2.2

## Scenario Definitions

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| Editor: | Berna Sayrac (FT) |
| Authors: | Patrick Tortelier (FT), Sebastien Grimoud (FT), Pascal Cordier (FT), Sana Ben Jemaa (FT), Lorenzo Iacobelli (TCF), Christophe Le Martret (TCF), Jaap van de Beek (HWSE), Siva Subramani (TREL), Woon Hau Chin (TREL), Mahesh Sooriyabandara (TREL), Liljana Gavrilovska (UKIM), Vladimir Atanasovski (UKIM), Petri Mähönen (RWTH), Janne Riihijärvi (RWTH) |
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Abstract:

FARAMIR project aims at conceiving and developing enabling concepts that increase the radio environmental and spectral awareness of future wireless systems. At the center of these awareness-providing concepts lies Radio Environment Maps (REMs), obtained by cooperatively combining measurements reported by multiple nodes of the network, with the purpose of having geo-localized information on the characteristics of the radio environment, like spectrum opportunities or interference sources. This information forms the basis of efficient radio resource management and optimization techniques whose proof-of-concept will be demonstrated through prototyping. In this document, a set of REM-relevant scenarios that are of interest to FARAMIR partners are presented and described. Further on during the project, some of these scenarios will be identified as target scenarios on which REM-based resource management and optimization solutions will be prototyped.

Keywords: Cognitive Radio, Cognitive Networks, Radio Environment Maps, Spectrum Sensing, Spectrum Sharing, Resource Management, Spectrum Measurements, CN Testbeds, Regulatory issues

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# 1 Introduction

Wireless systems are becoming increasingly complex with the co-existence of multi-frequency, multi-technology, multi-service and multi-layered systems. In this context, the need for optimizing future wireless systems in terms of cost, Quality of Service (QoS), resource management and spectrum efficiency is imperative.

Cognitive radio, with the original meaning introduced by Mitola in his PhD thesis, offers opportunities in increasing efficiency in radio resource utilization and management by providing automated, intelligent and flexible solutions. These solutions vary from self-organizing principles for network entities to dynamically allocating spectrum in a shared-spectrum setting.

In this wide variety of cognitive solutions, environment information in the form of geo-localized measurements is of tremendous utility. By storing, processing and retrieving such information, it is possible to optimize network management and achieve an efficient utilization of radio resources, including spectrum. Radio Environment Maps (REMs) is an emerging concept that realizes this gathering and exploitation of geo-localized environmental information. Although the concept of REMs has already been elaborated in the literature, almost no study has been done to have a concrete REM implementation. FARAMIR project targets at filling-in this gap, by providing prototypes on real-world implementations of REM-based cognitive solutions. Each one of these solutions addresses different challenges and takes place in different scenes.

This document aims at identifying and describing these scenes through scenario definitions. For each scenario, REMs can bring efficient solutions in terms of management complexity, cost, QoS and spectrum efficiency. The scenarios presented in this document vary from legacy system optimization in terms of Key Performance Indicators (KPIs) to Long Term Evolution (LTE) solutions in TV White Spaces (TVWS), covering a wide variety of spectrum access modes. Therefore, we will first give a brief overview of the taxonomy of spectrum sharing techniques, which allows to better situate the scenarios on the spectrum-access scale ranging from conventional licensed schemes to most flexible ones. Furthermore, a template will be given for each scenario that summarizes its main characteristics and that eases comprehension by providing a quick reference.

The scenarios described in this document can be grouped into three main groups according to their spectrum access modes described in the beginning of the document: intra-operator scenarios, hierarchical access in licensed bands and spectrum sharing on unlicensed bands. The first group contains scenarios where there is only one operator who owns the spectrum, and it uses REMs to enhance its radio resource management of its (heterogeneous) radio access networks. The second group involves a licensed spectrum with a license owner, and secondary users perform opportunistic access either with or without co-ordination with the license holder. The third group collects cases where the spectrum is unlicensed and users share this spectrum either with or without c-ordination. Finally, a dedicated spectrum sensing scenario is presented where there is a dedicated sensor network that belongs to a third party and that performs spectrum measurements at the disposal of any entity/stakeholder who wishes to access the spectrum.

The scenarios described in this document will later on be used to choose the target scenarios for prototyping purposes.

## 1.1 Overview and Taxonomy of Spectrum Sharing Techniques

In a growing number of papers we can see the emergence of several new schemes of spectrum access modes departing from the Command and Control scheme which is the way spectrum use is regulated today. These schemes are intended to provide a better use of radio spectrum than the Command and Control scheme, which is viewed as too static, by bringing in some flexibility in the way users access to the spectrum.

These new schemes range from exclusive use schemes (there is always only one licensed user in a frequency band, but its license is temporary), to shared use of a primary licensed spectrum (either underlay or opportunistic) to commons (unlicensed spectrum, as ISM band at 2.4 GHz or UNII bands at 5 GHz). For a comprehensive classification the reader is referred to [1] from which Figure 1 is taken.

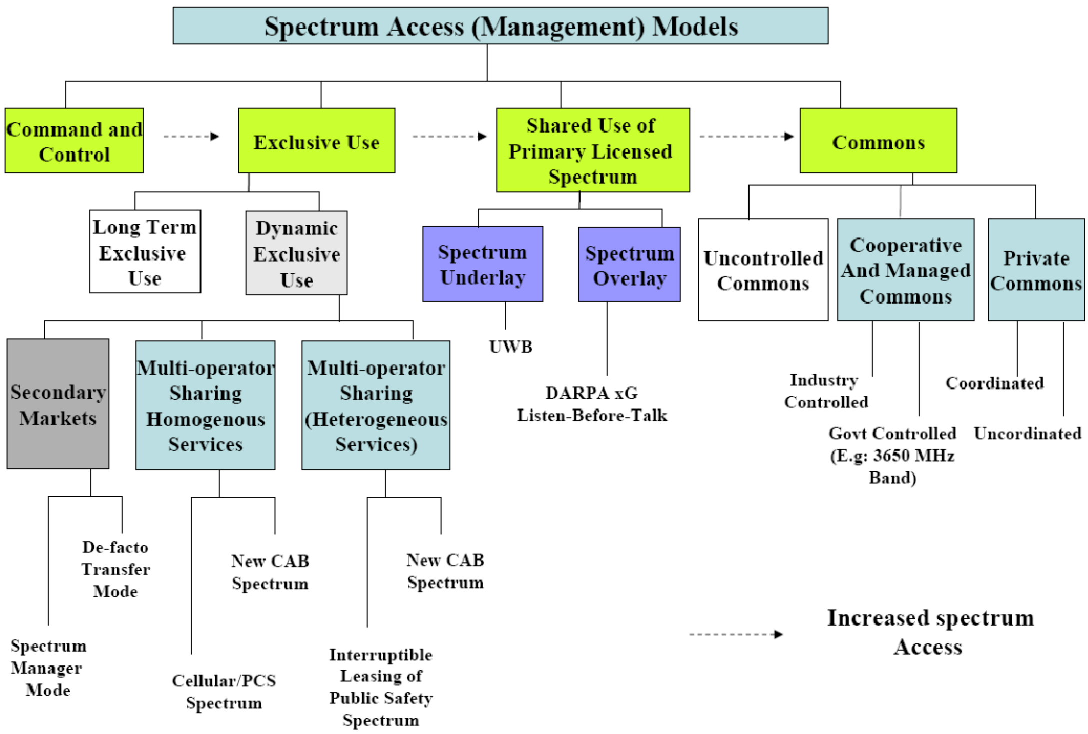


Figure 1: Classification of spectrum access schemes (from Buddhikot [1]).

There are many underlying principles behind these schemes but the innermost is simply the space and time variations of spectrum demand, which are related to space and time variations of traffic. The different schemes can be seen as different ways to dynamically allocate the spectrum in order to take advantage of these spatio-temporal variations. The spatio-temporal variations of spectrum demand allow a spatial reuse of spectrum (under interference constraints) resulting in a lesser amount of spectrum required to satisfy the user traffic; or alternatively, a higher achievable user traffic over the same amount of spectrum to satisfy an expected growing demand for data services.

We give hereafter some details on these schemes.

**Dynamic exclusive use**: It is the first step in introducing some flexibility in spectrum access while keeping safety because only one user is granted the access of spectrum at any time. This can be seen as a kind of short term license where some frequency bands are not allocated permanently to one user.

The DIMSUMnet project was an example of such a scenario [2]: a third party (called a spectrum broker) has a license for a given frequency band which is allocated (leased) dynamically to operators (they are the broker's client) via an auction mechanism. The broker's band is called a Coordinated Access Band (CAB) and is located near extant cellular spectrum. Parts of the CAB are leased to operators and a predefined part of the CAB is dedicated to a spectrum information channel whose function is to broadcast what is the current allocation of the CAB to the operators as depicted by Figure 2.

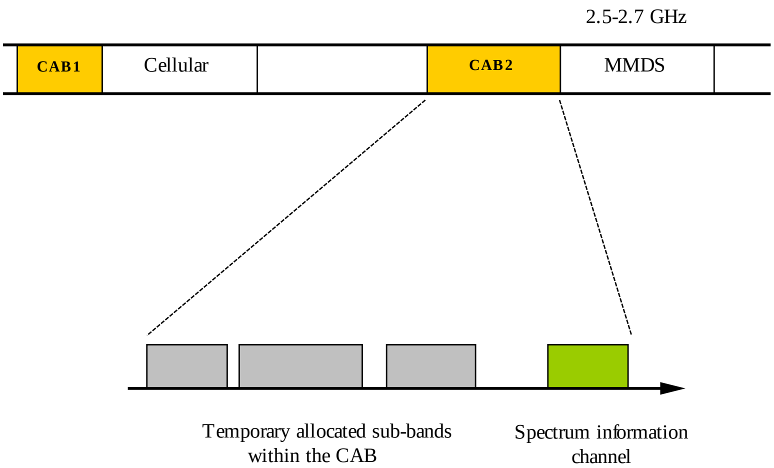


Figure 2: Sub-allocation of spectrum in a CAB.

In this example the broker has its own infrastructure (its own base stations) which has to be reconfigurable as client networks may be heterogeneous; this calls for SDR as an enabler of this reconfigurability. Moreover, the broker has to check that the spectrum allocation to the clients does not create harmful interferences, as well as co-channel interferences which stem from the reuse of frequencies, or adjacent channel interferences (coexistence between different radio technologies). Many papers by authors involved in this project give some insight in the algorithms that can be used to this end. DIMSUMnet or related solutions (secondary market of spectrum, for instance) are centralized approaches where spectrum use is coordinated (by the broker, by the primary user in secondary market), so we can expect that interferences are well managed; this is not the case for the opportunistic approach.

**Shared use of a primary licensed spectrum:** This scheme is widely addressed in the technical literature because it is closely related to Cognitive Radio studies (CR), especially when considering opportunistic use of spectrum. It is in fact a first attempt to relax the constraint on the exclusive use of a frequency band; there is still a licensee (the primary user) but, now, some users without a license (called secondary users) can share the same band under the condition that they do not interfere with the primary user. Furthermore there is no coordination between primary and secondary users. Two possible forms of sharing can be envisioned:

- *Spectrum underlay*. Secondary users can transmit at very low power so that they do not create interference to primary receivers. The classical example is UWB transmission with the FCC defined power mask. As interference is experienced at the receiver and as it is very difficult to detect receivers it is very difficult to ensure that no harmful interference will be created to a primary receiver; we can think of a laptop with a PC card for a wireless link to a cellular system, and a UWB interface to some peripheral (printer for instance). The signal of the cellular system incurs very high propagation losses, so that the downlink could be interfered by the UWB transmitter. This is the reason why, taking advantage of the multi-carrier implementation of UWB, a mechanism is defined to switch-off the sub-carriers in the same frequency band as the cellular system (Detect And Avoid). Moreover, we can expect a growing number of such low power devices, which raises the problem of the aggregation of their interferences.

- *Spectrum overlay*. This scheme is more commonly named opportunistic use of the spectrum or Dynamic Spectrum Access, this name being rather confusing with Dynamic Spectrum Allocation which involves licensed spectrum. Secondary users must implement sensing methods to detect idle periods (if any) of the primary user and transmit until they detect the primary user is transmitting again and stop their transmission.

**Commons:** Buddhikot distinguishes three types of commons:

- *Unmanaged commons*. Unmanaged does not mean unregulated as there exist some rules governing the use of these bands, like transmit power limitation, or MAC schemes for WLAN (Listen-before-Talk schemes, RTS/CTS mechanism to circumvent the hidden node problem…), which are an attempt to control the way users access to spectrum within a system. The well known example is the ISM band at 2.4 GHz, for WLAN devices. This band suffers from interferences due to the great number of devices operating in the same band, some of them do not obey any MAC schemes, (microwave ovens) or a different one (like Bluetooth devices) and there is no guaranty of quality of service.

- *Managed commons*. Although spectrum is not a depletable resource (there is the same amount of available spectrum after use, contrarily to physical resources like woods, fish stocks, gas, oil…) the crowding of ISM bands have led people to imagine a less anarchic form of unlicensed spectrum. Managed commons are non-exclusive frequency bands (either licensed or unlicensed) where all operating devices must comply a set of rules (PHY/MAC rules, or spectrum etiquette); an example is the US 3650-3700 MHz band designated by FCC for rural wireless internet service providers (WISPs). FCC has designed a non-exclusive license for nationwide operations in this 50 MHz band: All licensees must register in a public database, they are not granted any protection against interferences but all equipments must comply a contention based protocol to allow fair access to the spectrum to all registered users. This is a (government) controlled common, there is nevertheless a problem because no entity is really in charge of managing the common and enforcing the rules, the licensees have only the mutual obligation to cooperate and avoid harmful interference to one another. This is the reason to the introduction of a last kind of common.

- *Private commons*. The name sounds like an oxymoron (it is formed with two exclusive terms) but this is a logical consequence of the drawbacks of the managed commons solution. The private commons is a piece of spectrum which has an owner (a licensee). It may be a primary user which charges some predefined secondary users when they transmit opportunistically in its spectrum. In the scheme there is coordination between primary and secondary users as the primary network (the primary network tells the secondary users when they can transmit and when they must release the spectrum). An example of such a scheme could have been the FCC block D at 700 MHz [3], [4]. In another example, a wireless cellular operator shares its licensed spectrum between a macro cellular network and femto-cells located at user premises.

Several schemes will coexist. We can expect that these various types of spectrum access will coexist at the same time or location because they correspond to different requirements on QoS, management of interferences, and costs of deployment (infrastructure), as sketched by Figure 3; this is a two-dimensional representation where spectrum access schemes are located with respect to two parameters:

- Cost of deployment: low when the user equipment form the infrastructure or completes the operator's infrastructure (like femto-cells), high when an operator has to roll-out several antennas and base stations to ensure the coverage, either in a licensed spectrum (cellular operators) or as secondary user in an opportunistic way (this is the case of wireless rural access networks like IEEE 802.22).

- The second dimension pertains to the degree of cooperation between users (or access control of the users) to ensure quality of communication; from low (minimal cooperation, as in the ISM band, with a best effort QoS) to high, when a central entity (operator) controls user access to the resources. Femto-cells fall into this category because they operate in the same macro-cell spectrum and the operator has to coordinate femto-cells and macro-cells to control their mutual interferences.

Note that, amongst these various possible spectrum access schemes, Dynamic Spectrum Allocation (DS-Allocation) pertains only to those involving licensed spectrum (see Figure 3). In particular, DS- Allocation does not seem relevant to the opportunistic schemes, mainly because in opportunistic access there is not coordination between the primary and secondary users. That precludes any guaranty of QoS and besides, we have to perform a new dynamic spectrum allocation each time the primary transmitter restarts its transmission. This is very impractical because the optimization process must be performed very quickly, otherwise the spectrum occupancy may vary during the optimization process is under way. The way to envision DS-Allocation corresponds to a centralized approach where an operator which holds license(s) for a (or several) frequency band(s) try to maximize the overall traffic by a clever use of spatial and temporal variations of the demand. DS-Allocation allows operators to use at best the spectrum they have paid for and to make profit from this investment (license cost).

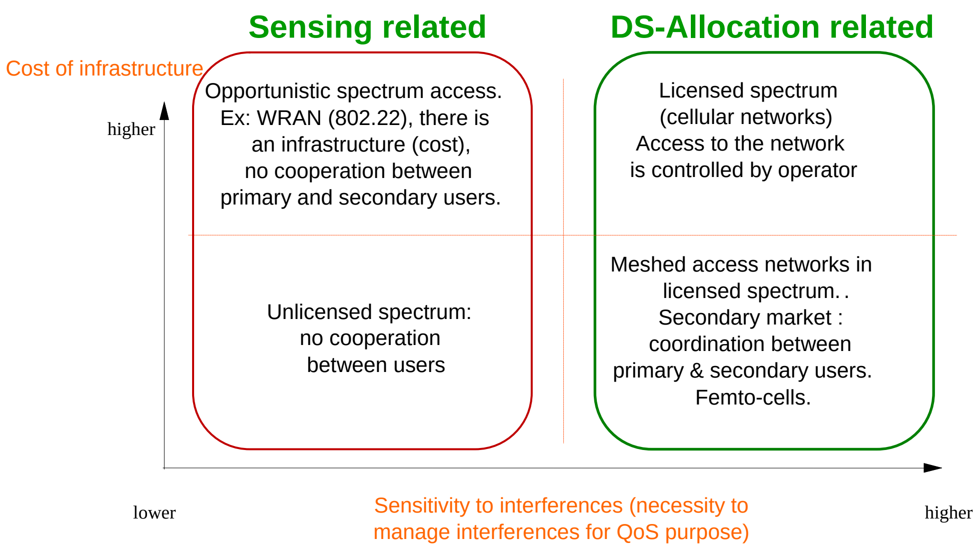


Figure 3: Another classification of spectrum access schemes.

Finally, Weiss et al. have recently discussed classification of dynamic spectrum access systems and scenarios based on level of cooperation between systems, on the rights different systems have with respect to spectrum access, and spatiotemporal characteristics of the scenarios [5], [6]. The first two aspects can be summarized as shown in Figure 4. In the classification depicted in the figure, systems are said to be cooperative if the license holder explicitly participates into the transmission decisions of the secondary systems, and non-cooperative otherwise. Further, primary sharing is said to occur if the systems in question have equal rights to access the spectrum. Otherwise secondary sharing occurs.

| | Non-cooperative | Cooperative |
|---|---|---|
| Primary | Unlicensed, Wi-Fi | Secondary markets |
| Secondary | Easements, Opportunistic use, TV white spaces, UWB | MVNO, negotiated secondary use |

Figure 4: Classification of spectrum sharing schemes based on level of cooperation and type of sharing taking place [5].

| | | Spatial characteristic | | |
|---|---|---|---|---|
| | | Static | Periodic | Stochastic |
| Temporal characteristic | Static | TV white spaces | Sensor network | CDMA mobile |
| | Periodic | Daytime broadcast | Rotating ant. radar | |
| | Fast periodic | LTE cell site | | LTE mobile |
| | Stochastic | Wi-Fi | | Public safety |

Figure 5: Classification of spectrum access schemes based their spatiotemporal characteristics [6].

In the recent work [6] Weiss et al. have refined this classification to further include the spatial and temporal characteristics of the systems in question into account. The authors call the arising taxonomy to be that of *operational contexts* for DSA systems. These are summarized in Figure 5. For example, TV white spaces are a prime example of a system that is static in terms of both spatial and temporal characteristics, whereas LTE systems would have rapidly changing temporal and also possibly spatial contexts (in the case of mobile devices).

As the present document is focusing on the scenario definitions for the project, we shall refrain from giving more extensive literature review than already included above, and refer the reader to the recent literature on the subject, and references therein [5]-[10].

## 1.2 Template for Scenario Descriptions

This section proposes a common template to describe the scenarios presented in this deliverable. This template is derived and extended from a model that was originally used in the E3 Project [11] where it was proved to be useful with the intention:

- To clarify the situation among partners to reach a common understanding of the situation;
- To get comparable inputs from the different partners; and
- To provide a guideline for the further analysis of the scenarios.

Table 1: Generic template to be used as a quick reference to the proposed scenarios.

| | |
|---|---|
| Scenario title | For practical reasons, short name and acronym of the scenario. |
| Purpose of the scenario and related use of Radio Environmental Maps (REMs) | This is the objective of the scenario, what is intended to be demonstrated and investigated. This should be a rather concise statement of what the scenario should achieve (what is the challenge).<br><br>The role of REMs in achieving the objective(s) of the scenario is also specified. |
| Implications in terms of sensing | This field provides information on what implications the scenario has in terms of sensing. |
| Actors and roles | This information lists all the actors which are involved in the scenario including the role and the characteristics for each actor. |
| Assumptions and pre-conditions | This information should give a clear description of the environment providing a clear context for the scenario.<br><br>Assumptions and pre-conditions should also be mentioned.<br><br>A list of all required system and environment conditions that must be true before the scenario can be triggered. |
| Triggering event | The name of the single event that triggers the scenario |
| Description of actions | This is the behavior of the system after the triggering of the scenario taking into account the specified assumptions and pre-conditions.<br><br>This information consists of a list of (successive and/or parallel) actions that depict the information flow related to the REM, mentioning the data treatment as well.<br><br>Action 1:<br><br>Action 2:<br><br>…. |
| Ends when | This event is optional.<br><br>Where appropriate, it identifies the event(s) that signal(s) the end of the scenario. |
| Evaluation criteria | This information gives an ordered list of all criteria to be used for the evaluation and the assessment of the system behavior in this scenario. |

In the following chapters we shall describe in detail the key scenarios selected in the project both in terms of free-formed descriptions as well as using the scenario template discussed above. The selected scenarios are an outcome of a significant amount of collaborative work and brainstorming between the different partners, and represent not only the interests of the individual members of the consortium, but have been further distilled to yield the most promising and relevant set of application scenarios for radio environment maps. We thus strongly believe that the selection of scenarios presented here is of interest to the wider research community as well. To improve readability, the scenarios have been further categorized into broader areas, corresponding to the division into different chapters in the following. In Chapter 2 scenarios related to spectrum management within the network of a single operator are given. Then, scenarios involving hierarchical access on licensed bands both in coordinated or non-coordinated fashion are discussed in Chapter 3. Scenarios involving the unlicensed bands are then given in Chapter 4, and scenarios focusing on spectrum monitoring are given in Chapter 5. Finally, the conclusions are drawn in Chapter 6.

# 2 Intra-Operator Spectrum Management

This category represents the command-and-control case of Figure 1 that involves networks and frequency bands belonging to a single operator. This gives the opportunity to the operator to perform Dynamic Spectrum *Allocation* (DS-Allocation) on its licensed spectrum. The operator optimizes the utilization and management of its spectrum resources in an autonomous and flexible manner based on measurements. Thanks to this optimization, users having different access technologies connected to a mobile network operator perform spectrum sharing on the licensed bands of that operator. Below are listed several scenarios that involve different cases of this intra-operator spectrum optimization.

## 2.1 In-band Coverage/Capacity Improvement by Relays

Within a cellular network, areas that suffer from high shadowing receive the serving signal with strength much lower than what the initial planning forecasted. This is commonly referred to as a *dead zone* or a *coverage hole*. Possible causes are a hilly terrain or buildings of great dimensions. In these areas, the service quality is usually severely impacted. However, depending on the size of a coverage hole and traffic needs, the deployment of a new base station may not be a cost-effective solution.

On the other hand, some areas might have a significantly high traffic demand for short periods, which necessitates a provision of capacity increase in order not to cause a notable degradation in the planned service quality. A cost-effective solution to alleviate such problems is the use of relays, whose deployment is foreseen as one of the new features to be included in LTE-Advanced. Relays are small base stations that use the radio access spectrum for backhauling and they forward mobile messages to/from the Base Stations (BSs). Capacity/coverage improvement is obtained by properly configuring the relays (adjusting the transmitting power, antenna parameters, etc.). In this context, REMs can be used to reach the following objectives:

- Detect and locate the above mentioned situations that require coverage and capacity improvements.
- Trigger a cognitive engine to handle the issue.
- Help to configure and optimize the solution in a way that does not require a re-planning.

Figure 6 provides an example of a relay-based solution to coverage improvement. The figure depicts a situation where the green area requires better coverage due to propagation issues or more capacity due to traffic issues. The left-hand sub-figure highlights the weakness of a hand-made solution: the transmission power of the relay is not optimally adjusted to cover the intended zone. The blue area that is due to the overshoot in relay coverage causes high interference, degrading the QoS for the users in the vicinity. Besides, the relay coverage does not completely cover the intended zone, leaving the initial problem partially unsolved. On the right-hand side, we can see the solution tailored with REM. The transmission power of the relay is optimally configured; its coverage matching the green area.

Table 2 lists the characteristics of this scenario.

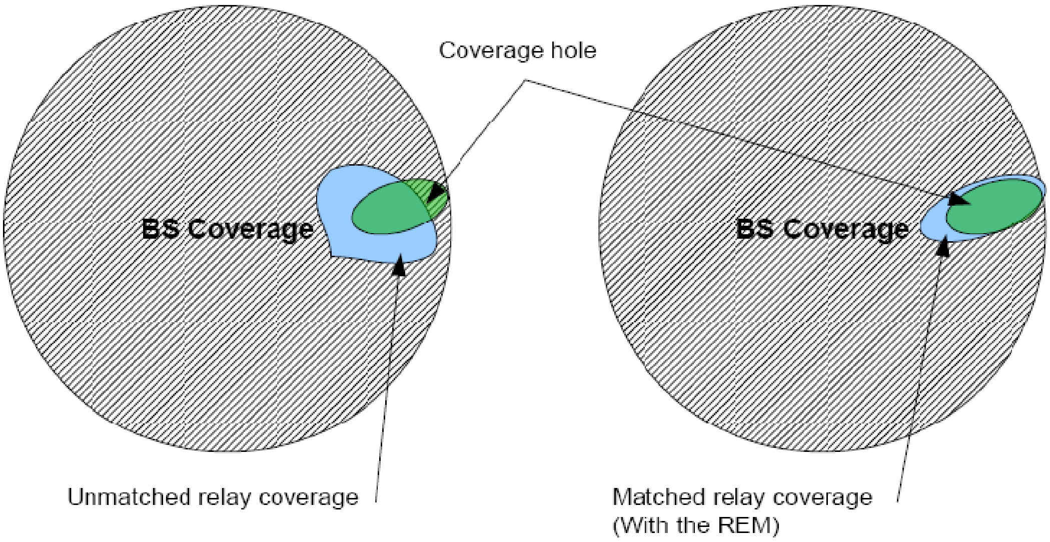


Figure 6: Relay scenario.

Table 2: Characteristics of scenario "In-band coverage/capacity improvement by relays".

| | |
|---|---|
| Scenario title | In-band coverage/capacity improvement by relays (CREL) |
| Purpose of the scenario and related use of Radio Environmental Maps (REMs) | REM helps detecting and locating coverage and capacity problems by supplying geo-localized information on the coverage/capacity indicators. As a remedy, it provides a means to dynamically adjust the transmit power of the emitters (i.e. auto-configuration of relays). |
| Implications in terms of sensing | Mobiles have the capability to do geo-localized measurements |
| Actors and roles | The existing BSs provide the coverage and capacity foreseen by the network planning.<br><br>Relays are intended to improve them (low-cost solution to coverage/capacity adjustments).<br><br>The REM stores geo-localized coverage/capacity information.<br><br>Mobiles report measurements for the REM. |

| | |
|---|---|
| Assumptions and pre-conditions | BSs and relays have a connection with the REM.<br><br>Relays are agile enough in configuration modifications (power adjustment, beamforming capability, etc.).<br><br>Mobiles can report their location information with sufficient precision. |
| Triggering event | Special events (sport, concerts, etc.) or network optimization based on KPIs triggered by the REM. |
| Description of actions | Action 1: The network operator deploys a relay<br><br>Action 2: The relay connects to the REM and extracts the necessary information to estimate its optimal configuration parameters<br><br>Action 3: REM asks for new measurements<br><br>Action 4: The relay adjusts its configuration parameters |
| Ends when | N/A |
| Evaluation criteria | Capacity/coverage indicators reported by mobiles in the relay zone. |

## 2.2 Wireless Network Performance Optimization

### 2.2.1 Self-Configuration and Self-Optimization of Femto-Cells

The aim of this scenario is to use REM information to ease self-configuration and self-optimization of femto-cells. Femto-cells are very small base stations that are located in customers' premises and that are operated by the customers. Backhauling is provided by the landline internet access of the customer (ADSL, fiber, etc.) and radio access is achieved by the radio access technology that defines the femto-cell (UMTS or LTE). Since they are operated by the customers, they must be plug-and-play type devices. Besides, since the operator has no role in their installation and their operation, the initial network planning process does not exist in femto-cells. The operator does not exactly know how many femto-cells will be deployed and therefore cannot carry out an initial dimensioning and planning of the femto-cell network. Being plug-and-play type devices, femto-cells must be completely autonomous in operations like transmission parameter settings (RF and antenna parameters, power levels, etc.), neighbor list definition, admission/congestion control parameter adjustment, mobility management (femto-femto as well as femto-macro) etc. Furthermore, femto-cells are deployed in the same frequency band as the macro cells of the same radio access technology (UMTS or LTE); and therefore interference mitigation with the neighboring macrocells is a challenging issue. Finally, systems involving femtocells are expected to be highly dynamic; as consumer equipment the rate of deployment is uncertain, the devices might be powered down for substantial period of time, and devices might be moved geographically significant distances without advance warning. Taking all these into account, issues like self-configuration, self-optimization and self-healing are of primary importance for femto-cells. Therefore, a lot of effort is being spent to obtain some improvement in autonomously setting and tracking the optimum femto-cell parameters in order to guarantee the required QoS on their coverage area without deteriorating the performances of neighbouring femto- and macro-cells. In this context, REMs can have a significant role in enhancing the self-x functionalities of the femto-cells.

Table 3 lists the characteristics of this scenario.

Table 3: Characteristics of scenario "femto-cell optimization".

| | |
|---|---|
| Scenario title | Femto-cell optimization (FCO) |
| Purpose of the scenario and related use of Radio Environmental Maps (REMs) | Efficient self-configuration, self-optimization and self-healing of femto-cells (transmission parameters, admission/mobility/congestion/interference control, etc.) |
| Implications in terms of sensing | Mobiles have the capability to do geo-localized measurements |
| Actors and roles | Performance indicators are reported by mobiles with corresponding location information to build the REM<br><br>The femto-cells use the information stored in the REM for optimum parameter setting |
| Assumptions and pre-conditions | Mobiles can report their location information with sufficient precision<br><br>The femto-cells can communicate with the REM |
| Triggering event | For self-configuration: when the femto-cell is switched on<br><br>For self-optimization: when a deterioration of the QoS is detected due to inappropriate parameter setting |
| Description of actions | Action 0: The REM gathers measurements reported by mobiles with location information.<br><br>Action 1: the femto-cell requests geo-localized information on related performance indicators over its target coverage area from the REM<br><br>Action 3: The REM sends this information if available<br><br>Action 4: The femto-cell adjusts its related parameters to optimize QoS performance or to recover from a failure. |

| | |
|---|---|
| Ends when | N/A |
| Evaluation criteria | QoS experienced in the femto-cell and in the neighboring femto- and macro-cells. |

### 2.2.2 System Optimization

System optimization aims to enhance the performance of Radio Access Network(s) based on Key Performance Indicators (KPIs) in terms of:

- Throughput
- Coverage
- Capacity and outage probability

In system optimization, there are several goals to be attained, and/or several constraints to be respected, which are related to the above metrics. The operator can assign priorities to each of them and the aim is to attain these goals, respecting the constraints by adjusting the system parameters. These parameters can belong to any aspect/functionality of the access network, but here, we focus particularly on the Radio Resource Management (RRM) parameters. Optimization processes usually require some kind of knowledge about the radio conditions, the radio access network environment and topology. This knowledge is provided by the mobile measurements, for example the SINR experienced by the mobiles, the interference caused by a transmission, the traffic demand, etc.

As an example, we can think of an algorithm aimed at automatically configuring the power masks of BSs which use OFDM-based PHY layer and whose target is maximizing the aggregated throughput of one or more BSs. The optimum power mask configuration clearly depends on the spatio-temporal characteristics of environmental factors like traffic density and SINR distributions.

In such a context, REM can be of tremendous use by gathering and storing the required data, which is then available for use by the optimization processes. Obviously, issues like gathering relevant data, storing it, building the REM and retrieving the necessary information when necessary must be handled timely and efficiently without excessive signaling overhead.

Table 4 lists the characteristics of this scenario.

Table 4: Characteristics of scenario "System Optimization".

| | |
|---|---|
| Scenario Title | System Optimization (SO) |
| Purpose of the Scenario – Related use of Radio Environmental Maps (REM) | REM provides accurate inputs to the optimization algorithms. It reduces the need for both modeling and hand-made measurements. |
| Implications in terms of sensing | Mobiles have the capability to do geo-localized measurements |
| Actor and Roles | RRM entities runs algorithms for improving the network performance<br><br>The REM gathers and store data, and triggers new measurements when needed.<br><br>A sensor network (possibly the MSs themselves) does the measurements |
| Assumptions and Preconditions | Algorithms need slowly varying measurements |
| Trigger Event | KPI exceed a threshold |
| Description of Actions | Action 1: The RRM notices a KPI change<br><br>Action 2: Optimization algorithm is run<br><br>Action 3: The algorithm queries the REM<br><br>Action 4: The RRM modifies parameters according to the algorithm output |
| Ends when | N/A |
| Evaluation Criteria | Utility value related to the optimization target. |

### 2.2.3 Introduction of New Technologies through Refarming

An operator willing to update its network with a new technology rarely fully deploys the network at once because of the CAPEX required. Also, brand new technologies might be a viable solution at some places and not at others. Usually the coexistence of two technologies at the boundaries of different technologies is handled by leaving enough spectrum (guard bands) or by using a less aggressive frequency reuse scheme (guard distances). This inevitably wastes more resources than necessary, due to the required frequency or spatial margins. REM might be used to automatically find and set the optimum parameters (frequency reuse factor, guard band interval, etc.), in these specific areas (cf. Figure 7).

Table 5 lists the characteristics of this scenario.

Table 5: Characteristics of the scenario "Introduction of new technologies through refarming".

| | |
|---|---|
| Scenario Title | Introduction of new technologies through refarming (NTR) |
| Purpose of the Scenario – Related use of Radio Environmental Maps (REM) | Utilization of REM information to optimize radio resources when a single operator deploys a new technology.<br><br>-> How to optimize joint radio resources management (JRRM) at the border of two adjacent areas that respectively correspond to:<br><br>An area covered by the current radio system only (e.g. GSM 900 MHz) and<br><br>The "coverage island" for the new technology (e.g. UMTS 900 MHz).<br><br>-> Perform optimized VHO (or JRRM) by timely and appropriate provision of relevant REM information when a mobile user is moving around/within the border area.<br><br>-> Avoid the waste of spectrum which usually results from the assumption of "worst case" coexistence constraints at the border, without adding unviable complexity to the system. |
| Implications in terms of sensing | Mobiles have the capability to do geo-localized measurements |
| Actor and Roles | Cellular Operator: operates RAN1 and also deploys RAN2 in geographical areas:<br><br>RAN1 cellular technology T1 (e.g. GSM 900 MHz) or cluster of neighboring T1 base stations (BS)<br><br>New RAN 2 cellular technology T2 (e.g. UMTS 900 MHz) or cluster of neighboring base stations T2.<br><br>REM database updated by the operator focusing on the geographical border areas of T1 and T2 coverage. |
| Assumptions and Preconditions | Mobile terminals are multimode (T1 &T2).<br><br>They are capable of vertical Hand Over (VHO) between RAN1 and RAN2. |
| Trigger Event | Mobile user approaches the borderline between T1 and T2 coverage and a VHO from T1 to T2 is envisaged. |

| | |
|---|---|
| Description of Actions | Action 1: The network detects that the mobile is approaching the border zone (this can also be accomplished via geo-localized measurements).<br><br>Action 2: The corresponding REM information is identified/selected by the network<br><br>Action 3: REM information is analyzed and optimum parameters for the VHO are determined.<br><br>Action 4: VHO is performed accordingly.<br><br>Action 5: REM is updated accordingly |
| Ends when | VHO has been performed successfully. |
| Evaluation Criteria | - Quality of the VHO,<br><br>- Quality of the new radio link (no creation of interference, even if the worst case conditions have been "fine tuned", in terms of guard bands)<br><br>- Amount of spared spectrum |

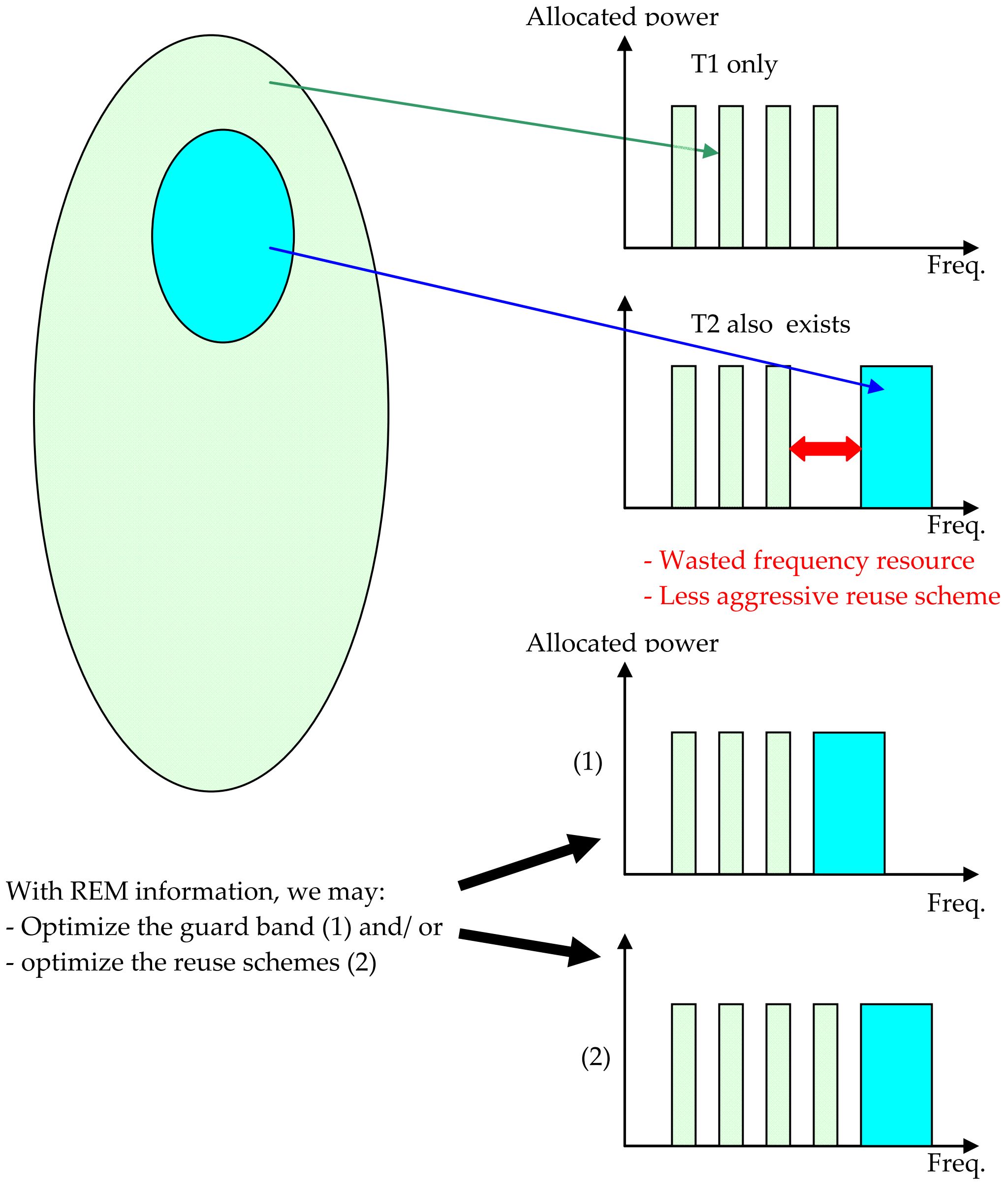


Figure 7: Co-existence of two technologies (refarming scenario).

## 2.3 Handover Optimization

### 2.3.1 Vertical Handovers

This scenario aims to enhance the performance of vertical handover (HO) in multi-frequency and multi-technology RANs. The entity responsible for HO, (Radio Network Controller –RNC-, Mobility Management Entity -MME, etc.), denoted here as the "HO Manager", will use coverage information given by the REM to order a "blind" handover to the mobile. The mobile does not need to perform inter-frequency/inter-technology measurements to check the coverage on target system as this information is available via the REM. This will decrease the battery consumption and in systems with continuous transmission (UMTS/FDD), this will avoid the degradation of the transmission quality due to compressed mode.

Table 6 lists the characteristics of this scenario.

Table 6: Characteristics of scenario "Vertical handover"

| | |
|---|---|
| Scenario Title | Vertical handover (VO) |
| Purpose of the Scenario – Related use of Radio Environmental Maps (REM) | To speed and enhance the performance of Inter-Frequency/ Inter-RAT (vertical) Handovers: minimization of inter-Freq/inter-RAT measurements |
| Actor and Roles | - Coverage information on each freq/Techno are reported by mobiles with corresponding location information to build the REM<br><br>- Decision on target Freq/RAT and cell for HO based on REM info. |
| Assumptions and Preconditions | - Mobiles report their location information |
| Trigger Event | Any trigger of inter-freq/ Inter-RAT HO (coverage, load, service, …) |
| Description of Actions | Action 0: The REM gathers measurements reported by mobiles with location information.<br><br>Action 1: HO Manager requests MT location<br><br>Action 2: MT reports its location info<br><br>Action 3: HO Manager sends a "coverage info request" to the REM with the potential target systems/freq list and the MT location<br><br>Action 4: The REM sends coverage information if available<br><br>Action 5: The HO Manager chooses the target system/freq and sends a HO order to the MT<br><br>Action 6: the MT performs HO towards the target cell |

| | |
|---|---|
| Ends when | N/A |
| Evaluation Criteria | Inter-freq/ Inter-RAT HO failure rate improvement<br><br>Dropping rate |

### 2.3.2 Intra-System Handovers

Currently, in most cellular systems, handovers are said to be "mobile-assisted". It means that mobile terminals provide the serving BS with measurements of the field strength from neighboring BSs. Based on these measurements, the BS decides whether to perform the HO or not. This has the following main drawbacks:

- It requires the mobile to maintain a list of valid neighboring BSs.
- It causes the mobile to periodically monitor neighboring signals which consumes resources.
- Because of its local point of view, the mobile is not able to cope with tunnel effects which results in a ping pong HO.
- It requires parallel RF chains (and therefore it is costly) to do sensing during transmission. Hence the current generation mobiles are not capable of doing sensing and transmission simultaneously.
- During communication, the mobile is not able to reconfigure its RF chain for sensing different frequency bands, while next generation systems are likely to be frequency-agile over several bands.

Figure 8 depicts a case where the first mobile (MS1) has no interest in performing a HO from the outdoor BS to the indoor BS, whereas the second one (MS2) does. A REM would avoid MS1 to perform an unnecessary HO and allow MS2 to be connected to the indoor BS. Table 7 lists the characteristics of this scenario.

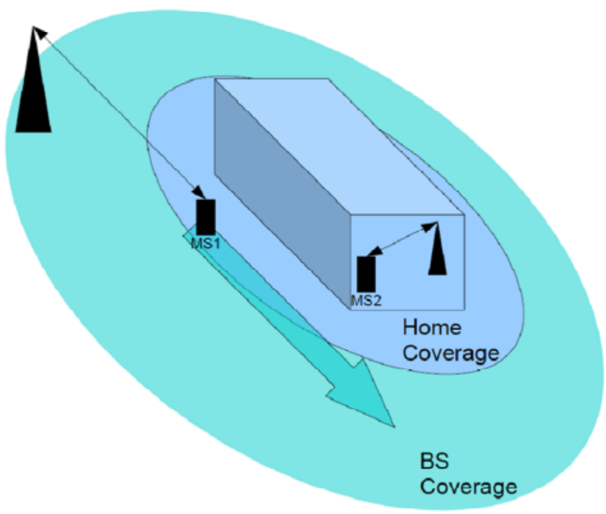


Figure 8: Intra-system handover.

Table 7: Characteristics of scenario "Intra-System Handover".

| | |
|---|---|
| Scenario Title | Intra-System Handover (ISHO) |
| Purpose of the Scenario – Related use of Radio Environmental Maps (REM) | The knowledge of the radio environment is used so as to take optimal HO decisions. |
| Implications in terms of sensing | Mobiles have the capability to do geo-localized measurements |
| Actor and Roles | -The BS evaluates HO possibilities for its MSs, based on information located in the REM.<br><br>-The mobile updates its location when needed and provides a feedback on the link quality |
| Assumptions and Preconditions | Mobiles are capable of finding their locations |
| Trigger Event | -The SINR experienced by the mobile is below a threshold<br><br>-The BS wants to perform load balancing by triggering HOs. |
| Description of Actions | Action 1: The mobile sends its measurements reports<br><br>Action 1b: If needed the MS updates its location<br><br>Action 2: The BS decides to check whether another BS would be more suitable for the MS<br><br>Action 3: The BS triggers the HO procedure if needed |
| Ends when | The HO succeeds |
| Evaluation Criteria | Handover quality (Failure probability and QoS experienced)<br><br>Cell capacity increase (When used for load balancing) |

# 3 Hierarchical Spectrum Access on Licensed Bands

This category corresponds to the case where secondary users (SUs) perform opportunistic access on a licensed band. The sub-categories can be listed as follows:

## 3.1 Coordinated Spectrum Access between PUs and SUs

The primary and secondary networks have coordination on when and how the SUs access the spectrum. There are two cases depending on the number of secondary networks: single secondary network and multiple secondary networks. In the first case, there is only one secondary network (with or without infrastructure) that coordinates with the primary network. In the second case, there is more than one secondary network that coordinates with the primary network. The secondary networks may or may not have coordination between them. In case of coordination, the secondary networks may perform cooperative sensing. The coordination between the PU and the SU might be explicit in terms of frequency bands or time slots, or also involve statistical information such as activity patterns of the primary user traffic, or locations of PU base stations. We shall place emphasis here on the first type of coordination, but note that radio environment maps can be used to support both types.

In the following sub-sections, we give two examples of coordinated spectrum access between PUs and SUs, one for a single secondary network, and one for multiple secondary networks.

### 3.1.1 Single Secondary Network: FCC Block D at 700 MHz

We shall first use the FCC Block D auctions and related scenarios as a good and concrete example of the general coordinated spectrum access concept, with relevance to possible developments in other market areas including Europe as well. Also, one should note that the consortium has to consider also U.S. markets as many of its players and potential adopters of REM technologies are global enterprises and organizations, and thus their actions and technology development roadmaps have relevance in Europe as well.

FCC Block D is a public/private partnership involving a commercial primary user which would hold a nationwide license for a 10 MHz frequency band to be shared with a public safety network (2 x 5 MHz bands at respectively 758-763 MHz and 788-793 MHz, known as D Block in FCC auctions of 2008).

In fact the problem is more intricate than it would seem at a first glance. Due to the nature of the public safety network, we can immediately understand several important constraints that would hamper the commercial network business:

1. The main point is that the public safety network would not deploy an infrastructure (for obvious reasons of cost), but would use the infrastructure of the commercial user(s). This is a very heavy constraint because the commercial user would have to face the cumulative cost of the license and the cost of a nationwide infrastructure.

2. We can expect that the safety network will not operate continuously over the whole area covered by the license. It is extremely unlikely to have the whole country in an emergency state at the same time. So we can expect a sparse traffic with respect to time and space. This is a hint for a possible shared use.
3. At the same time the safety network has the highest priority: it is unimaginable to wait for the end of transmission of a commercial user to start emergency transmissions. This indicates that the safety network has the privileges of a primary user while it is not the licensee who has paid for the spectrum. This is the main reason of the failure of the 2008 auctions.
4. Lastly, the very different possible environments (tunnels, towers, streets ...) or the possibility that the infrastructure is out of service (due to an earthquake or a hurricane, for instance) show that the primary transmissions will have to face the difficulty to transmit very important messages in a number of very tough transmission channels.

FCC did not succeed to sell this block D in 2008 (bids did not reach the minimum amount), but it is likely that a new auction will start in 2011 (Auction 76) with a possible modification: there would be several regional licenses (primary commercial users) instead of a single nationwide licensee. In order to ensure interoperability between all safety stakes (firemen, police, ...) all these regional networks should use the same radio technology, LTE, see [3][4] for more information. This scheme does not involve sensing since there is a complete cooperation between primary and secondary users.

### 3.1.2 Multiple Secondary Networks: Spectrum Leaser

This scenario corresponds to the case when a company acts as a spectrum leaser. It might either have a band dedicated to leasing purposes or share it with its legacy primary system. This might be particularly suitable in combination with a primary system using OFDM (see Figure 9).

In order to get a better return on investment, an operator might be willing to lease its spectrum to secondary users, for instance a special event organizer who wants to deploy a PMSE network. The two parties involved sign an agreement specifying the band to be used, power, space and time restrictions as well as interference level guarantees.

In this scenario, the REM (especially a “coverage” REM with transmit/receive power information) provides valuable information to check easily whether the agreements are respected mutually (in terms of coverage area and max transmission power). It also helps to identify the zones of interest for both parties and facilitate temporary reconfiguration of the legacy network.

Table 8 lists the characteristics of this scenario.

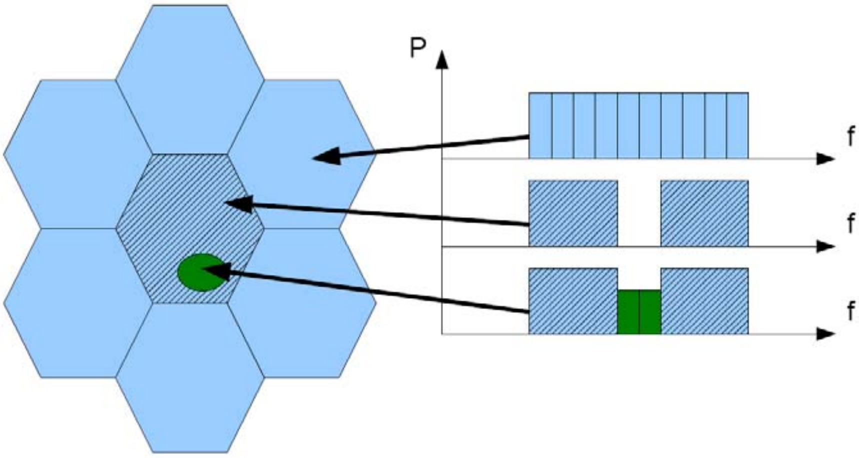


Figure 9: Spectrum leaser scenario.

Table 8: Characteristics of scenario "Spectrum leaser".

| | |
|---|---|
| Scenario Title | Spectrum leaser (SL) |
| Purpose of the Scenario – Related use of Radio Environmental Maps (REM) | REMs are deployed in order to identify areas of interest, guarantee quality of bandwidth and monitor spectrum use. |
| Implications in terms of sensing | Mobiles have the capability to do geo-localized measurements |
| Actor and Roles | -The PU operator owns the band and leases it. He guarantees the quality is met on this band for at a particular time and location.<br><br>-The SU deploys its own temporary network setting parameters according to the agreement. |
| Assumptions and Preconditions | The band is neutral |
| Trigger Event | A SU operator needs some bandwidth |
| Description of Actions | Action 1: The PU operator checks the availability of its resource with respect to the need of the client.<br><br>Action 2: The SU operator deploys its network<br><br>Action 3: The PU operator might adapt the parameters of its own network so as to meet its own requirements<br><br>Action 4: The PU controls that agreements are respected and bills accordingly. |

| | |
|---|---|
| Ends when | As specified in the contract |
| Evaluation Criteria | Interference level in the leased band |

## 3.2 Non-coordinated Spectrum Access between PUs and SUs

The primary and secondary networks do not have coordination, so SUs access the spectrum in an opportunistic manner, i.e. depending only on their sensing results and without having any coordination with the primary network. The secondary network(s) may or may not have infrastructure. A very well-known example to the former case is the IEEE 802.22 standard.

This category involves the famous opportunistic access scenario, as a sub-category of the well-known Dynamic Spectrum Access (DSA) (cf. Spectrum Overlay scheme of Figure 1). The secondary networks may or may not have coordination between them, the former case paving the way to cooperative sensing.

In the following, several example scenarios, all of which is based on opportunistic access, will be given.

### 3.2.1 Out-of-band (cognitive) Femto-cells

Femto deployment is expected to increase the cellular network capacity, improve indoor coverage, and offer new domestic broadband services/applications. The current trend is to dedicate a proportion of the dedicated macro-cell bandwidth to the femto cells. This leads to a diminution of resources of the macro-cell network, giving rise to a trade-off.

Another solution can make use of the existing white spaces, i.e. the unused portions of the spectrum, where femto-cells can automatically configure their RF front-ends to work in an unoccupied band (see Figure 10). It has to be pointed out that the band must be locally free in space, and different femto-cells might use different bands. These unoccupied bands can be any band, licensed or unlicensed (broadcast, radar, navigation, ISM, etc.)

The main issue to address is the well known hidden node problem: a femto-cell may degrade the PU transmission as a result of erroneous sensing due to fading/shadowing. In this case, REM allows alleviating this issue by providing geo-localized measurements on the whole femto-cell interference zone. It is possible to detect the presence *and the location* of the PU transmitter much more reliably using the geo-localized information if the REM.

Table 9 lists the characteristics of this scenario.

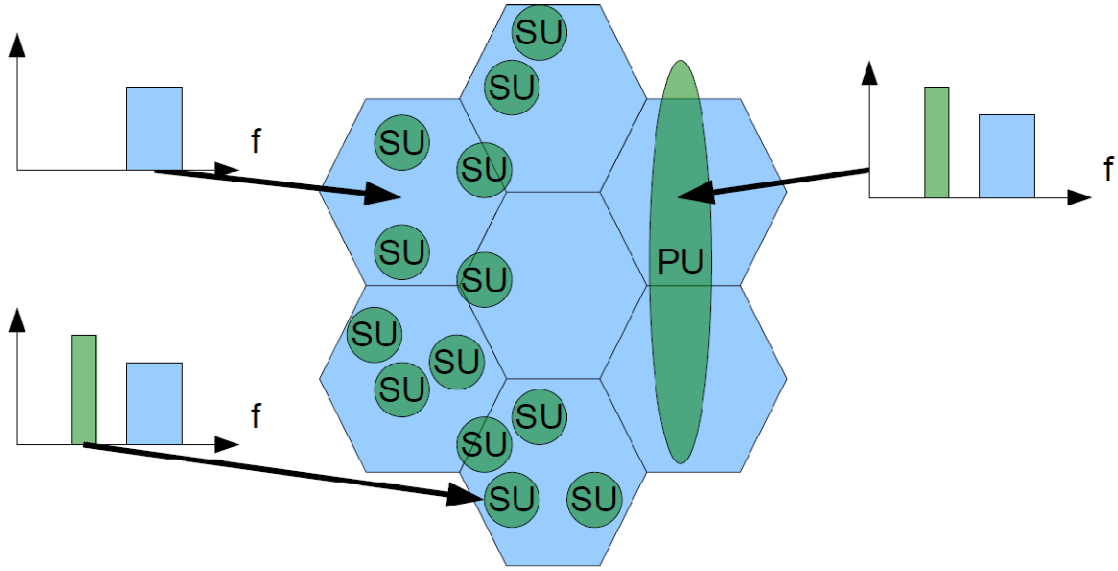


Figure 10: Out-of-band femto scenario.

Table 9: Characteristics of scenario “Out-of-band femto-cells”.

| | |
|---|---|
| Scenario Title | Out-of-band femto-cells (OOBFC) |
| Purpose of the Scenario – Related use of Radio Environmental Maps (REM) | -To configure femto-cells on a locally spare band, and avoid causing any trouble to existing systems.<br><br>-To provide a record of the femto-cells location and bandwidth. |
| Implications in terms of sensing | Mobiles have the capability to do geo-localized measurements |
| Actor and Roles | -PU transmitters and their coverage zones are to be detected<br><br>-A sensor network is required to build the REM<br><br>-SU femto-cells have the flexibility to configure their RF chains on several bands of interest. |
| Assumptions and Preconditions | -Regulators allow the opportunistic spectrum access<br><br>-The system on the primary band has a dynamic slower than the update time of the REM |
| Trigger Event | Lack of resource on the macro network |

| | |
|---|---|
| Description of Actions | Action 0: The REM gathers measurements from its sensor network.<br><br>Action 1: The femto-cell asks the REM for a free band in its neighborhood.<br><br>Action 2: The femto-cell auto-configures its front-end and acknowledges the REM<br><br>Action 3: The REM continuously monitors the PU arrival<br><br>Action 4: REM imposes a fallback frequency to the femto-cell |
| Ends when | N/A |
| Evaluation Criteria | Capacity improvement<br><br>QoS on the FEMTO network<br><br>Interference caused to the primary network |

### 3.2.2 Home Networks (IEEE 802.11af)

IEEE 802.11af is a quite recent (January 2010) IEEE technical group which aims at defining an "An amendment that defines modifications to both the 802.11 physical layers (PHY) and the 802.11 Medium Access Control Layer (MAC), to meet the legal requirements for channel access and coexistence in the TV White Space"; in fact the purpose is to adapt 802.11 to TV white spaces operations, that is in another frequency band than the original ISM (or UNII at 5 GHz) frequency band. Due to this lower frequency one can expect a better indoor coverage (lower path loss at lower frequency, especially when compared with UNII band at 5 GHz). Other expected advantage is to find a substitute to crowded ISM bands suffering from interferences.

Among the topics to be addressed in this technical group there is the proposal of an OFDM PHY layer having the capability to use up to 4 contiguous TV channels and non-contiguous ones. The aim is to have as few modifications of existing 802.11 PHY as possible.

Sensing is also a study item, although the use of TVWS database seems mandatory and is expected to provide much better performance, but it may be of interest to ensure coexistence of either 802.11af or non 802.11af devices in the same TV channels. If we consider that 802.11af access points are connected to internet (via a copper line or a fiber) the use of TVWS database seems natural.

An interesting document, a draft report from Spectrum Engineering working group 43 (SE43) of the European Communication Office [12], provides assessments of the available amount of spectrum in the frequency band 470-790 MHz in Annex B, with measurement from United Kingdom , France and Italy.

For France, three rural regions were considered: Morbihan, Creuse and Vosges and two scenarios according to the antenna height of the White Space Device: 1.5 m (WiFi device), 10 m (rooftop device) and the use of geo-location (database) or sensing based detection of white spaces (see Figure 11). The main result is that there is a real opportunity for devices operating at 1.5 m with a white space database while very little spectrum is available in the outdoor scenario. Indoor scenario is expected to provide better amounts of available spectrum. This is an indication for the 802.11af scenario.

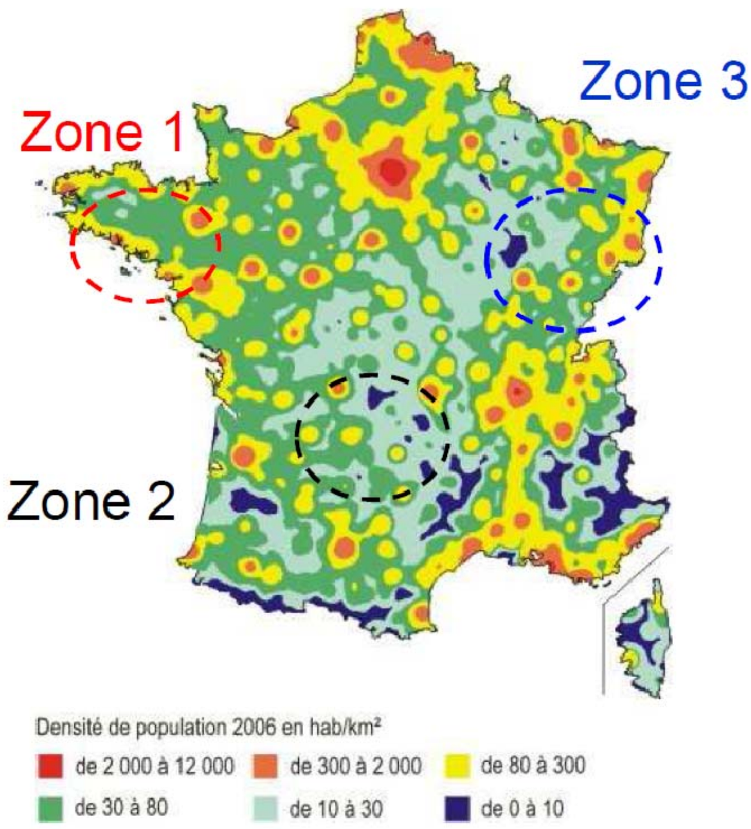


Figure 11: The three areas for ANFR measurements [12], [13].

For FARAMIR project, 802.11af could be a relevant scenario to address Radio Environment Maps use in an indoor scenario. Indeed, knowing if a given TV channel is idle is expected to be insufficient: one has to address other impairments such as adjacent channel interference caused by poor out-of-band transmit or receive filters characteristics (leakage, poor selectivity). One has also to take into account the place of TV receiver antenna (rooftop, on the TV set top box, or even cable TV) as described in [14][15] for instance. All this information can be conveniently stored in a local (home) REM.

Table 10 lists the characteristics of this scenario.

Table 10: Characteristics of scenario "Home networks (IEEE 802.11af)".

| | |
|---|---|
| Use Case Title | Home networks (IEEE 802.11af) (HN) |
| Purpose of the Use Case – Related use of Radio Environmental Maps (REM) | Unlicensed access to TV white spaces for re-banded 802.11 devices in indoor environment. |
| Implications in terms of sensing | The mandatory TVWS database may be complemented with sensing carried out by 802.11af devices |
| Actor and Roles | Database containing TV transmitters positions and characteristics<br><br>An access point for the home network (802.11af) which can access the above database to check unused TV channels<br><br>A local REM could account for multiple secondary devices trying to access white spaces and for adjacent channel interferences |
| Assumptions and Preconditions | 802.11af AP has a wireless access to the internet<br><br>Indoor propagation models for TV bands available<br><br>Characteristics of present TV receiver(s): position of the antenna, receive filter selectivity are known |
| Trigger Event | Installation and operation of a 802.11af network |
| Description of Actions | Action 1: A communication request is initiated to/from the 802.11af terminal<br><br>Action 2: The AP consults the REM to determine the availability of TVWS for this communication request<br><br>Action 3: Upon the ACK of channel availability by the REM, 802.11af AP grants the channel to the requested communication |
| Ends when | N/A |
| Evaluation Criteria | Need some metrics to assess CR and/or DSA(access) systems: we could consider propositions made in [16] for instance. |

### 3.2.3 Smart metering communication in White Space

The scenario described is aimed at enabling smart meter communication in the white space spectrum by making use of REM and spectrum sensing information to establish the wireless mesh access network.

Smart metering is a paradigm whereby the Home Area Network (HAN) gateways or home grids report their real-time (or near real-time) meter readings to the utility company for monitoring and billing purposes. A smart meter is an advanced meter (which could be an electrical meter or a non-electric meter such as gas, water and heat meters) that measures energy consumption in much more detail than a conventional meter. Smart meters are expected to provide accurate and up-to-date readings automatically at requested time intervals to the utility company, electricity distribution network or to the wider 'Smart Grid'. Given the privacy concerns, meter readings will only be sent by the meter to the utility and registered third parties only (if any), and potentially give the end users fine-grained and even near-real-time information on energy consumption within their households. A smart meter may also potentially communicate with a number of appliances and devices within buildings and will play an important role in building automation and building energy management system applications.

Figure 12 shows a simple illustration of smart meter network deployment where access network between the smart meter gateways and data concentrator is realized as a mesh network. In each home, electrical appliances the meter measures usage in the home in real time and sends the consolidated meter reading to the neighbourhood concentrator. The concentrator node forwards (near) real-time data to the utility company or distribution system over WAN infrastructure. In this scenario, we are particularly interested in establishing the wireless mesh network that is formed among the smart meter gateways and neighbourhood data concentrator. Currently, a number of wired and wireless LAN technologies are considered by the industry for smart meter networks including ZigBee, WiFi, PLC and WiMAX. In this proposed deployment scenario, we consider use of white space and dynamic spectrum access networking technologies.

Some of the characteristics of smart meter communication are as follows:

- The access network is likely to be mesh type.
- The metering information reaches the concentrator by relay communication
- The traffic is bursty and low bit rate
- It is not a real-time communication, however near real-time communication would improve performance (may become common in future).
- Many of the related access locations for metering information are indoors and in locations with hostile propagation conditions that cannot be easily accessed by wireless technologies operating on high frequency bands.

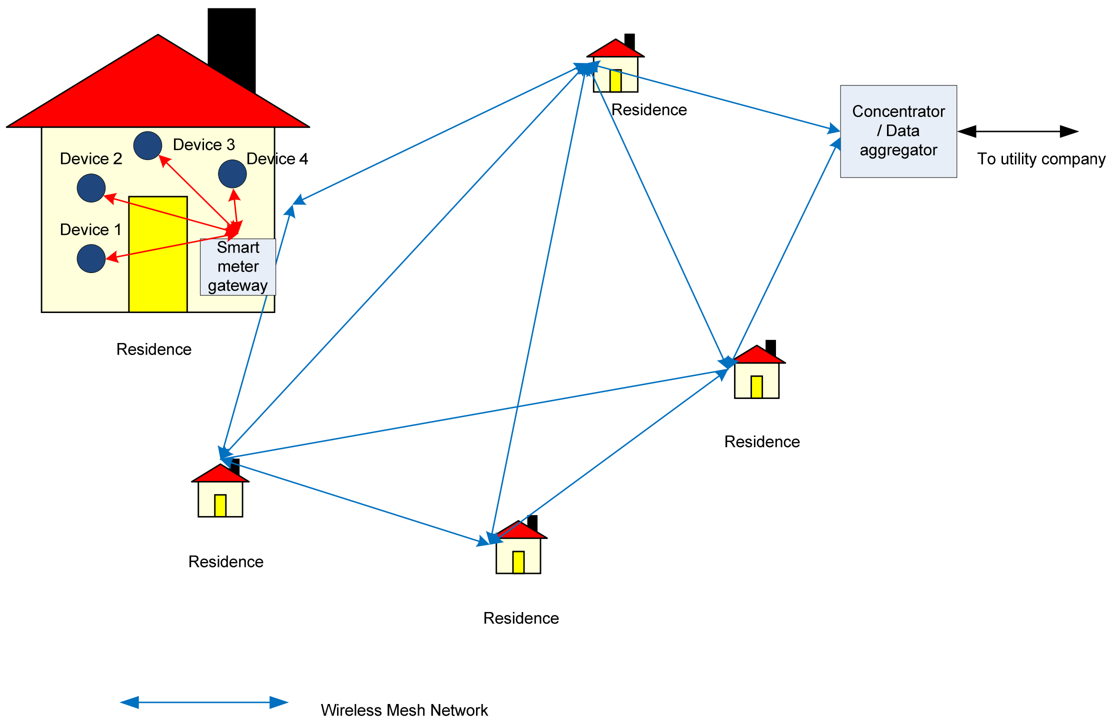


Figure 12: Smart meter communication - a simple illustration.

The radio environment map (REM) could assist the smart meters in establishing the access mesh network. The REM provides the smart meters with a list of available channels, transmit power, and other such radio environment information in establishing the mesh network all the way to the neighbourhood concentrator. Since the traffic is low bit rate and delay-tolerant type, the channel access in establishing mesh networking is less demanding compared to other type real-time communication links.

Table 11: Characteristics of scenario "Smart metering communication".

| | |
|---|---|
| Use Case Title | Enabling smart meter communication in white space spectrum (SM) |
| Purpose of the Use Case – Related use of Radio Environmental Maps (REM) | To establish a smart metering communication over wireless cognitive mesh network by making use of REM and spectrum sensing information. |
| Implications in terms of sensing | REM information could be used establishing the mesh network and the relay link among the gateways. |
| Actor and Roles | Home Area Network (HAN) smart meter gateway<br><br>Concentrator<br><br>A sensor network is necessary to build the REM<br><br>A local REM providing necessary spectrum information to the gateways |
| Assumptions and Preconditions | Regulators / utility company decide to use white space spectrum for wireless mesh network<br><br>The gateways have cognitive radio capability (reconfigurable, location-aware, etc.)<br><br>REM available in the locality or the sensors report to form a REM |
| Trigger Event | Installation and operation of a smart meter gateway |
| Description of Actions | Action 0: REM gathers real-time measurements from the sensors for location information<br><br>Action 1: Residence smart meter gateway requests REM for accessing neighboring / mesh links and the availability of channels.<br><br>Action 2: With the response from REM, the smart meter gateway establishes the link with neighboring mesh node.<br><br>Action 3: The mesh network is thus established all the way to the concentrator and transfers data. |
| Ends when | The link terminates when metering data is transferred successfully |
| Evaluation Criteria | Access/link establishment success rate<br><br>Acceptable time delay |

### 3.2.4 Smart Grid and Demand Response communication in White Space Spectrum

This scenario is aimed at enabling a wider and advanced smart grid communication in white space spectrum. Smart grid is a new paradigm that covers modernization of generation, transmission and distribution of power grids. It will take into account micro-grids, distributed and alternative energy generation and storage. Additionally, the aim is also to bring the user in the loop by providing incentives e.g. through variable pricing to defer consumption during times of peak demand. It is an aggregation of multiple networks and utility companies with several operators employing varying levels of management, communication and coordination. It is necessary for energy consumption efficiency, real-time management of power flows and to provide the bi-directional metering as an enabler for resale of excess energy by the end user. Smart metering could be considered as a cog in a complex wheel of smart grid communication. Figure 13 illustrate the building blocks of smart grid.

Demand response is a feature of smart grids which will enable utilities and consumers to manage consumption and supply of electricity through the adjustment of tariffs and demand. Demand response can reduce the load on utility companies during peak periods by increasing the tariffs on the fly. Consequently, this reduces the fluctuation of electricity demands and prevents electrical outages. It will also lower the peak load of utility companies and reduce the number of peaker plants the utility companies may have to maintain.

The communication sub-layer of the smart grid facilitates the communication of demands, supplies, and tariffs between consumers and utilities. Smart grid communication is characterised by the bi-directional flow of electrical energy and control data associated with it. The communication link is near real-time. The reliability of the link is critically important, since failure and tariff reports cannot tolerate any delay or loss.

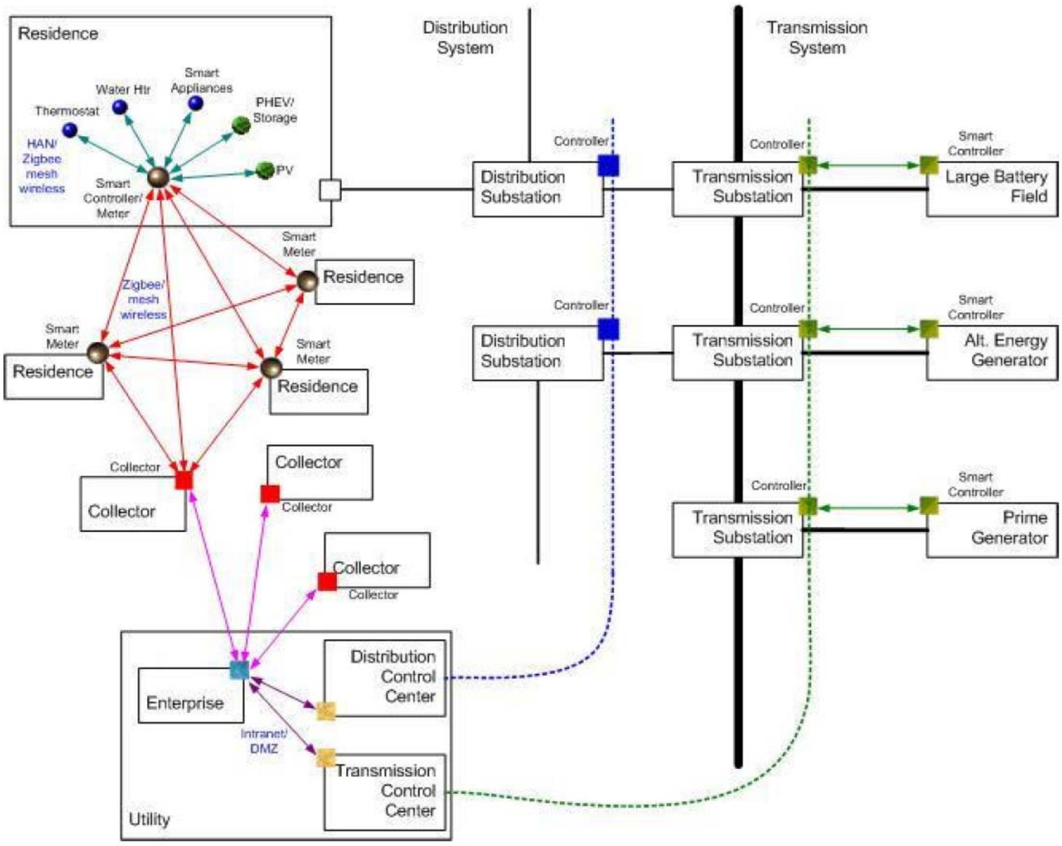


Figure 13: Smart Grid Communication [17].

In this scenario, we explore the use of white space spectrum to establish the smart grid communication and intelligently optimize the spectrum resource allocation in the several levels of this hierarchical network. Figure 14 illustrates the several levels of communication links, from home smart meter to the neighbourhood concentrator and then concentrator to the substation. Only the REM could provide the necessary radio resource and spectrum sensing information to establish the wider smart grid communication. This hierarchical spectrum access could be modelled as optimization problem with the usage of REM.

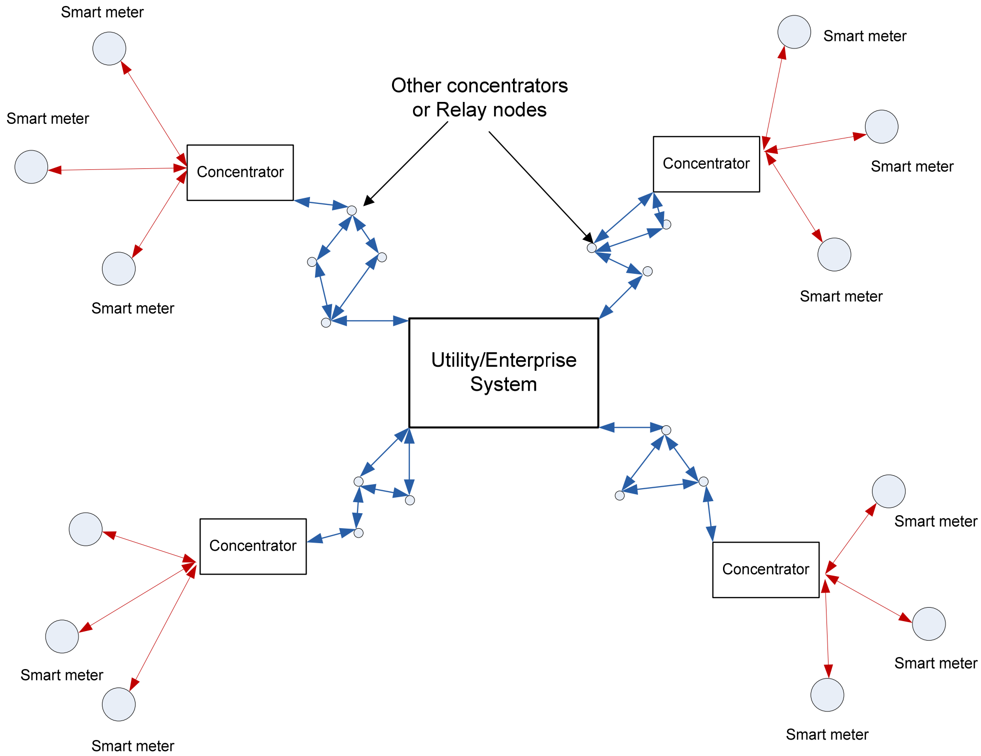


Figure 14: Smart grid communication links.

Table 12: Characteristics of scenario "Smart grid communication".

| | |
|---|---|
| Use Case Title | Enabling smart grid communication in white space spectrum (SG) |
| Purpose of the Use Case – Related use of Radio Environmental Maps (REM) | To establish a smart grid communication by making use of REM and spectrum sensing information to optimize spectrum access. |
| Implications in terms of sensing | REM information could be used smart grid and multiple levels of resource allocation. |
| Actor and Roles | Home Area Network (HAN) smart meter gateway<br><br>Concentrator<br><br>Distribution substation<br><br>A sensor network is necessary to build the REM<br><br>A local REM could provide necessary spectrum information to the gateways |

| | |
|---|---|
| Assumptions and Preconditions | Regulators / utility company decide to use white space spectrum for complete smart grid communication<br><br>The smart meters, concentrators and substations have cognitive radio capability (reconfigurable, location-aware, etc)<br><br>REM available in the locality or the sensors report to form a REM |
| Trigger Event | Initiation of communication between substation and user(s) (for reporting, requests, etc) |
| Description of Actions | Action 0: REM gathers real-time measurements from the sensors for location information<br><br>Action 1: Utility/relay/concentrator allocates resources for communication between Utility and concentrator<br><br>Action 2: Communication between Utility and users |
| Ends when | End of report or request completed |
| Evaluation Criteria | End to end packet delay<br><br>Reliability of link (outage probability)<br><br>QoS<br><br>Signal-to-interference-and noise ratio<br><br>Capacity of link |

### 3.2.5 LTE in TV white space

The scenarios described in this section aim at capitalizing on the potential of the VHF and UHF bands, where European TV broadcasters operate portions of the spectrum exclusively licensed for TV broadcasting. Pioneered in the US during the last few years, the idea to open up these bands for usage by secondary equipment, typically in those frequencies and those locations where transmission does no harm to any of the primary TV receivers, is now also being studied in the UK and continental Europe. See [18] and references therein for the seminal work on evaluating the resulting potential availability of TV white spaces in USA.

Figure 15 illustrates a typical example of how the field strength of a TV transmitter decays with the distance (this figure uses the model in [19]). Plotted in the same figure is the field strength of a secondary transmitter of lower power operating the same frequency band but located at a distance from the TV transmitter. Provided that the secondary transmitter is sufficiently far away from the primary transmitter a certain minimum required SNR can be guaranteed to a sufficiently large portion of the TV receivers in the vicinity of the TV transmitter. The *white space* in this context thus constitutes all those locations beyond a no-talk radius from the primary TV-transmitter. The actual size of this no-talk radius is then tightly associated with the required SNR of the TV receivers with the assumed radio path-loss model, and, often ignored in the literature, with the transmitted power of the secondary transmitter.

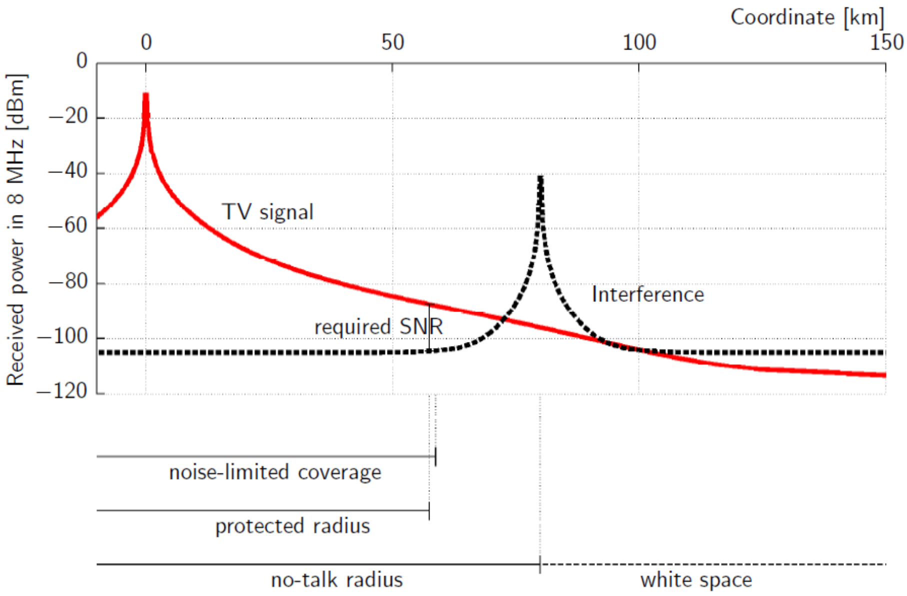


Figure 15: Illustration of the field strength due to the primary TV transmitter (red) and the secondary LTE base station transmitter (black) at various locations.

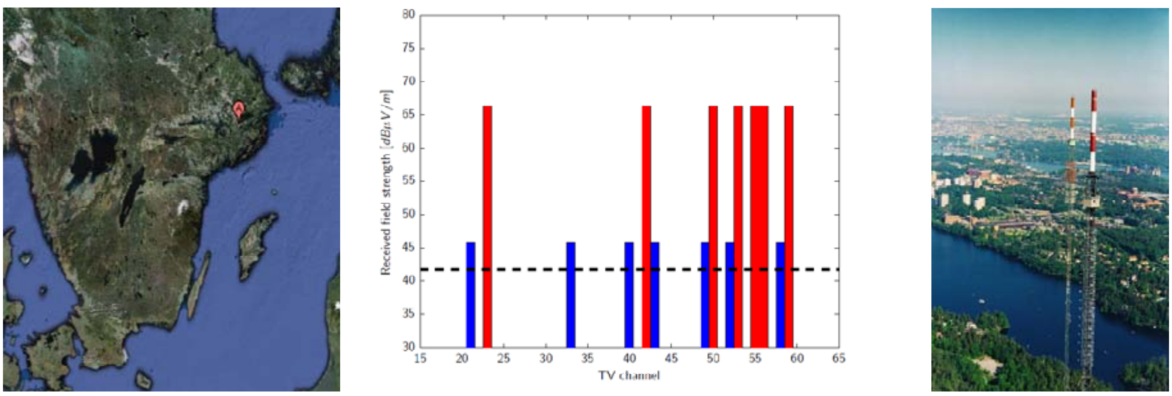


Figure 16: TV channel occupancy at the sample position (59.462N, 18.041E), just north of Stockholm (left). This location is within the protected radius of 2 TV broadcast towers: Stockholm-Nacka at 19.805 km, deploying the red-barred TV channels with antenna height 228 m, and power

47dBW ERP, photo right, and Uppsala-Vedyxa at 46.328 km, with antenna height 219 m, and power 47dBW ERP. In total 14 channels are occupied - the remaining 27 channels are “white space”. The dashed line illustrates the minimum required field strength for proper TV reception.

A collection of the digital TV network transmitters in the TV bands 21-61 in Sweden has been analyzed so as to quantify the amount of white space available according to the concept of Figure 15. Figure 16 illustrates the results for the fixed position (59.462N, 18.041E), a location in the Stockholm region. This position appears in the no-talk region of *two* TV transmitters. Each of these transmitters operates 7 disjoint TV channels and hence 14 TV channels are forbidden at this position to be used for secondary use. The remaining 27 TV channels amounting to 216 MHz can potentially be used for secondary transmission provided that adjacent channel interference is sufficiently small. Even if adjacent channels are avoided by disregarding them because adjacent channel interference would be a problem, still 15 channels or 120 MHz of the UHF spectrum would be available as white space frequencies at this example position.

In addition to this frequency-based example for a fixed position, a second example, shown in the left-hand side of Figure 17 shows the white spaces associated with channel 26 (a fixed frequency evaluated at many locations). Well over 50% of the country could use this channel for secondary transmission.

Generalizing both examples, the right-hand side of Figure 17 illustrates the *total* white space measured in ‘number of available TV channels’ at any point in the country. Dark spots indicate that few TV channels are available, whereas the true white spots indicate the absence of any primary transmitter in its vicinity: all 41 channels could potentially be used for secondary transmission.

The distribution of this white space measure is illustrated in Figure 18. The solid blue curve shows the complementary cumulative distribution of the number of available TV channels per location in Sweden (the right-hand side of Figure 17). 80% of the country’s area experiences over 24 unused TV channels which potentially could be used for secondary transmission if adjacent channel transmissions are allowed. On the other hand, if adjacent channel transmissions are not allowed to avoid adjacent-channel interference, the blue dashed curve indicates that 80% of the country’s area experiences at least 8 unused TV channels that could be used for secondary transmission.

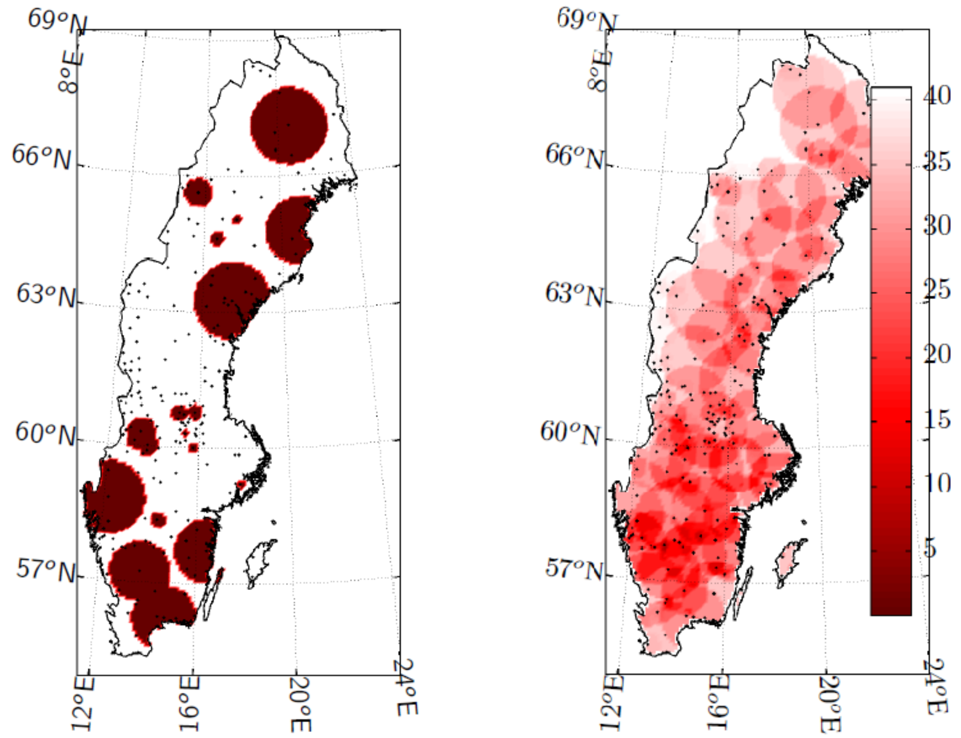


Figure 17: Example of the spatial white space of TV channel 26 (left) and the total number of white space channels (right). The results account for 239 (typically the strongest) of about 550 TV transmitters constituting the Swedish digital TV network.

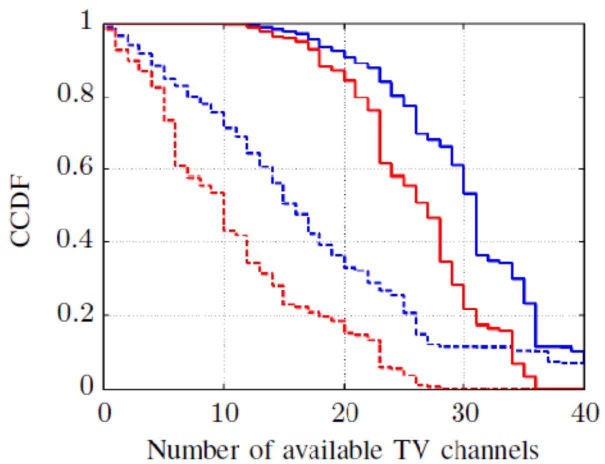


Figure 18: The complementary cumulative distribution of the number of TV white spaces - by area (blue lines) and by population (red lines). The solid lines assume adjacent channels are white; the dashed lines account for 1 channel of guard band interval.

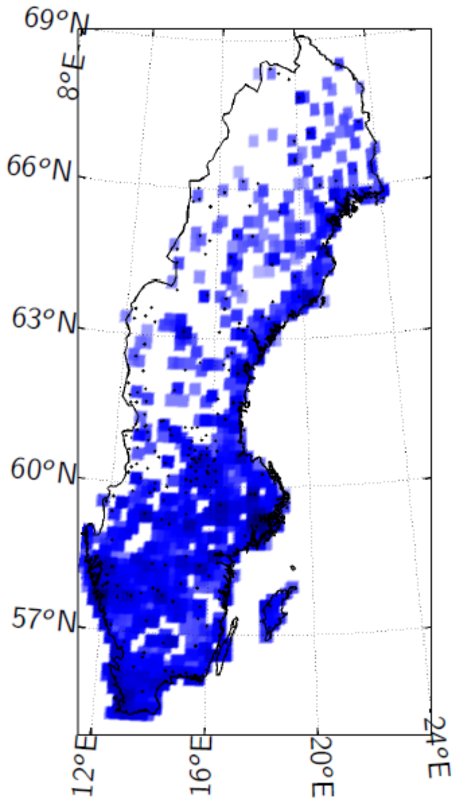


Figure 19: The geographical distribution of the Swedish population.

Finally, the red curves in Figure 18 illustrate the associated figures when the non-uniformity of the Swedish population is taken into account. Since the population in Sweden is highly concentrated in the south and in the coastal regions (see Figure 19), figures change when white space is counted per person (rather than per area). The red curves in Figure 18 indicate that to 80% of the Swedish population, over 22 TV channels appear white. When adjacent channels cannot be used, 80% of the people can exploit over 5 TV channels (40MHz).

The indicative results above form the background and the motivation for the three scenarios described in the following:

1. LTE Home base stations (Home eNodeB's, or HeNB's) in TV white spaces
2. LTE rural coverage in TV white spaces
3. LTE-multicast/broadcast services (deploying the *multicast/broadcast single frequency network* (MB-SFN) mode) in TV white spaces.

The *common* intention in the study of these scenarios is :

- to show the technical feasibility of deploying an LTE network in TV white space frequencies,

- to analyse which LTE network deployment is most appropriate, that is, which technical network characteristics (e.g. macro/micro/pico/femto deployment; duplex scheme, MBMS-only network, etc.) are most suitable for this secondary type of spectrum usage,
- to analyse the technical aspects of the associated business cases (rural coverage, femto-cell capacity, dedicated MBSFN carriers for broadcasting/multicasting services, etc),
- to develop technology enablers required to realize the preferred LTE-deployment, and
- to demonstrate the feasibility through prototyping.

In each of the scenarios, the radio environmental map (REM) serves a more or less important role as the key enabling technology for a feasible deployment of a centralized cellular LTE -network.

Important aspects to investigate*, common* for the three scenarios are:

- What are the minimum required field-strength requirements of the various European countries' DVB-T networks?
- How much protection to the primary TV receivers (quantitatively) should the LTE system provide? And in the adjacent channels? What are the typical frequency guard bands that need be employed?
- How much white space is there? The answer to this question is key element in determining the business case for this scenario. A study that deepens the initial above-mentioned results and extends them to other European countries (with different population distributions) can shed light on this.
- Which LTE-deployment can best exploit this white space? Macro-, micro-, pico-, femto-cells? TDD? MBMS-only? What are the trade-offs in terms of capacity/coverage? What is the impact of the various deployments on the actual amount of available white space?
- How does this relate to the population density and the possible business cases?
- What are the regulatory issues with allowing LTE in the TV bands? Which thresholds (in space, time and frequency) should be defined by the regulator?
- How can a REM be generated and represented in these scenarios? This is important to address in the analysis of potential architectures of the deployment.
- How can a REM be exploited by proper signalling-formats and RRM-mechanisms?
- How can sensing- and database-generated REMs complement each other? What are proper sensing algorithms for detecting wireless microphones?

#### 3.2.5.1 TVWS scenario I: Increasing capacity with LTE Home eNodeB's (HeNB's)

The first scenario covers the attempts of LTE operators to increase the capacity of the network in urban areas and extend their indoor service coverage. In 3GPP, a base station of the smallest kind, with low power characteristics and a typical target indoor cell coverage (also known as a femto-cell) is referred to as Home eNodeB and abbreviated as HeNB. As described in section 2.2.1, these base stations are typically connected to an operator's network through a broadband connection as xDSL or TV cable network. In this scenario these HeNB's are envisaged to access the TV white space spectrum for the LTE radio access. Note that this scenario is a special case of the generalized *cognitive femto-cell* scenario of section 3.2.1 where the unused portions of spectrum is particularly the TVWS and the femto-cell uses particularly the LTE technology. Table 11 lists the relevant characteristics of this scenario.

Table 11: Characteristics of scenario "LTE Home eNodeB's in TVWS"

| | |
|---|---|
| Scenario Title | LTE HeNB's in TVWS (LTE-H-TV) |
| Purpose of the scenario–related use of Radio Environmental Maps (REM) | Besides complementing the primary transmitters' locations and characteristics the sensing-based REM also records and registers other secondary HeNB's operating in the white spaces. |
| Implications in terms of sensing | A sensor network complements a database with information on both TV transmitters and other primary devices such as wireless microphones |
| Actors and roles | The primary network may need to provide a TV transmitter database.<br><br>The secondary network needs to maintain a sensor-network-based REM.<br><br>The HeNB's access the TV spectrum in an agile manner. |
| Assumptions and pre-conditions | The regulator opens the TV bands for secondary usage. |
| Trigger event | A HeNB needs operating resources. |
| Description of actions | The HeNB consults the REM for available frequencies<br><br>The HeNB auto-configures its front-end and informs the REM<br><br>The REM continuously monitors a database with TV transmitters<br><br>The REM continuously monitors measurements provided by a sensor network<br><br>Upon arrival of new TV transmitters, the REM manages proper retreat and reassignment of the relevant HeNB's |
| Ends when | N/A |
| Evaluation criteria | Interference imposed by LTE HeNB's onto the TV network.<br><br>Interference imposed by the TV network onto the LTE network.<br><br>Capacity improvement of the HeNB LTE network |

### 3.2.5.2 TVWS scenario II: Providing LTE rural mobile coverage

The second scenario covers the business case of providing mobile services by means of an LTE network to rural areas. The propagation characteristics in the UHF band cater for a less dense deployment of the LTE network and hence coverage can be accomplished with fewer base stations than in other frequency bands.

The essential difference with the above HeNB scenario is the power employed by the LTE base station transmitter. Whereas the HeNB improves the network capacity by transmitting with very low power and hence covers only very small cells, typically in a dense urban environment, the rural coverage scenario typically uses higher power LTE transmitters to extend the network's coverage to remote locations in a country.

Recall that the actual *amount* of available white space depends on the transmit power employed by the secondary transmitter. Hence we expect that the available white space is less in the rural coverage scenario than in the HeNB scenario. A feasibility study of this scenario addresses questions about the enabling technologies beyond those in the current 3GPP's LTE-standard's releases. Typically the REM is such a key enabler. Table 12 lists the relevant characteristics of this scenario.

Table 12: Characteristics of scenario "LTE rural coverage in TVWS".

| | |
|---|---|
| Scenario Title | LTE rural coverage in TVWS (LTE-R-TV) |
| Purpose of the scenario–related use of Radio Environmental Maps (REM) | A sensor-measurement based REM may complement a TV transmitter database for improved primary detection, and for recording wireless microphones and similar devices. |
| Implications in terms of sensing | A sensor network complements a database with information on both TV transmitters and other primary devices such as wireless microphones |
| Actors and roles | The primary network may need to provide a TV transmitter database.<br><br>The secondary network maintains a complementary sensor-network-based REM.<br><br>The eNB's access the TV spectrum in an agile manner. |
| Assumptions and pre-conditions | The regulator opens the TV bands for secondary usage |
| Trigger event | A (group of) LTE eNBs needs resources to operate in a rural area |

| | |
|---|---|
| Description of actions | The eNB consults the database of primaries and possibly the REM for available frequencies<br><br>The eNB auto-configures its front-end and informs the REM<br><br>The REM continuously monitors the database with TV transmitters<br><br>The REM may also continuously monitor measurements provided by a sensor network<br><br>Upon arrival of new TV transmitters, the REM manages proper retreat and reassignment of the relevant eNB's |
| Ends when | N/A |
| Evaluation criteria | Interference imposed by LTE eNB's onto the TV network<br><br>Interference imposed by the TV network onto the LTE network<br><br>Throughput/capacity of the rural broadcast connections |

#### 3.2.5.3 TVWS scenario III: Providing multicast/broadcast services on stand-alone LTE MBSFN-carriers

The third scenario attempts to employ the white space frequencies in a way this VHF/UHF-spectrum is originally meant to be used: for broadcasting services. The scenario deploys a broadcast/multicast network but with the apparent characteristics that this is done through the (existing) LTE network nodes, by deploying *stand-alone* LTE carriers that only operate in the "Multicast/Broadcast Single Frequency Network" (MB-SFN) mode. The MB-SFN mode is available in current LTE standard releases. In the current releases, this mode appears on a certain LTE carrier always in conjunction with true unicast services (the MB-SFN-service shares resources with unicast services) and hence the stand-alone carrier functionality would have to be developed in the standard to accommodate this service. Operated in the MB-SFN mode, a number of LTE base stations cooperate by transmitting exactly the same broadcast signal to all users (broadcast) or a group of users (multicast) in the service area covered by the group of base stations.

This scenario explores the feasibility of employing stand-alone LTE carriers in the TV white space frequencies in a downlink-only MB-SFN mode. Notably this scenario is not necessarily categorized as "opportunistic spectrum access" scenario. Rather, fruitful cooperation between the incumbent TV broadcasters and the additional LTE MB-SFN operators could pave the way for a very efficient use of this traditional radio spectrum band. TV operators provide wide area coverage with high towers and high-power transmitters, while the LTE network provides local or regional multicast services with their extensive network of small transmitter masts and low-power transmitters.

Possibly, an associated uplink connection can be maintained in another, LTE-licensed frequency band. Table 13 lists the relevant characteristics of this scenario.

Table 13: Characteristics of scenario "LTE-MBSFN in TVWS"

| | |
|---|---|
| Scenario Title | LTE MB-SFN in TVWS (LTE-M-TV) |
| Purpose of the scenario–related use of Radio Environmental Maps (REM) | The knowledge of the radio environment is used to take optimal frequency planning decisions |
| Implications in terms of sensing | Sensing might be a complementary technology to the TV broadcasters' databases and also provide information on other primary devices as wireless microphones |
| Actors and roles | The primary network need to provide a TV transmitter database<br><br>The secondary network could maintain a complementary sensor-network-based REM<br><br>The eNB's could access the TV spectrum in either a (semi-statically) planned or in an agile manner<br><br>The primary and secondary actors could also cooperate on the spectrum access. |
| Assumptions and pre-conditions | The regulator opens the TV bands for secondary broadcast/multicast usage (downlink traffic) |
| Trigger event | A (group of) LTE base stations wants to set up a broadcast or multicast service |
| Description of actions | The group of eNBs consults the database of primaries and possibly the REM for available frequencies<br><br>The eNBs auto-configure their front-end and informs the REM<br><br>The REM continuously monitors the database with TV transmitters<br><br>The REM may also continuously monitor measurements provided by a sensor network<br><br>Upon arrival of new TV transmitters or other primary devices, the REM manages proper retreat and reassignment of the relevant eNB's |
| Ends when | N/A |
| Evaluation criteria | Interference imposed by LTE eNB's onto the TV network<br><br>Interference imposed by the TV network onto the LTE network |

# 4 Spectrum Sharing on Unlicensed Bands

This category corresponds to the case where there is no primary user; mobile users perform opportunistic access on an unlicensed band (for ex. Wi-Fi).

## 4.1 Coordinated spectrum access: Coordination among ad-hoc networks

The networks have coordination on when and how the users access the spectrum. We can imagine a scenario where several different mobile ad-hoc networks collaborate to share the spectrum.

The networks apply the same technique to access the spectrum, but they could have different requirements in terms of bandwidth needed, transmission power, expected data-rate, etc. Moreover it is possible that all of the networks are not at the same hierarchical level: one could have more priority than another. For example if we consider a natural disaster, an eventual ad-hoc network put in place to guarantee intercommunication among rescue actors should have maximum priority with respect to other existing networks.

In this scenario the objective is to optimize the interaction among networks trying to minimize the signaling overhead while guaranteeing the requirements of each network. The REM will be exploited to fulfill these purposes, that is, optimizing the allocation of resources, but also guaranteeing fast reaction to changes in the respective positions of networks (and then in the interference profile) due to mobility.

A further problem could be the presence of interferers that do not participate in the coordination process. In this case coordinated networks should be able to distinguish among the different interferers by combining REM and sensing information.

More generally, there are two steps to be foreseen: in the first one, coordination will lead to frequency sharing among networks; in the second one frequencies allocated to each network are shared among their users according to intra-network communication needs.

A channel reserved for exchanging signalization messages to allow coordination should be foreseen as well. Figure 20 provides an example where networks with different priority levels have to be coordinated in order to manage spectrum access.

Table 14 lists the characteristics of this scenario.

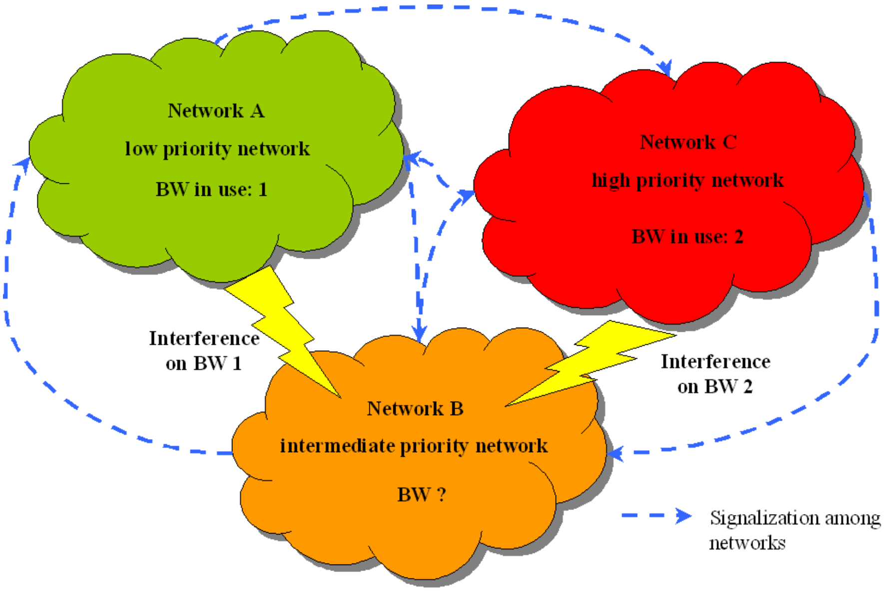


Figure 20: Example of coordinated spectrum access of ad-hoc networks. Network B has to choose a bandwidth to use: in the case BW1 and BW2 are the only available bands, coordination should force Network A to free BW1 for Network B that has higher priority.

Table 14: Characteristics of scenario “Coordinated mobile ad-hoc networks”.

| | |
|---|---|
| Scenario Title | Coordinated mobile ad-hoc networks (CMANET) |
| Purpose of the scenario–related use of Radio Environmental Maps (REM) | The information about location and characteristics of other networks present in the area provided in the REM could influence the resource allocation strategy of mobile ad-hoc networks increasing their overall capacity. |
| Implications in terms of sensing | Sensing must be able to distinguish among other coordinated network interferers and eventual external interferers, providing their positions |
| Actors and roles | Each network has a Cluster Head (CH) that is aware of the needs of resources of the network and responsible of the intra-network resource allocation |
| Assumptions and pre-conditions | Existence of a common narrow band signalization channel.<br><br>Each network runs the same resource allocation policy. |
| Trigger event | A network “A” needs resources for intra-network communications |

| | |
|---|---|
| Description of actions | Action 1: CH of network "A" consults REM about frequency opportunities and location of interferers<br><br>Action 2: CH of network "A" takes a frequency allocation decision in coordination with CHs of other networks<br><br>Action 3: when CH of network "A" has a set of frequencies available to use, it proceeds to allocate resources to users of the network according to each user needs |
| Ends when | Resource needs of all networks are satisfied |
| Evaluation criteria | Signaling overhead<br><br>Time to converge |

## 4.2 Non-coordinated Spectrum Access

In this category, the networks do not have coordination; they have a Listen-Before-Talk-like set of rules. They access the spectrum in an opportunistic manner, i.e. depending only on their sensing results and without having any common agreement on the access strategy. Below, we give two example scenarios: independent (non-coordinated) mobile ad-hoc networks and extension of LDR (Low Data Rate) licensed network to out-of-band HDR (High Data Rate) unlicensed bands.

### 4.2.1 Independent (non-coordinated) mobile ad-hoc networks

We can build a scenario with several independent ad-hoc networks that try to guarantee communications among their users. The networks are mobile and compete to access the spectrum. From the perspective of one of these networks, several interferers (other ad-hoc networks) are present, each of them with a different interference profile that evolves in time (due to mobility). The network considered has to exploit its own sensing information in order to find opportunities to access the spectrum avoiding interferences. The choice of the frequencies to use should take into account not only the actual situation, but also the probable future situation(s) reducing as much as possible the risks of having to change frequencies several times in the future. The network can achieve this objective by exploiting the REM information, more specifically, by relating informations like network movements, landscape and interference profiles. In Figure 21, a simple example is provided: Network A needs to choose one of the two bands (identified as BW1 and BW2). If we assume that, at the moment to take the decision, interference due to Network B is higher than the one due to Network C, without any knowledge of the origin of interferences, the most logical choice for Network A to minimize interference will be BW2. On the other hand, if Network A knows the location of interferers, it will more probably choose BW1 looking at the fact that it is moving towards the origin of interference on BW2.

Table 15 lists the characteristics of this scenario.

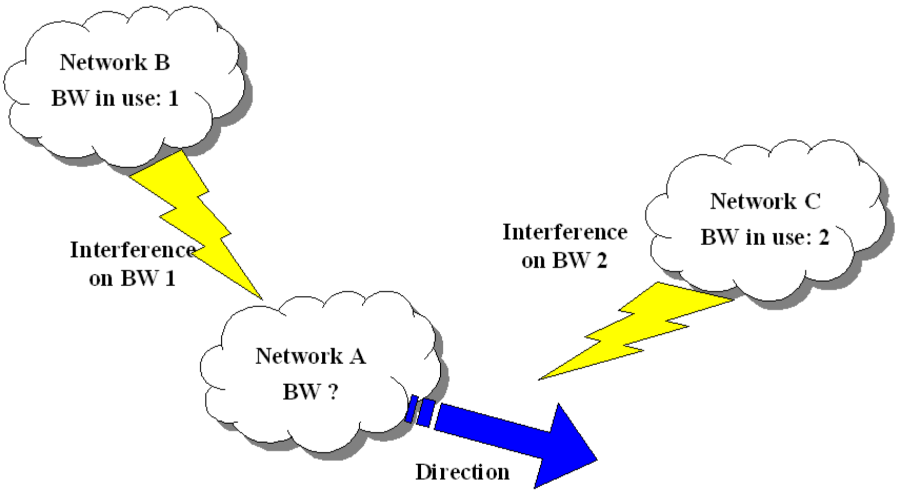


Figure 21: Example of non-coordinated spectrum access of ad hoc networks in which decision can be improved by knowledge of the interference profile.

In this scenario, quality of service cannot be guaranteed to networks, so a best effort based policy will be used. On the other hand the focus should be put in satisfying the capacity requirements of each network combining dynamic frequency allocation, power allocation and, if necessary, link optimization techniques. The efficiency in terms of satisfaction of capacity requirements should be evaluated and compared with the overall capacity that can be obtained with a fix resource allocation policy.

Table 15: Characteristics of scenario "Independent (non-coordinated) mobile ad-hoc networks".

| | |
|---|---|
| Scenario Title | Independent (non-coordinated) mobile ad-hoc networks (IMANET) |
| Purpose of the scenario–related use of Radio Environmental Maps (REM) | The information about location and direction of interferers (i.e. other networks present in the area) provided in the REM will determine spectrum access decisions and link optimization strategy of each network. |
| Implications in terms of sensing | Sensing must be able to distinguish among different interferers, providing position of interferers and their activities. |
| Actors and roles | Each network is independent and considers other networks as interferers<br><br>Each network has a Cluster Head (CH) that is aware of the needs of the network in terms of resources and responsible of the intra-network resource allocation |

| | |
|---|---|
| Assumptions and pre-conditions | Each network has a minimum SINR based threshold that has to be guaranteed to use a certain band<br><br>Each network has a capacity need to fulfill that can vary with time<br><br>A narrow band licensed signalization channel is present for each network |
| Trigger event | A network “A” needs resources for intra-network communications |
| Description of actions | Action 1: CH of network “A” consults REM about frequency opportunities and interference location<br><br>Action 2: CH of network “A” takes a resource allocation decision according to REM information and SINR-based threshold<br><br>Action 3: CH of network “A” optimizes intra-network links allocating resources to users to fulfill capacity needs |
| Ends when | Resource needs of all networks are satisfied |
| Evaluation criteria | Time to converge<br><br>Efficiency in terms of capacity needs |

### 4.2.2 Extension of LDR (Low Data Rate) licensed network to out-of-band HDR (High Data Rate) unlicensed bands

An existing network uses a licensed band to guarantee low data rate communication to their users. It can happen that, sometimes, some users need to exchange big amount of data. The licensed band is not sufficient to satisfy the increased data rate requirements, so the users can take advantage of unlicensed bands to build opportunistic high data rate links for the time that is necessary.

This is a very typical situation for security actors like police or firemen. For example usual communications among police units consists of voice traffic. Nevertheless, in particular cases like special interventions, the transmission of a video from one unit to another could strongly help the operations. This is exactly the case in which a temporal high data rate link in unlicensed bands will be helpful to satisfy the increased requirements.

Figure 22 summarizes this scenario underlying the main challenge given by the presence of eventual other networks on unlicensed bands.

Table 16 lists the characteristics of this scenario.

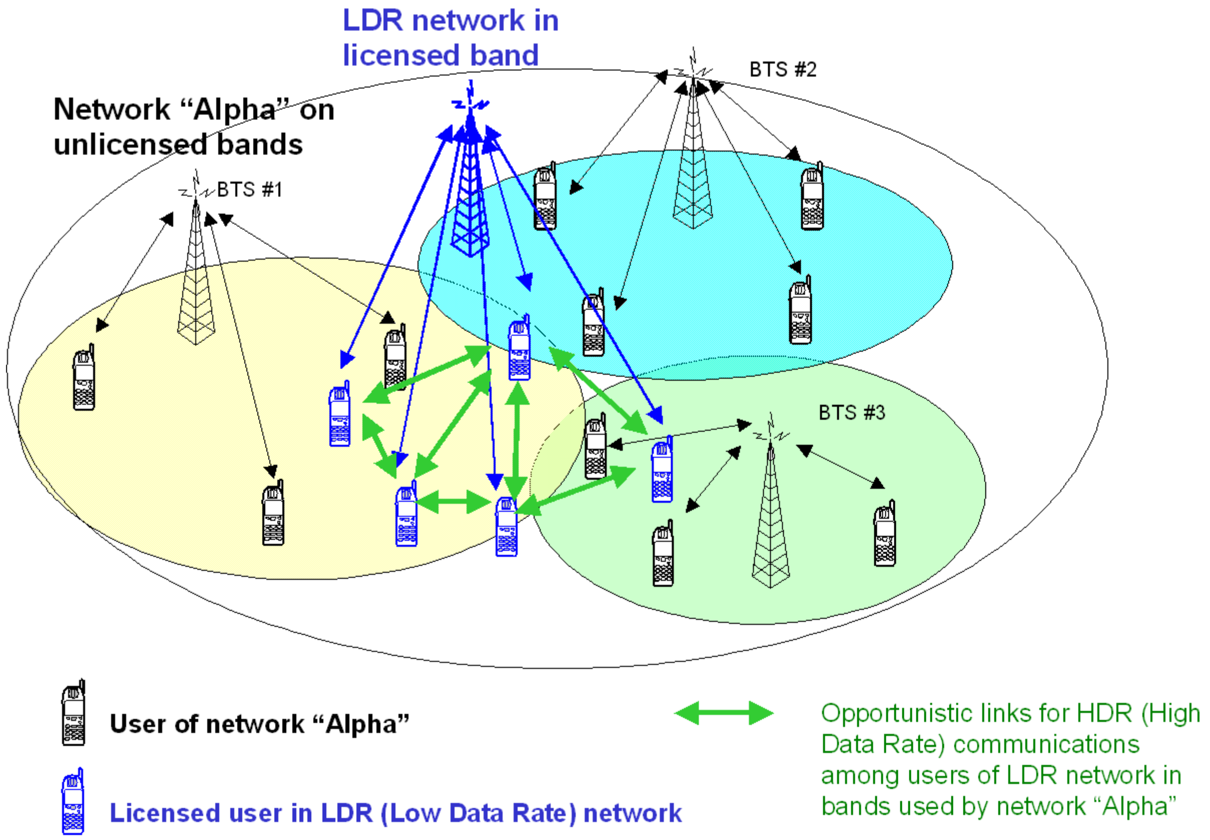


Figure 22: Some users of LDR network need to exchange large amount of data at a certain time instant. To satisfy this temporal requirement, HDR links are built among users in unlicensed bands used by network Alpha. The main challenge is to select the best band for each link allowing the coexistence with network Alpha.

Table 16: Characteristics of scenario “HDR out-of-band links for LDR licensed networks”.

| | |
|---|---|
| Scenario Title | HDR out-of-band links for LDR licensed networks (HDROOB) |
| Purpose of the scenario–related use of Radio Environmental Maps (REM) | Some users of a LDR network need temporally a larger data rate to exchange large amount of data. The information about systems using unlicensed bands in the area provided in the REM will permit the opportunistic creation of HDR (High Data Rate) links among users on these unlicensed bands. |
| Implications in terms of sensing | Sensing have to provide information about variation of activities of unlicensed networks present in the area |

| | |
|---|---|
| Actors and roles | LDR licensed network composed by a BTS and several users<br><br>Each user of LDR network is most of the time satisfied by the data rate provided by the network, but occasionally, it can have the need of an increased data-rate for some specific reason.<br><br>There are other networks present in the area which operate over unlicensed bands |
| Assumptions and pre-conditions | LDR licensed communications are possible among users<br><br>Signalization messages can be exchanged among users through LDR licensed network |
| Trigger event | A user *u1* of LDR network needs a high data rate link with another user *u2* of the network |
| Description of actions | Action 1: User consults REM about frequency opportunities in unlicensed bands<br><br>Action 2: According to information provided by REM user *u1* proposes (through LDR network) to user *u2* parameters to build an HDR link<br><br>Action 3: User *u1* acknowledges the proposition<br><br>Action 4: The HDR link is build |
| Ends when | End of data transmission requiring HDR link |
| Evaluation criteria | Data rate provided on the HDR link<br><br>Interference on other networks using unlicensed bands |

# 5 Dedicated Spectrum Monitoring on Licensed and Unlicensed Bands

This category implies a dedicated sensing network that performs sensing to be used for spectrum sharing purposes (for example by a regulatory body). The sensing data that is collected by the dedicated network is combined and processed at a central entity to arrive at spectrum usage information. This central entity use this information to update a data base on the spectrum use in a given region (what frequencies are used in any locations, what systems etc.) and broadcast this database on an information channel. This channel can either be a dedicated channel, such as the Cognitive Pilot Cannel (CPC) [20], or an information channel, like the Media Independent Handover (MIH) [21] channel, thanks to an application running on terminals. Any network entity that demands spectrum access is provided with this information. Multiple regulatory and business models can arise based on this scenario. For example, as discussed by Weiss et al. in [22], there are potential business cases in spectrum sensing, some of which might result dedicated organizations to emerge carrying out high fidelity spectrum measurements. Depending on the model adopted, spectrum data could become either a commercial commodity to be bought and sold, or made publicly available through, for example, governmental or regulatory bodies. Naturally different outcomes are possible in different regions, and also in different bands of frequencies. The scenario description below is thus formulated focusing on the technological characteristics and requirements it imposes on the radio environment map technology, without specifically targeting any of these deployment models. Successful REM architecture should naturally be applicable to all of them.

This scenario targets long-term monitoring of the spectrum occupancy in a wider frequency range in different surroundings (e.g. urban, suburban and rural). The main idea behind is to gather relevant statistical information about spectrum usage and possible opportunity discovery for secondary usage. The wideband measurement setups can be made on multiple different fixed positions, in urban and rural areas, and the spectral measurements can be performed with long durations (in the order of weeks and/or months). This scenario indicated strongly measurements as a business situation. One can envision either a situation, where a company or public body deploys a permanent or semi-permanent measurement grid into place, or a certain spectrum user, e.g. an operator, sees so high value in accurate spectrum measurement data that it deploys its own infrastructure. The potential for dedicated organizations or public bodies for carrying out measurements is also quite strong (even to the extent that the US congress has considered legislation stipulating spectrum occupancy measurements to be carried out, with yet to be decided granularity levels and regions). Carrying out large-scale measurements accurately is an expensive undertaking with high setup costs and complex planning requirements, and also investing into the required high fidelity infrastructure might be prohibitive for some players that could still benefit from such data. Therefore a role for dedicated entity for carrying our such measurements clearly exists.

Table 17 lists the characteristics of this scenario.

Table 17: Characteristics of scenario "Infrastructure based measurements".

| | |
|---|---|
| Scenario title | Infrastructure based measurements (IM) |
| Purpose of the scenario and related use of Radio Environmental Maps (REMs) | The scenario aims to provide high quality, long-term information on spectrum occupancy in wide frequency bands and over longer time periods. The spectrum observatories and the measurement grid may be used also for national security purposes. The REMs report on the spectrum utilization and may be used exclusively by a certain entity (e.g. regulatory body or an operator), or more openly or through commercial agreement by larger set of users for more efficient resource management. |
| Implications in terms of sensing | High-end measurement equipments with high robustness, fidelity, calibration stability, and availability of infrastructure |
| Actors and roles | Spectrum measurement actors (companies, operators and/or regulators)<br><br>Spectrum data users (infrastructure owners as users, or terminal centric users or REMs). |
| Assumptions and pre-conditions | Due to costs a clear commercial or regulatory value for deployment<br><br>Long-term need for updated high-fidelity spectrum measurement information. |
| Triggering event | None |
| Description of actions | Deployment and utilization of measurement infrastructure<br><br>Making the measurement data available either through commercial means or otherwise (e.g. through public body)<br><br>Obtaining access or copy of measurement data or statistics computed thereof, with details dependent on the sharing model<br><br>Applying obtained data or models for network operation, planning etc. |
| Ends when | N/A |
| Evaluation criteria | Spatiotemporal resolution of data and performance characteristics of the measurement infrastructure<br><br>Cost efficiency and obtained benefits from use of data |

# 6 Conclusions

This document has presented a collection of scenarios where utilization of geo-localized measurement data in the form of REMs brings important advantages in terms of ease in network management, radio resource usage optimization, QoS enhancement, cost reduction, spectrum efficiency etc. These scenarios cover a wide range of spectrum sharing modes: from the conventional intra-operator command-and-control mode to the opportunistic use of licensed/unlicensed bands.

The intra-operator scenarios involve cases where an operator who is the exclusive owner of the spectrum foresees the use of REMs to better manage its heterogeneous radio access networks in terms of cost, QoS and radio resource (including spectrum) efficiency. On the other hand, opportunistic access scenarios focus on the use of REMs for the purpose of better detecting the presence, the activity and the location of the incumbent users in order not to create harmful interference and to enhance the efficiency and the QoS of opportunistic users.

We have chosen the presented scenarios after careful analysis of the different potential use cases based on their importance to the project partners and real technical challenges they impose. The future work in the project will be mapped against these chosen scenarios. This will also result in further refinement of the chosen scenarios, and the eventual selection of a small final subset for deeper investigation and prototype implementations. Construction of real-time REMs will be assessed through demonstrations and relevant measurement campaigns taking into account the selected scenarios. Ultimately, REM exploitation in radio resource management and optimization will be investigated and evaluated within the scope of these scenarios. This will be a way to assess the real-world added-value of the REMs, an aspect that has not been addressed so far.

Among the scenarios presented in this document, scenarios on femto-cell optimization and on opportunistic use of TVWS can be put forward as potential high-value candidates for further investigation due to their rising importance and increasing share in the ongoing discussions in the wireless communities. These two scenarios are thus currently forming our first-level baseline scenarios for further mapping and investigation, although all scenarios will be kept in mind still for the first year of the project as source for additional requirements and use cases.

## Glossary and Definitions

| *Term* | *Description* |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| ACK | Acknowledge |
| AP | Access Point |
| BS | Base Station |
| C/I | Carrier to Interference Ratio |
| CAB | Coordination Access Bands |
| CPC | Cognitive Pilot Channel |
| CR | Cognitive Radio |
| CRM | Cognitive Resource Management |
| DVB-T | Digital Video Broadcasting – Terrestrial, |
| DIMSUMNet | Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile-access Network |
| DSA | Dynamic Spectrum Allocation or Dynamic Spectrum Access |
| FCC | Federal Communications Commission |
| FDD | Frequency Division Multiplexing |
| FPGA | Field-Programmable Gate Array |
| HeNB | Home eNodeB |
| HO | HandOver |
| IEEE | Institute of Electrical and Electronic Engineering |
| ISM | Industrial Scientific and Medical band |
| JRRM | Joint Radio Resource Management |
| LTE | Long Term Evolution |
| MAC | Medium Access Control |

| *Term* | *Description* |
|---|---|
| MME | Mobility Management Entity |
| MIH | Media Independent Handover |
| OFDM | Orthogonal Frequency Division Multiplexing |
| PHY | Physical Layer |
| PU | Primary User |
| QoS | Quality-of-Service |
| RAN | Radio Access Networks |
| RAT | Radio Access Technology |
| REM | Radio Environmental Maps |
| RF | Radio Frequency |
| RNC | Radio Network Controller |
| RRM | Radio Resource Management |
| SDR | Software Defined Radio |
| SNR | Signal to Noise Ratio |
| TV | Television |
| TVWS | TV White Space |
| UMTS | Universal Mobile Telecommunications System |
| UHF | Ultra High Frequency |
| UNII | Unlicensed National Information Infrastructure |
| UWB | Ultra Wide Band |
| WiFi | Wireless Fidelity |
| WS | White Spaces |

# References


[1] M. Buddhikot: "Understanding Dynamic Spectrum Access: Models, Taxonomy and Challenges", Proceedings of IEEE DySPAN 2007, Dublin, Ireland, April 17-21, 2007.

[2] DIMSUMnet: Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile networks (http://www.bell-labs.com/user/mbuddhikot/dimsumnet/index.htm)

[3] Public Safety Spectrum Trust Named Broadband Licensee, (http://www.psst.org/documents/PSSTPSBLSelectionPressRelease111907.pdf).

[4] http://www.broadband.gov/plan/16-public-safety/

[5] Martin BH Weiss and William H. Lehr, "Market based approaches for dynamic spectrum assignment," University of Pittsburgh, Pittsburgh PA, Working Paper http://d-scholarship.pitt.edu/2824/, 2009.

[6] M. Weiss, M. Al-Tamaimi, L. Cui, “Dynamic Geospatial Spectrum Modelling: Taxonomy, Options and Consequences”, Telecommunications Policy Research Conference 2010, accepted.

[7] K. Woyach, P. Pyapali and A. Sahai, “Can we incentivize sensing in a light-handed way?”, IEEE Symposium on Dynamic Spectrum Access Networks, Singapore, April 2010.

[8] H. Palaiyanur, K. Woyach, R. Tandra, A. Sahai, “Spectrum Zoning as Robust Optimization”, IEEE Symposium on Dynamic Spectrum Access Networks, Singapore, April 2010.

[9] B. Fette (ed.), “Cognitive Radio Technology”, Newnes, 2006.

[10] A. Wyglinski, M. Nekovee, T. Hou, ”Cognitive Radio Communications and Networks”, Academic Press, 2009.

[11] ICT-2007-216248 E3 Project Deliverable D2.1, “System Scenarios, Use Cases, Assessment” June 2008.

[12] SE43 Draft Report: “TECHNICAL AND OPERATIONAL REQUIREMENTS FOR THE POSSIBLE OPERATION OF COGNITIVE RADIO SYSTEMS IN THE ‘WHITE SPACES’ OF THE FREQUENCY BAND 470-790 MHZ

[13] Agence Nationale des Fréquences (ANFR): “Availability of spectrum for white spaces devices in rural environment in the band 470-790 MHz”

[14] E. Obregon,L. Shi,J. Ferrer, J. Zander: "Experimental Verification of Indoor TV White Space Opportunity Prediction Model" , In Proc. of The 5th international conference on cognitive radio oriented wireless network and communications (CrownCom 2010), Cannes, France June 2010.

[15] E. Obregon, J. Zander: “ Short Range White space Utilization in Broadcast systems for Indoor environment”, In Proc. of IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, (DySPAN 2010), Singapore, April 2010.

[16] Y. Zhao, S. Mao, J.O. Neel and J.H. Reed: “Performance Evaluation of Cognitive Radios: Metrics, Utility Functions, and Methodology”, Proceedings of the IEEE, 2009.

[17] Boyer W. F. and McBride S. A., “Study of Security Attributes of Smart Grid Systems – Current Cyber Security Issues”, INL/EXT-09-15500, Idaho National Laboratory – Critical Infrastructure Protection/Resilience Center, USA, April 2009

[18]K. Harrison, S. Mishra, A. Sahai, ” How much white-space capacity is there?”, In Proc. of IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, (DySPAN 2010), Singapore, April 2010.

[19] Constantino Pérez-Vega and José M. Zamanillo, “Path-Loss Model for Broadcasting Applications and Outdoor Communications Systems in the VHF and UHF Bands”, IEEE Transactions on Broadcasting, Vol.48, no.2, June 2002, pp.91-96.

[20] ETSI TR 102 683: “Reconfigurable Radio Systems (RRS); Cognitive Pilot Channel (CPC)”, 2009.

[21] V. Gupta, et al, "IEEE 802.21 Media Independent Handover: Tutorial," Jul 2006, 65pp., http://www.ieee802.org/802_tutorials/july06/802%2021-IEEETutorial.ppt
[22] M. Weiss, S. Delaere, W. Lehr, "Sensing as a Service: An Exploration into Practical Implementations of DSA," IEEE Symposium on Dynamic Spectrum Access Networks, Singapore, April 2010.