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

FARAMIR

Document Number D4.1

Radio Environmental Maps: Information Models and Reference Model

Contractual date of delivery to the CEC:	30.04.2011
Actual date of delivery to the CEC:	30.04.2011
Project Number and Acronym:	248351 - FARAMIR
Editor:	Ioannis Dagres, Andreas Polydoros (IASA)
Authors:	Ioannis Dagres, Andreas Polydoros (IASA), Janne Riihijärvi, Jad Nasreddine, Petri Mähönen, (RWTH), Liljana Gavrilovska, Vladimir Atanasovski (UKIM), Jaap van de Beek (HWSE), Berna Sayrac, Sebastien Grimoud (FT), Miguel Lopez Benitez, Jordi Perez Romero, Ramon Agusti, Fernando Casadevall (UPC)
Participants:	RWTH, UPC, HWSE, IASA, UKIM, FT
Workpackage:	WP4
Security:	PU
Nature:	R
Version:	1.0
Total number of pages:	73

Abstract:

We describe herein the envisioned improvements of the REMs due to advanced sensing and processing. In relation to that, we also discuss the underlying modelling assumptions. Finally, we comment on how REMs can be of use in different scenarios as established in WP2.

Keywords: Cognitive Radio, Cognitive networks, Radio Environment Maps, Spectrum Sensing, Spectrum Sharing, Spectrum Measurements.

Document Revision History

Version	*Date*	*Author*	*Summary of main changes*
0.1	9/2/2011	IASA	Opened the document; written the introduction and TOC
0.2	11/3/2011	IASA	Second version of TOC including modifications decided on the Barcelona meeting
0.3	22/3/2011	FT	First contribution for Section 6.1
0.4	23/3/2011	HWSE	First contribution for Section 6.2
0.5	23/3/2011	UKIM	First contribution for Chapter 5
0.6	24/3/2011	RWTH	First contribution to Chapter 2
0.7	24/3/2011	UPC	First contribution to Section 6.3
0.8	25/3/2011	FT	Additional contribution to Section 6.1
0.9	8/4/2011	IASA	Inclusion of latest contribution, editing and contribution to Chapters 2,3,4
0.95	14/4/2011	UPC	Updated contribution for Section 6.3
0.97	15/4/2011	HWSE	Enhanced contribution for Section 6.2
	18/4/2011	UKIM	Updated contribution for Chapter 5
	21/4/2011	IASA	Inclusion of latest contribution.
	22/4/2011	FT	Updated contribution for Section 6.1
	26/4/2011	RWTH	Contribution to Section 4.3
	26/4/2011	UKIM	Additional contribution to Chapter 5
	27/4/2011	UPC	Updated contribution for Section 6.3
	29/4/2011	IASA	Re-editing, additions and new structure for the material
1.0	30/4/2011	IASA and RWTH	Final editing and integration
1.0f	30/4/2011	Petri Mähönen	Final coordinator review and approval

Table of Contents

1 Introduction

Radio Environmental Maps (REMs) constitute a major building block in FARAMIR's goal of providing practical means for cognitive-radio realization in a large number of applications, as detailed in previous deliverables. They are meant to be easily accessible, fluently updateable, rich information repositories often implemented through database techniques, which are endowed with all the necessary interfaces and tools for information provision to the cognitive radios (CRs) that seek their help. Key issues to be tackled are how exactly to design them, what information they should contain and in what form, how such information is to be arranged, indexed and interpreted, how to receive and process various requests by end-users and how to respond in informative yet bandwidth-economic fashion (a process that usually will require the active solicitation of radio-sensing elements). All these aspects must be examined synergistically and answers must be produced in ways that are, on the one hand, tailored to the specific application under consideration, yet, on the other hand, possess enough generality to qualify as a valid scientific framework in the emerging CR field. The end goal for such a construct is clear: it must serve as an able "navigator" of CR's on their "way" to some specific, well-defined action or mission. The REM will have achieved its goal *if it can enable CR's become situation-aware and action-ready by a simple consultation with it.*

As of necessity, such a design must be comprised of multiple heterogeneous, multi-domain information fields such as geographical features, available services, spectral regulations, locations and activities of radio devices, relevant policies, past experience, learning rules, updating mechanisms, sensing abilities, the physics of propagation and interference, and so on. To narrow the scope to a meaningful size, the FARAMIR project has chosen to focus on the most challenging part of the design of REM's, namely the dynamic aspect of information gathering and processing, achieved mainly via the deployment and active exploitation of various types of spectrum-assessing (measuring and processing) devices. Why this would be a most useful idea in the context of overall (multi-system, intra- and inter-) radio-resource management and related optimization has already been amply documented for multiple different scenarios in deliverable D2.2 [1]. In the present deliverable the focus is different: it is on proper models describing information data as would be needed for each envisioned scenario of interest, presented however as special cases of a broad, generic information-representation-and-flow model. Such an information model is needed to enable organization and categorization of the information stored in REMs, and in order to meaningfully discuss issues such as representation of the data. In close association with these models, specific Application-Programming Interfaces (API's) are also described in detail in order to pave the way towards pragmatic implementation of such models. Furthermore, since any potential implementation will relate to some specific scenario of interest, we delineate a number of typical scenarios and demonstrate a systematic mapping of the broad architecture and information process to each such case, identifying all the related components that comprise it. In each such case, a thorough description of the information data modeling, gathering, exchanging and processing is detailed in a way that is hopefully validating the proposed general framework. Also due to this approach our focus is on information that is especially relevant for decision making and optimization from the RRM/CRM points of view, including policy framework applications, but in principle the techniques developed can be extended towards more general contextual information as well, although such extensions are beyond the scope of the project.

It should be emphasized that this deliverable basically outlines the architectural framework that must always be present, at least in a conceptual sense. Individual cases may call for a more consolidated version of the whole construct, or distributed instantiations of the database, they may demand more or less resources for the individual parts (in particular, the many information flows encountered), or even prove very challenging in actual implementation and in real-time requirements. The present deliverable only marginally addresses the quantitative dimensions of the design with a special emphasis, as mentioned, on the dynamic dimension. There is, however, a main, well-grounded reason for that omission: namely that only after the specific algorithms and protocols for sensing, relaying, updating and responding have been concluded and evaluated can such architectural quantifications take place. This will occur in subsequent deliverables in this WP4, which will then "close the loop" back to the REM architecture and allow for a holistic appraisal for any such system at hand. It is also our intention to treat the present deliverable as a living document that will be updated and made more detailed as the project progresses in the design of the final REM data model. As such, snapshots of the evolving design will be used both in implementation work, as well as part of the final architecture documentation.

The document is structured as follows. Chapter 2 provides a brief description of the FARAMIR architecture for constructing the REM, highlighting the different architectural elements and the type of the information exchange between them. A REM data model categorization is then presented that illustrates most of the different types of radio environmental data that should appear in a complete REM database. The specific REM subtype that interest FARAMIR, called Dynamic REM is introduced in Chapter 3. In Chapter 4 we present generic data model options for building a DREM, starting with the sensing data modeling, the Radio Interference Field Estimation (RIFE), and the radio element parameter modeling. Chapter 5 focuses on the specific application of REM-based policy derivation, viewed and interpreted as a specific DREM instantiation. This should help connect the previously-introduced concepts with a fairly familiar application, thereby clarifying the role of the various information elements. In Chapter 6, REM instantiations for various scenarios of interest are presented, where specific formulations of the generic models (covered in earlier sections) are given. Finally, we draw conclusions and outline future work in Chapter 7.

2 FARAMIR architecture and generic REM data model

In this chapter we discuss briefly the FARAMIR architecture for the construction, update and use of REMs. It was introduced in [2] and further analyzed in [3]. The distinct roles of the architectural elements and the needed information exchange will provide to the reader a full picture of the REM operational information flow. Continuing, we provide a categorization of the information content that could be present in a generic REM database, highlighting those elements most important for DREM construction.

2.1 FARAMIR REM architecture and information flow

The broad concept of how a REM is created relies on the systematic exchange of different types of data between the different architectural elements. This is depicted in Figure 1 below, which shows all the individual elements of information flow for the type of REM that has been adopted in the FARAMIR architecture. This Figure has been defined in detail in the previous deliverables [2], [3]. It is a very general diagram that encompasses other, simpler forms of information flow, but it is adopted here as the broadest framework possible:

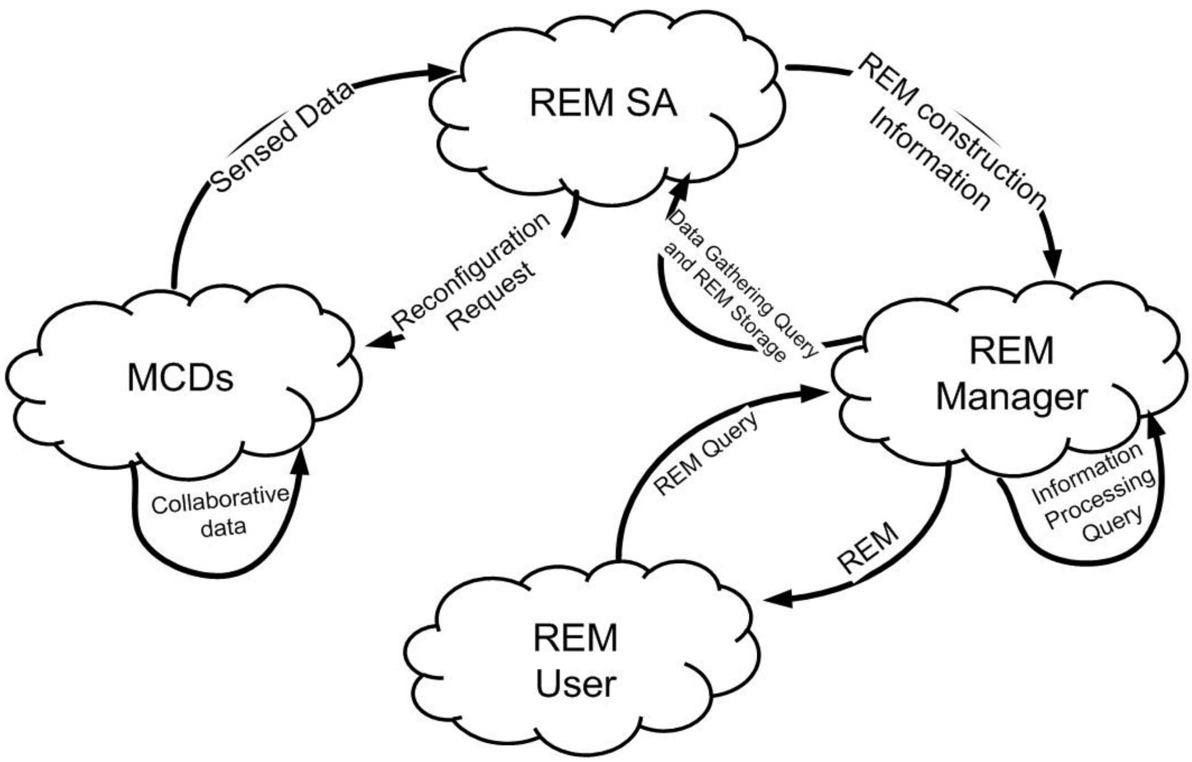


Figure 1: REM operational information-flow diagram.

We now delineate in more detail the various elements shown in Figure 1:

(a) The **Collaborative data** denotes what is exchanged between the various Measurement Capable Devices (MCDs) or subsets thereof. In general, this type of data can carry sensing information, interpolated/fused information, as well as any type of collaborative control information which enables the collaboration between the MCDs. The amount of the exchanged data and its frequency of the exchange depend chiefly on the type of collaboration technique adopted as well as the number of collaborative MCDs. A parameter of interest for collaborative data is the *control channel latency*, i.e. the resulting delay (until the collaborative data is fully exchanged between the MCDs) as a result of (possibly) limited bandwidth for the control channel. A large control channel latency can result in decreased efficiency for the collaborative approach. Therefore, mitigating this effect is crucial for acceptable performance.

(b) The information exchange between the **REM data Storage and Acquisition unit (**REM SA) and the MCDs is defined via the *MCD-REM_SA* interface and two information flows: **Sensed Data** and **Reconfiguration Request**. The **Sensed Data** carries the information acquired by the MCDs and it is stored in the REM SA. The amount of data exchanged mainly depends on the number of MCDs: larger number of MCDs will result in larger amount of **Sensed Data** that passes through the MCD-REM_SA. Also, different MCDs can transmit different types of **Sensed Data** with different frequency**,** in accordance with their configuration and assigned tasks. The **Reconfiguration Request** flow carries information concerning the tasks and configuration of the individual MCD. The frequency of the flow in general depends on both the scenario as well as on what the REM Manager and REM User require at a given moment. For example, a scenario incorporating mobile MCDs will imply that the **Reconfiguration Request** will be more frequent than a scenario incorporating static MCDs, because of the higher dynamics involved in the mobile case.

(c) The **Reconfiguration Request** flow is directly triggered by the **Data Gathering Query and REM storage** from the REM Manager. The **Data Gathering Query** and **REM storage** are used to inform the REM SA about the information required by the REM Manager in order to perform the REM creation and to store this newly constructed REM. The flow containing the information for the REM Manager is the **REM construction Information.** The **REM construction Information** flow carries larger amounts of data and, as a result, it is used more frequently than the **Data Gathering Query and REM storage**. Both the **REM construction Information** and the **Data Gathering Query and REM Storage** are exchanged throughout the *REM SA - REM Manager* interface.

(d) The **Information Processing Query** is an internal flow within the REM Manager and is employed between the different processing modules residing within the REM Manager; for instance, between a module that constructs the REM and a module responsible for localization of the transmitters. The **REM** flow is defined via the REM Manager – REM User interface. It transfers the newly constructed (or dynamically updated) REM to the REM User from the REM Manager. The amount of data in this flow depends on the size of the REM, while the frequency of the data flow depends on the type of the REM User and the scenario.

(e) The **REM Query** information flow is used by the REM User to inform the REM Manager about the features and characteristics of the REM which are required by the User for its desired jobs.

In summary, Table 1 shows the main characteristics of the different types of information flow previously discussed.

Table 1: Information flow characteristics.

Information flow parameters	Collaborative data	Reconfiguration Request	Sensed Data	Data Gathering Query and REM storage	REM construction Information	Information Processing Query	REM	REM Query
Data amount	MCD and Collaborative scheme dependent	Scenario dependent	MCD and scenario dependent	Scenario dependent	High	Very High	Scenario dependent	Scenario dependent
Frequency	MCD and Collaborative scheme dependent	Scenario dependent	Scenario dependent	Scenario and REM Manager dependent	High	Very High	Scenario dependent	Scenario dependent
Type of flow	Data and control	Control	Data	Control and Data	Data	Data	Data	Control

2.2 REM data model classification

The total information content of the REM can be classified within three categories, all of which pertain to a specific "quantum" in the space-time continuum. The first category contains the information related to the radio devices, the second category contains all information that describes the radio scene and the third is related to the radio-environment characteristics. A brief description of the type of the information content within each category is given, highlighting the information relevant to DREM (depicted in red in Figure 2).

2.2.1 Radio elements

This category contains all the information related to all devices that are capable of emitting and/or receiving radio signals in the band of interest. Under this broad definition a broad range of devices can be included, from large base-stations to small cell phones, and from a cognitive radio to a non-cognitive microwave oven.

A subcategory present in all elements is the *Tx/Rx operation*. It contains information that describes the generated Tx radio wave and/or the Rx operational characteristics of each element. In addition to typical information about the instantaneous power profile of the transmitted signal, it could also contain statistical information about the past and (predicted) future behavior, acquired through proper knowledge representation and inference models.

The Location and Mobility subcategory contains all types of information related to the current location and mobility of each radio element in the area of interest. Statistical models that characterize the expected behavior for an area or a specific type of radio elements could also be employed. Transceiver capabilities include all the information related to the Tx/Rx operational characteristics. It is mostly static information in nature, derived from the radio type. Another similar type of static information is the sensing capability available in a device. The latter applies only to MCDs and includes all the information related to the supporting sensing functionalities, the needed parameterization and the expected performance. Note that, in many cases, the communication transceiver and the MCD may be physically co-located in a single device, but this is not always the case.

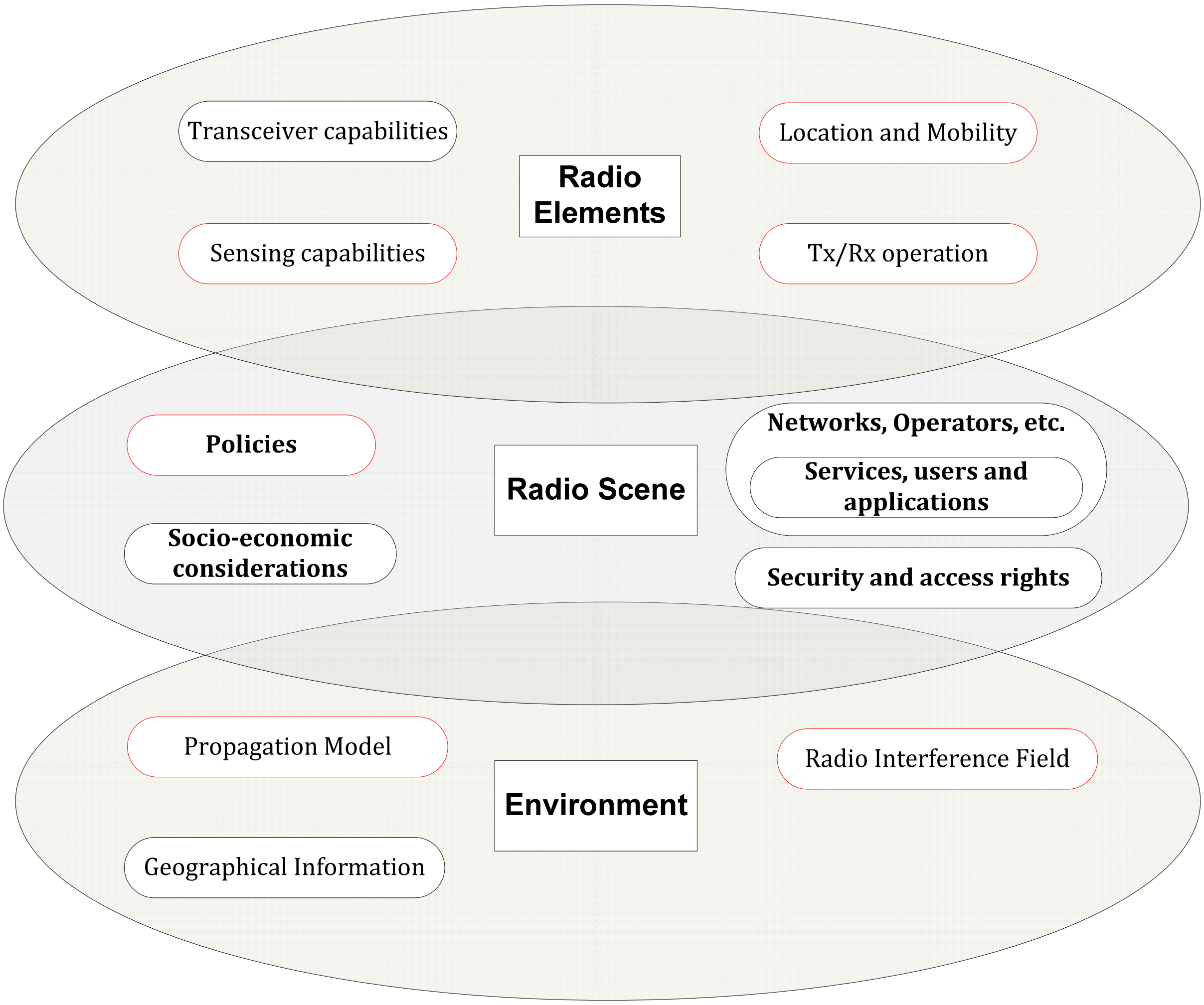


Figure 2: REM information classification.

2.2.2 Radio scene

This category pertains to all the information that describes the typical or expected or allowed behavior of the radio elements in a specific area. This includes both static information related to specific networks and operators, as well as dynamic information that is provided usually in the form of derived policies that reflect the detected spectrum opportunities. Policy derivation and management is actually one of the most important applications of REMs and thus constitutes one of the most important REM-usage generic scenarios within FARAMIR. Socio-economic information could also exist in various forms for the purposes of recourse optimization.

2.2.3 Radio environment

This category contains all the information about the interference field existing in a specific area plus all the related information. By the term "related information" we mean the propagation characteristics in an area. This includes the propagation models along with geographical information that may enhance the propagation model parameterization. This information is used in one of the most important features of the REM, namely the *radio interference field estimation*. These models can either be chosen once, based on previous measurement campaigns or the specific characteristics of the area of interest, or can be dynamically adjusted through proper learning mechanisms that utilize fresher measurements.

3 Dynamic Radio Environmental Maps

Here we delve further into a specific sub-type of REM, as defined in [4], namely the Dynamic Radio Environment Map (DREM). This concept has all the features of the common REM described previously, but also dynamically tracks the changes of spectrum occupancy in **real time**. The design of the DREM relies on the following related processes:

- Data gathering
- Data representation
- Data processing/fusion

*The DREM will not only be able to provide information about the radio elements, but also mainly produce estimates of the RF field based on previous knowledge and/or hypothesized scenarios***.** This is the basic functionality that enables a large number of DREM-based applications. Many optimization scenarios can be envisioned, all of which have the DREM model as the main building block.

Clearly, it is important to create a DREM model which stands as a compromise between storage-processing complexity and performance accuracy. The level of this accuracy requirement is a function of specific applications. The general goal should be to propose and represent models that require the minimum amount of information in order to meet certain QoS goals.

We now provide a theoretical model for all those elements that characterize the dynamic aspect of a REM. The goal is to build a system that not only monitors but also accurately models the *physical radio environment* concerning the RF energy propagation between any two points in the multi-dimensional space-time-frequency-angle domain. Based on this model, the sensing data representations are introduced. The information-exchange loop between the DREM, the sensing architecture and the specific application at hand is termed a "reference information description model".

3.1 A model of physical radio environment

A model for the physical radio environment could be described by the following collective information:

a) The position vector and the effective radiated power level of all radio elements $\mathbf{r}^i(t)$, $p^i(t, f, \varphi)$,where *i* is the radio index, t is the *time t, f* the *frequency* and *φ* the *angle* of the plane wave.

b) The total RF propagation loss of radiated power traveling between two points in *space-time-frequency-angle* is $G(t_s, f_s, \varphi_s, \mathbf{r}_s, t_e, f_e, \varphi_e, \mathbf{r}_e)$.

Given this information, one can compute the average power received by a given point in *space-time-frequency-angle* as

$$p_{\mathbf{x}}(t,f,\varphi)=\sum_i \int_{t^i}\int_{f^i}\int_{\varphi^i} G(t^i,f^i,\varphi^i,\mathbf{r}^i(t^i),t,f,\varphi,\mathbf{r}_x)\,p^i(t^i,f^i,\varphi^i)dt_i df_i d\varphi_i \tag{1}$$

A block diagram of (1) is given in Figure 3. Information on the phase of the Tx signals is not incorporated in this model. Only the energy is described. We should note that even this very rich and rather impractical (from a complexity standpoint) model implies simplifications. For example, the phase information of the signals is omitted since we are interested only in the RF strength.

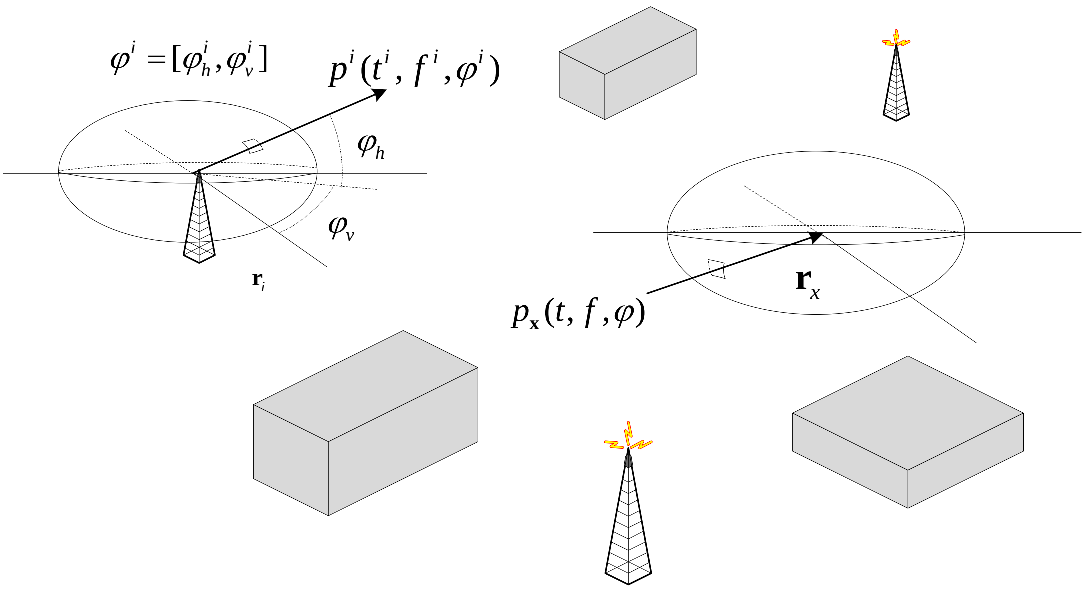


Figure 3: Block diagram of RF propagation model.

The time parameter is assumed to run across the whole real axis. This is actually the most important feature of a REM, since it is mostly going to be used in *predicting* the interference level at a given point in the space-frequency-time-angle domain, or providing radio-related information for some future use. There are, however, significant issues to be resolved here: For instance, how can a REM know in advance the transmission plans and positions of all radios, including those that are going to use the REM to decide whether to transmit or not in the first place? In other words, although ideally perfect information about the propagation characteristics can "in theory" be assumed known, we realize that that the position and transmission plans ("p&t" plans) of all relevant radios must also be known in advance or somehow be predicted, if the temporal evolution of the radio field is to be estimated accurately. Clearly, there are some hefty assumptions that need to be engaged in the construction of the REM.

This line of thought purports to show the desired role of a REM, whose mission is to provide radio awareness to anyone wishing to plan his future radio-communication actions. In drawing an analogy with a normal map, the propagation model is akin to the geographical information whereas the radio elements resemble the traffic information. In practice, the real p&t's are not known, so a REM can only provide estimates and predictions, just like a normal map endowed with traffic predictions (not measurements, *predictions*). In addition, the exact propagation model is very hard to obtain, so that statistically approximate models can only be used. This is similar to a regular map that visually provides multiple probable paths connecting two points in space.

3.2 DREM information exchange

As already argued, $p^i(t, f, \varphi)$ and $\mathbf{r}^i(t)$ cannot be assumed perfectly known, even theoretically, in order for the REM to have a purpose. Thus, by relaxing the modeling and knowledge assumptions it is clear that only *statistical knowledge* can be assumed for the RF environment and the related parameters. Not only as a result of the needed simplification steps for reducing the model complexity but also because only statistical knowledge can be reasonably assumed for most of the parameters of the RF propagation model. The exact model choice for representing the random field in the REM is a very crucial decision that greatly affects the chances of success for the overall concept. A first division for modeling this information can be made by distinguishing between a) the propagation model, and b) the radio-elements information.

In order to obtain a clear picture of the information exchange between the different elements we will describe a simple setup. For simplicity, we reduce the parametric space of the complete model by using the following approximations: 1) address one frequency only; 2) no delay spread; 3) no Doppler spread; 4) omni-directional antennas; and 5) the propagation characteristics are time-invariant. Then,

$$G(t_s, f_s, \varphi_s, \mathbf{r}_s, t_e, f_e, \varphi_e, \mathbf{r}_e) \approx G(\mathbf{r}_s, \mathbf{r}_e) \tag{2}$$

and

$$p^i(t, f, \varphi) \approx p^i(t) \tag{3}$$

Let t_D be the feedback delay of one sensing-learning cycle. Let also $\hat{p}^i(t), \hat{\mathbf{r}}^i(t)$ represent the new estimates and $P\left(G(\mathbf{r}_s, \mathbf{r}_e), t - t_D\right), P\left(\mathbf{r}^i(t), t - t_D\right)$, $P\left(p^i(t), t - t_D\right)$ the prior knowledge (prior distributions in this example), already stored in the REM SA. Then, the data exchange could be described as follows:

1) The flow starts with a specific Query from the REM Manager to the REM SA.
2) Based on the Query and the prior knowledge, a Reconfiguration Request is given to the MCDs.
3) The new estimates are generated (Sensed Data, $\hat{p}^i(t), \hat{\mathbf{r}}^i(t)$) and send back to the REM SA.

4) The prior knowledge together with the new estimates are sent from the REM SA to the REM Manager.

5) The newly created knowledge, $P\left(p^i(t)\right), P\left(\mathbf{r}^i(t)\right), P\left(G(\mathbf{r}_s, \mathbf{r}_e), t\right)$, is send back to the REM SA for storage.

The block diagram related to the needed information exchange and model representation is shown in Figure 4. This diagram is based on the FARAMIR architecture and displays a simple but indicative example.

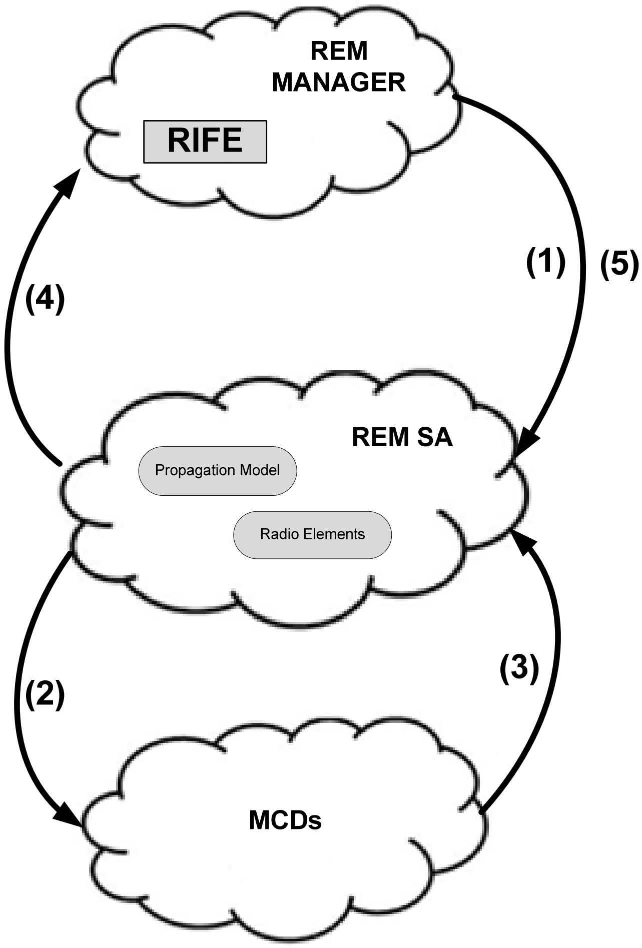


Figure 4: Information exchange and model representation.

An application query example from a CR could be the following: "what is the minimum transmitting power that will not cause harmful interference to a PU?" This query requires not only the knowledge of the positions of the PUs but also the propagation model between the CR and the PUs. Given an interference outage probability, the minimum CR Tx-power could be computed based on the described modeling of DREM.

4 DREM information modeling

Key issue regarding the formation of DREM is the establishment of a suitable information or data model. Such model should specify which kinds of information are stored within the REM in relation to each of the categories discussed in Figure 2, and how that information is represented. For example, location information can be stored and represented either as explicit coordinates of the radio elements, or summarized into statistical information. The latter approach often results in loss of precision, but can yield significant savings in terms of overhead of the information exchanged. We discuss in this chapter such modeling choices for selected information types in the DREM context, and revisit these choices in the context of the different scenarios in Chapter 6.

4.1 Sensing data information modeling

The list of all possible estimated parameters is already described in [3], and contains in particular the following elements.

- *Time of Arrival*: This is the Time of Arrival (ToA) of a known or unknown (Blind ToA estimation) Rx signal. Known signals are usually pilot signals, pre-specified for a specific communication system. Information about the key parameters of a known signal (for which the ToA is to be estimated) is assumed to be provided by the "SA to MCD" data exchange. For blind estimation, the classified (sorted) Tx signal parameters are also sent to the Fusion center.

- *Angle of Arrival*: This is the Angle of Arrival (AoA) of a known or unknown (Blind AOA estimation) Rx signal. The same assumptions hold as in ToA estimation.

- *Power*: The total power reception of a known or unknown signal. The measurement bandwidth can be narrowband (in order to sense a small number of transmitters) or wideband (for sensing a potentially large number of transmitters). The time horizon of the measurements is also a pertinent parameter.

- *Radio-emitter position*: Combining some of the above parameters, position estimates can be directly derived and provided to the SA from the MCDs. The positions can be represented by specific geographical regions or grid points from a pre-specified list or just points in space. All three forms of representation can be of statistical nature.

- *Signal modulation/features*: The modulation characteristics or other features of the detected signal.

The statistical description of the estimated data is straightforward (at least in principle) as they can be derived based on the estimation method used. General Cramer-Rao Bounds for the estimation accuracy of position localization based on various estimated parameters, such as Tx-power, TDOA, AOA, can be found in [5]. These bounds can be used as proxies to assess the accuracy of the estimated values

At the next two paragraphs, the usage and modeling of this information is presented.

4.2 Radio Interference Field Estimation

Also known as Interference Cartography, radio interference field estimation (RIFE) accounts for Power Spectral Density (PSD) of RF environment as a function of spatial coordinates in a pre-defined area and, possibly, time (for a dynamic environment). Methods for RIFE can be divided into the following two categories:

- **Direct methods**: Estimating the PSD directly from the observations w/o source estimation.
- **Indirect Methods**: Explicitly accounting for potential RF sources, estimating their relevant parameters, and then extrapolating in the spatial dimension.

At the following two sections we analyze the relevant modeling assumptions followed for the two methods.

4.2.1 Direct field estimation

One modeling approach that is able to build knowledge related to the radio elements (transceivers) behavior is the ***spatial statistics*** modeling approach. The method can be of importance when the process of building the radio transceivers knowledge actually is the REM creation.

4.2.1.1 Spatial statistics

Spatial statistics is an approach that examines and uses the topological, geometrical or geographical properties of a given area (entity). The fusion of the data from the examined area (entity) is commonly based on different types of *interpolation methods (techniques)*. Possible interpolation techniques that are of interest within the FARAMIR architecture for the REM Manager are:

- *Kriging* – the approach uses variograms for estimation of the propagation model and distance based weighted coefficients, between the measurement and interpolation points for calculation of the interpolated data.
- *Gradient plus Inverse Distance Squared interpolation (GIDS)* – uses multiple linear regression and inverse distance based weighted coefficients for the interpolation process.
- *Inverse Distance Weighted (IDW)* – utilizes the inverse distance based weighted coefficients, but also defines so called neighboring influence that can reflect the nature of the propagation model.

Table 2 compares their characteristics in terms of information modeling.

Table 2: Interpolation techniques comparison.

Information parameters	**Parameter definition**	**Kriging**	**GIDS**	**IDW**
Number of measurement points	This parameter relates to the amount of data fed to the interpolation technique for its normal operation. The number of MCDs can be correlated to the amount of data exchanged, i.e. high amount of data → large number of MCDs, small amount of data → small number of MCDs. The number of MCDs can have an impact on the utilization and capacity of the control channel. High amount of data needs a larger channel capacity and efficient MAC scheme for better channel utilization.	High	Medium	Low
Update frequency	The update frequency defines the interval of transition of the sensed information. High or real time update frequency results in higher utilization of the control channel.	Real time	Real time	Real time
Interpolation data	This represents the type of the sensed information from the MCDs, e.g. RSSI, SINR, SIR etc.	All data types	All data types	All data types
Previous channel knowledge	Previous channel knowledge, i.e. modeling before the interpolation, can be valuable for achieving more precise results, but requires higher processing power and increases the interpolation time.	Yes	No	No
Interpolation method	The type of interpolation used.	Variogram /Distance based	Weighted coefficient/ Distance based	Multiple linear regression/Distance based

Data position type	Type of positioning of the MCD: gridded or scattered.	Scattered /Gridded	Scattered /Gridded	Scattered /Gridded
Density of the measurement points	The density of the MCDs (in terms of number of nodes per unit area) for a given interpolated area needed for optimal operation of the interpolation technique.	Large	Small-Large	Small-Medium
Processing requirements	Processing requirements in terms of processing power.	High	Low	Low
Fidelity/Precision	The fidelity of the interpolated data compared to the real data.	High	Medium	Medium to Low

4.2.1.1.1 Resource engagement analysis

The kriging interpolation method requires a substantial amount of measurement points (in terms of the grid dimensions) for proper operation. As a result, the method allows a high fidelity environment reconstruction. For instance, in a 10 x 10 grid kriging would roughly yield more than 20 measurement points to interpolate the entire grid.

Unlike kriging, GIDS and IDW require lower amount of measurement points to perform the interpolation of the gird. For example, in a 10 x 10 grid, these two methods can operate with as low as 3 or 4 measurement points. This feature enables the usage of GIDS and IDW in sparse measurement environments. On the other hand, the GIDS and/or IDW interpolated grids lack on fidelity.

It can be generally concluded that kriging requires high number of measurement points and always performs with high precision, whereas GIDS and IDW can perform the interpolation with lower number of measurement points resulting in degradation of the fidelity of the interpolated grid. In terms of the required processing power, kriging is the most demanding spatial statistics method resulting in longest processing periods for the interpolation. GIDS requires modest processing power and has modest performance in terms of the processing period and precision, while IDW is low processing based method and has the ability to perform the interpolation fastest sacrificing the interpolated grid's precision.

4.2.2 Indirect Field Estimation

While techniques for radio interference field estimation and approaches used for interference cartography can be used also without reference to transmitter locations, there are various use cases in which use of location information becomes useful. In a number of scenarios high quality location information is readily available to the party constructing REMs, and thus can be used to enhance the accuracy of other inference procedures that directly or indirectly depend on locations of transmitters. Often this requires in addition estimation of the relevant *propagation model*, usually understood as decomposition of path loss into distance dependent component and a residual often treated as a random field itself. Transmitter locations, the radio interference field, and propagation model are all tightly coupled, and selection of which one to infer or estimate and which one to treat as known or separately estimated depends on the application scenario at hand. Nevertheless, each of these has a clear place in the overall FARAMIR data model. At the next paragraph, an introduction about the propagation modelling options, a very crucial choice for the successful adoption of indirect techniques for RIFE.

Modeling the wireless channel is a topic under investigation from the very beginning of wireless communication systems. It involves the understanding of the underlying physical laws of electro-magnetic wave propagation and the adoption of proper mathematical models to describe it. As pointed in Section 3.1, having such a model is a very tedious task, often leading to the adoption of various approximations. In the case of building REMs, only the large and medium scale effects are considered as a reasonable choice due to complexity limitations.

Propagation models for the large-scale effects, calculate the mean signal reception strength for an arbitrary transmitter-receiver (Tx-Rx) separation distance, and are useful in estimating the radio coverage (or interference) area of a transmitter. They characterize the signal strength over large Tx-Rx separation distances (several hundreds or thousands of meters). Again, the adoption of the most appropriate model for the large scale effects has to do with a large number of parameters that characterize the area and the system of interest.

A first important categorization is (a) the case where a strong direct signal is available together with a number of weaker multipath echoes, i.e., line-of-sight (LOS) conditions; and (b) the case where a number of weak multipath echoes are received and no direct signal is available, non line-of-sight (NLOS) conditions.

The typical model used for calculating the path loss between two points is [6]:

$$L(\mathrm{dB}) = A + 10n\log(d\mathrm{km}),$$

where A and n are dependent on the frequency and a number of other factors as listed below. Parameter A is the loss at a reference distance, in this case, 1 km, and n is the propagation decay law (or path loss exponent). Several factors, apart from the distance that influence path loss, are taken into consideration by existing propagation models affecting the expressions for A and n. These factors are:

- the height of the Rx antenna and the height of the Tx relative to the surrounding terrain (effective height);
- the terrain irregularity (sometimes called *undulation*, or *roughness*);
- the land usage in the surroundings of Rx: urban, suburban, rural, open, etc.
- the Tx/Rx antenna gains
- the system loss factor (not related to propagation)
- the wavelength of the signal under consideration

Some examples of the typical values (see [6]) of the path loss exponent are given on Table 3.

Table 3: Path Loss Exponent in various environments.

Environment	**Path Loss Exponent**
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-site	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

When calculating the path loss, all such factors must be taken into account. This path loss is used to calculate the mean energy reception, measured over a large number of Tx-Rx points having distance *d* inside the area of interest. The actual energy reception varies between different points with the same distance due to the existence of different obstacles between them. A model that tries to captures this distance depended variations includes the shadowing factor (medium-scale effect). A random parameter, used to model the uncertainty of the energy reception around the mean for a given distance. Including now the shadowing factor, the received power in logarithmic units can be represented by the expression:

$$P(d) = P_{1km} - 10n\log(d\mathrm{km}) + s(0, \sigma_s^2)$$

where $P(d)$ is a random variable, representing again the received power at distance *d* km, P_{1km} is the received power at 1 km, and *s* is a Gaussian random variable with zero mean and standard deviation σ_s. This standard deviation, also called the location variability, tries to capture the terrain irregularities or the type of the land usage (urban, suburban, rural, etc.). It should be noted here that P_{1km} is used for the macrocell scenario, while smaller distances are used for indoor, urban microcell, etc. Some typical values are given in Table 4 based on [7].

Table 4: Standard deviation of Shadow Fading.

Environment	**Std Value**
Urban macrocell	8 dB
Suburban macrocell	8 dB
Urban microcell	NLOS: 4 dB, LOS 3 dB
Indoor Small Office	NLOS (Room to Corridor) 4 dB, NLOS (through-wall) 6 dB (light wall), 8 dB (heavy-wall)
Indoor Hot Spot	LOS 1.5 dB, NLOS 1.1 dB
Outdoor to indoor	7 dB
Open Rural Macrocell	NLOS: 8 dB, LOS: 6 dB

There exist a large number of prediction models that differ on the complexity requirements and their applicability over different terrain and environmental conditions. Some, like the ones presented here, purport to have general applicability, others are restricted to more specific situations. What is certain is that no one model stands out as being ideally suited to all environments, so careful choice is required based on the characteristics of the target scenario for building a successful DREM.

4.3 Radio element parameter modeling

This pertains to the information models that build up knowledge related to the transmission, movement or placement of radio elements, based on current and past parameter estimates. Spatial statistics will be one of the evaluated modeling approaches, since they combine the nice properties of being descriptive, concise, and generic.

4.3.1 Transmitter activity patterns

Activity patterns of a given access technology can be a very useful information for some RRM techniques. For instance a secondary network can choose between different available channels at a given model based on the probability that this channel will be available after a given period. This probability cannot be estimated unless some information, such as the distribution of the ON/OFF periods, about the activity pattern is known.

Based on the application, the activity pattern can be associated to transmitted signal or to the output of a receiver, i.e., aggregated signal. The first one is normally used when the interference probability is to be estimated at a node receiving a signal with given activity pattern; Based on the received power from the interferer and the period of time that this power interfere with the useful signal that follows a given activity pattern the interference probability can be estimated. The second type of activity pattern, which is associated to the output of a receiver, is normally used by the nodes that want to detect the presence of transmitters in a given channel based on received power. The activity pattern in this case is an aggregated activity pattern from different transmitters. In the REM database *transmitted signal and receiver output related activity patterns should be stored in two separate entries but will have the same format*.

Based also on the application, the activity pattern can be represented in different ways reflecting the application requirement related to precision and access time. The following representation are the most common and important ones: Duty cycle, means of the ON/OFF periods, ON/OFF parametric distribution, ON/OFF non-deterministic distribution, and information on time allocation. The REM data model developed enables all these representations, and the user can select between them based on application requirements.

In the following we discuss in more detail the different representations of ON/OFF activity patterns.

4.3.1.1 Duty cycle

The *Duty Cycle* (DC) of a channel (i.e., transmitter transmission or output of a receiver) is defined as the time a channel is occupied as a fraction of the total time considered. This type of representation is suitable, for instance, in dynamic spectrum access to choose the best channel for transmission. The DC can be stored in one byte of memory representing 256 levels, or as a floating point number between zero and one.

4.3.1.2 Means of the ON/OFF periods

The means of the ON and OFF periods give more precise representation of the activity pattern with the price of increasing the needed memory. This type of representation is important since, for the same activity pattern, we can have very long ON/OFF periods or very short ones. This is very important to decide for instance if sensing-based opportunistic access is feasible or not in a given channel; if the average OFF periods are much shorter than the sensing time in a given channel, opportunistic access will not be possible. Then main problem of representing such data is the long range in which it varies, which can go from few milliseconds to minutes. Therefore, one way to represent this data is specify the unit used especially that high granularity (i.e., milliseconds) is not required when the mean is in the order of seconds or minutes. Therefore, 4 bytes (2 bytes for the ON period and 2 other for the OFF period) will be used to store this type of data where the first bit represents the unit (seconds or milliseconds) and therefore 32 milliseconds can be represented with a granularity of 1 milliseconds, whereas more than one hour can be represented with a granularity of 1 second.

4.3.1.3 Parametric ON/OFF period distributions

This is more precise representation of the traffic pattern especially used if the tail of the distribution is need for instance to estimate the probability of interference. This type of representation is especially useful for characterising transmissions when the traffic pattern can be represented with well known distribution such as Normal, Weibull or Poisson. All these distributions have one or two parameters. Therefore we need at least 10 bytes to represent this type of data (5 bytes for the ON period and 5 other for the OFF period) as shown in Table 5.

Table 5: Required memory for ON/OFF parametric distributions.

Number of bytes	**Stored information**
Byte 1	A constant representing the distribution (e.g., Normal, Weibull, Poisson)
Byte 2-3	First bit for the selection of time scale and the other 15 bits to represent the first parameter
Byte 3-4	First bit for the selection of time scale and the other 15 bits to represent the second parameter

4.3.1.4 ON/OFF non-parametric distribution estimates

This type of representation is used when the parametric distribution cannot be found. In this case, a set of values is given with a probability of occurrence. This gives more accurate representation of the data especially if the parametric one is assessed using the best fit for a set of measured data. However non-parametric representation requires more memory to store it and cannot be used if analytical models are needed by the application. Several methods can be used for non-parametric distribution. The most important ones are histogram distribution and kernel density estimation. Other models can be used also such as non-parametric regression and semi-parametric regression as well as data envelopment analysis.

To represent the traffic pattern using *histogram model* we need *N* bytes to represent the set of values where the first bit of each byte represents the used unit and the seven other bits represent 100 levels, where *N* is the number of represented values. Similarly, *N* bytes are used to store the probabilities of the occurrence of each value should be stored. The required memory will depend on the fact if information coding is used or not.

Kernel density estimation gives better representation of the traffic pattern and can require less memory since the number of values to store can be reduced since this method give more smooth representation of the real distribution. The same data mode as in the histogram model is used in addition to two bytes representing the type of kernel function (i.e., a string that can be uniform, triangular, biweight, triweight, Epanechnikov, normal, etc.) and one byte to represent the bandwidth of the kernel function.

4.3.1.5 Time allocation

Some data traffic has a periodic pattern as in the case of most cellular networks where Time Division Multiple Access (TDMA) is used. In this case the following information should be stored to represent such patterns:

- One byte to represent the length of one frame with the first bit represent the used unit,
- one byte to represent the length of each slot with the first bit represent the used unit,
- one byte to represent the Transmission Time Interval (TTI) with the first bit represent the used unit, and
- two bytes per control channel to show the situation of the control channel in time and space.

The latter type of information is needed for instance if higher priority is given to control channels when interference probability is estimated.

4.3.2 Spatial statistics for radio element modeling

There are in general two types of spatial data on the radio environment that will be stored in the REM. First type is for representing locations of transmitters and receivers of different technologies, whereas the second type is used for representing phenomena that depend continuously on the location, such as power spectral density on a given frequency band, or the location-dependent shadowing field. Both of these correspond closely to two classical frameworks of spatial statistics, namely *point process* models and their statistical characterizations, and models and statistics for *random fields*. The latter have already been briefly discussed in the context of the direct interference field estimation above.

In both of these frameworks the chosen data set can either be characterised using various statistics, or modelled in parametric or non-parametric fashion. For point processes the key statistics include densities of locations (corresponding to the expected number of transmitters / receivers in a given region) and various measures of location correlations (measuring how clustered or regular the distributions of locations are compared to the "null hypothesis" of uniformly random locations). These can be used directly in order to estimate wireless networking related characteristics such as interference levels or traffic densities. The representation of these statistics in the REM would consist either of single real number associated to a region, or a parametric or non-parametric representation of a function of one or more variables that can be encoded in a manner similar to the ON/OFF distributions discussed above. Models of point processes on the other hand are usually given in terms of a probability density function, measuring the probability of a given pattern of locations to occur compared to the baseline case of uniformly random locations. Again both parametric and non-parametric representations of the corresponding probability density functions are possible.

For random fields similar division between statistical descriptions and models exists as for point processes. The relevant statistics include moments of the marginal distribution of the field, represented as real numbers, parametric or non-parametric representation of the whole marginal distribution, as well as various correlation functions such as the semivariogram or the autocorrelation function of the field. In terms of representation the latter types of statistics are identical to their point processes counterparts. Random field models are usually specified directly through these statistics, and are thus in a sense simpler to represent than their point process counterparts.

5 REM based policy derivation and spectrum access management

In order to put the above concepts on a firmer footing, the present section focuses on the specific application of REM-based policy derivation, viewed and interpreted as a specific DREM instantiation. This should help connect the previously-introduced concepts with a fairly familiar application, thereby clarifying the role of the various information elements.

5.1 General characteristics and assumptions

The spectrum access and usage in wireless cognitive environments can be efficiently managed by dynamically changeable spectrum policies. Here, the policies reflect the detected spectrum opportunities in the wireless environment representing rules of behavior for the controlled radios. The policies are expressed using an ontology language and they are separated from the radio firmware leading to a dynamic and flexible spectrum management policy framework. The basic concept of policy controlled networking [8] comprises two main entities in the network: a ***Policy Decision Point*** **(PDP)** (*i.e. a* ***Policy Engine*** **(PE)**), in charge of the policy decision process based on environment and policy information, and a ***Policy Enforcing Point*** **(PEP)**, enforcing the policy decisions in practice.

In [8], the basic policy concept is extended into a general policy management framework for cognitive radio networks. This is achieved by introducing two additional fundamental policy entities in the network (as presented on Figure 5):

- ***Policy Manager*** **(PM)** is a network policy entity in charge of the policy planning and derivation process. This is performed dynamically, based on the environment information processing. The PM adds/changes/deletes policies stored in the other central policy entity – the Policy Server.
- ***Policy Server*** **(PS)** is the network entity performing the policy storing and distribution tasks. It also performs the classification and registration of the ***Policy controlled Cognitive radio Devices*** **(PCDs)**.

The PCDs include the other two basic policy entities, the PE and PEP, reasoning on the policies received from the PS and enforcing the policy decisions while operating in the detected spectrum opportunities. The practical implementation of the general policy architecture comprises an extended CoRaL [9] language for policy specification and XG Prolog Policy Reasoner [10] for policy reasoning purposes.

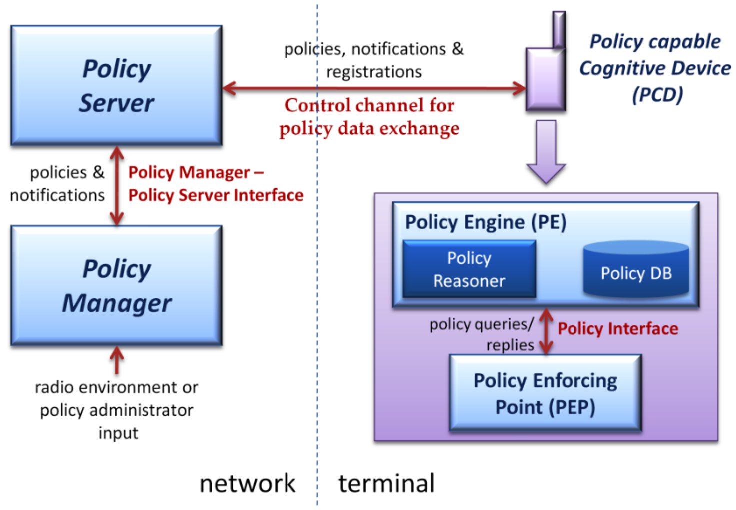


Figure 5: A general policy framework for cognitive radio environments.

The previously explained policy framework accommodates most of the FARAMIR targeted scenarios as proposed in [1]. Table 6 presents the possible data models for the policy based DREM instantiation.

Table 6: Main choices for the data models.

Parameter		**modeling choice**	**alternative choice**
Frequency band		2.4 GHz ISM band	470-790 MHz, cellular bands
Primaries	Service	WLAN network services	Terrestrial broadcast television, cellular networks services
	Technology	IEEE 802.11 WLAN	DVB-T, GSM, UMTS, WiMAX
	Rate of change	Order of hours, days, weeks	Order of weeks, months
	REM provides	Spatial signal power levels, historical spectrum data	TV database available, transmitter location, power, height, propagation model
Secondaries	Service	Data, streaming	Cellular services
	Technology	Various	Cellular
	Rate of change	Order of minutes, hours	Order of minutes, hours
	Regulation	Shared use	Exclusively licensed
	REM provides	Location, power	Location, power

Sensors	Reside in	UEs	UEs
	Provide	RSS, location, timestamp	RSS, location, timestamp
	Mobility	None	Pedestrian (~3 km/h)

5.2 REM facilitated policy management architecture

The dynamic REM input can be used by the policy system to plan and enforce policies that manage the access and usage of the detected available resources. Figure 6 illustrates the integration of the general policy framework with FARAMIR REM architecture. The presented architecture allows for dynamic derivation of spectrum policies and dynamic spectrum management for different types of radio devices.

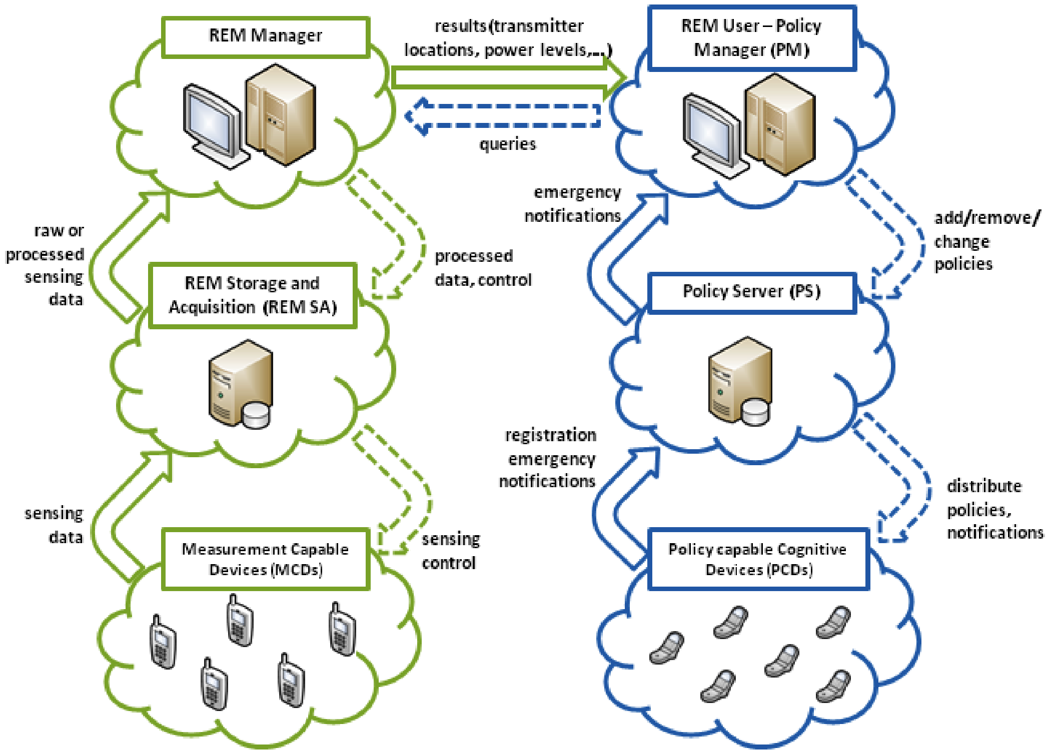


Figure 6: REM facilitated policy derivation framework.

The MCDs provide the sensing data stored in the REM SA, which are post-processed by the REM Manager. The PM queries the REM Manager for REM data needed for policy derivation purposes in periodical or triggered manner. Based on the dynamic REM input, the spectrum policies are planned and stored in the PS and afterwards distributed to the PCDs. The PCDs dynamically utilize the spatiotemporal spectrum opportunities complying with the rules of the dedicated policies. If an emergency situation is detected by the PCDs, i.e. a primary user appearance, a new triggered

REM query is sent to the REM Manager by the PM in order to refresh the environment awareness and update the active policies.

5.3 Sensing data information modeling

The sensing data records required by the REM based policy derivation application should be associated with the location, the time period and the frequency range of data collection. Besides the raw sensing data extraction, the estimation of the primary transmitters' locations is also required for the policy management purposes. The raw data is also an input to the calculation of the radio interference field as well as the radio element parameter data models.

5.3.1 Raw sensing data

The sensing data records should contain the following information:

- Received primary (and/or secondary) signal levels
- Location of the measurement (longitude, latitude, altitude) and time instance
- Inspected frequency bands

Based on these requirements, the MCDs (besides the sensing capabilities) should also be enabled with geo-location and time extraction capabilities. Table 7 summarizes the model of the data reported by the MCDs to the REM SA.

Table 7: The model of the data reported by the sensors.

Parameter	**Size**	**Units**	**Comments**
RSS	vector	[dBm]	measurements
Frequency band	vector	[MHz]	TV bands of the measurement
Time instance	scalar	[seconds]	time of the measurement
x-coordinate	scalar	[Latitude]	latitude of the measurement
y-coordinate	scalar	[Longitude]	longitude of the measurement
MCD label	scalar	[no dimension]	An unique MCD identifier

5.3.2 Transmitters' locations

The PM can query the REM Manager for the detected transmitters' locations. This information can be used for disallowing of the engaged frequency bands in the respective location areas. An example of a CoRaL policy disallowing the usage of a frequency band in the area around a detected transmitter location is presented below.

```
policy forbidArea is
  use request_params;
  defconst loc1 : Location = loc(42, 21.26, 0.0);
  disallow if
      centerFrequency(req_transmission) in {488000..500000} and //in KHz
      distance(onLocation(req_transmission),loc1) =< 10000; // in meters
end
```

The model of the data representing transmitters location is described in details in Table 8.

Table 8: The model of the data representing transmitters locations.

Parameter	Size	Units	Comments
Transmit power	vector	[dBm]	measurements
Frequency band	vector	[MHz]	TV bands of the measurement
Time label	scalar	[seconds]	time of the measurement
x-coordinate	scalar	[Latitude]	latitude of the transmitter
y-coordinate	scalar	[Longitude]	longitude of the transmitter
z-coordinate	scalar	[Altitude]	altitude of the transmitter

5.4 Radio Interference Field Estimation

This subsection focuses on the RIF-related data requirements of the REM based policy derivation application. The policy management part of the REM based policy derivation architecture requires the following input data related to the Radio Interference data models:

- Spatial signal power levels
- Propagation model

This information can be calculated and supplied in a direct or indirect manner as explained in section 3.

5.4.1 Spatial signal power levels

This type of information can be utilized by the PM to detect and localize areas where spectrum opportunities in the inspected band might exist. These areas can be the ones to have an acceptable interference level for secondary transmissions.

5.4.2 Propagation model

The PM can require this type of information for the estimation of the caused interference to the primary system. In this manner the transmission levels at specific areas can be constrained in order not to surpass certain acceptable level of primary system interference. The PM can get the propagation model type as well as the propagation model coefficients. The following two CoRaL policies present an example how this information can be used in the policy derivation process (usage of specific transmission power levels in ring-like areas around a detected primary transmitter location):

```
policy allowArea1 is
  use request_params;
  defconst loc1 : Location = loc(42, 21.26, 0.0);
  disallow if
      meanEIRP(req_transmission) =< -10 and //in dBm
      centerFrequency(req_transmission) in {488000..500000} and //in KHz
      bandwidth(req_transmission) =< 5 and //in MHz
      distance(onLocation(req_transmission),loc1) in {10000..20000}; // in meters
end

policy allowArea2 is
  use request_params;
  defconst loc1 : Location = loc(42, 21.26, 0.0);
  disallow if
      meanEIRP(req_transmission) =< 20 and //in dBm
      centerFrequency(req_transmission) in {488000..500000} and //in KHz
      bandwidth(req_transmission) =< 5 and //in MHz
      distance(onLocation(req_transmission),loc1) in {20000..30000}; // in meters
end
```

5.5 Radio element parameter modeling

Related to the radio element parameter modeling, the REM based policy derivation application requires the following REM-related data:

- Primary system characteristics and spectrum licenses
- Historical spectrum occupancy
- Predictions on future activities

This information should be supplied to the PM in order to assist the policy derivation and management purposes.

5.5.1 Primary system characteristics and spectrum licenses

This information can be extracted from the REM SA and presented to the PM. It reflects the characteristics, capabilities and limitations of the primary system. Based on this information the PM can set the parameters (e.g. allowed interference thresholds) required to calculate whether a specific band at a location area can be classified as spectrum opportunity and allowed for usage by the policies.

5.5.2 Historical spectrum occupancy

The historical spectrum occupancy can be also queried by the PM in order to get some statistical knowledge of the usage on a specific frequency band in specific locations and periods. This type of information can be used by the PM to plan policies for secondary usage, to enable frequency bands in specific time periods and areas when/where they have been detected unused. A simple strategy for historical data – facilitated policy derivation can be the strategy to allow frequency bands in time periods they have been detected to have activity duty cycle below a predefined threshold (e.g. 5%). The following CoRaL policy is an example of this type of time-constraining policies:

```
policy allowTime is
  use request_params;
  defconst allowedPeriod : TimePeriod;
  startTime(allowedPeriod,"T02:00:00");
  endTime(allowedPeriod,"T06:00:00");
  allow if
      inTimePeriod(onTime(req_transmission), allowedPeriod) and
      centerFrequency(req_transmission) in {488000..500000} and //in KHz
      bandwidth(req_transmission) =< 5 and //in MHz
      meanEIRP(req_transmission) =< 30 //in dBm
end
```

5.5.3 Predictions on future activities

This type of information can be also used by the PM to plan policies. For example, the PM can have the strategy not to allow frequency bands with high probability of near future activity (e.g. evaluated from the historical data).

5.6 Description of query/answers to the REM

The PM in the REM facilitated policy derivation scenario should be able to query the REM for the estimation of the radio interference field at a certain time instant/s, location/s and frequency/ies:

$$\hat{P} = f(X, Y, F, T)$$

Table 9 summarizes the possible queries and responses by the REM related to the radio interference field. The information contained in the answer will assist the PM to decide whether or not to allow the frequency band at specific time and location.

Table 9: Queries and answers for the radio interference field.

Id	Query	Answer
PMQP-001	"What is/are the values of the interference field at location/s (**X**,**Y**), at frequency/ies **F** and at time instant/s **T**?"	"**P**" (scalar/ vector)
PMQT-001	"At what time instant/s is the value of the interference field at location/s (**X**,**Y**) and at frequency/ies **F** below **P** dBm?"	"**T**" (scalar/ vector)
PMQF-001	"At which frequency/ies is the value of the interference field, at location/s (**X**,**Y**) and at time/s **T,** below **P** dBm?"	"**F**" (scalar/ vector)
PMQL-001	"At which location/s (**X**,**Y**) is the value of the interference field, at frequency/ies **F** and at time/s **T,** below **P** dBm?"	"(**X**,**Y**)" (scalar/ vector)

Besides the questions related to the radio interference field, the PM can also query for the locations of the primary system transmitters, as well as some history statistics of the activity of the referred transmitters (Table 10 and Table 11).

Table 10: Queries for primary transmitters.

Id	Query	Answer
PMTL-001	"What is/are the location/s **(X,Y)** of the primary system transmitter/s at frequency/ies **F** and at time instant/s **T**"	"**(X,Y)**" (scalar/ vector)
PMTP-001	"What is/are the transmitting power/s **P** of the primary system transmitter/s at location/s **(X,Y)** at time instant/s **T**"	"**P**" (scalar/ vector)
PMTP-001	"What is/are the transmitting power/s **P** of the primary system transmitter/s at location/s **(X,Y)** at time instant/s **T**	"**P**" (scalar/ vector) "
PMTT-001	"At which time/s **T** is (or will be) the transmitter/s at the location/s **(X,Y)** active"	"**T**" (scalar/ vector)

Table 11: Queries for historical data.

Id	Query	Answer
PMHD-001	"What is/are the duty cycles of the activity at location/s (**X**,**Y**), at frequency/ies **F** and at time instant/s **T**?"	"**D**" (scalar/ vector)
PMHT-001	"At which time instant/s is the value of duty cycle of the activity at location/s (**X**,**Y**) and at frequency/ies **F** below **D** %?"	"**T**" (scalar/ vector)
PMHF-001	"At which frequency/ies is the value of duty cycle of the activity, at location/s (**X**,**Y**) and at time instant/s **T,** below **D** %?"	"**F**" (scalar/ vector)
PMHL-001	"At which location/s (**X**,**Y**) is the value of duty cycle of the activity, at frequency/ies **F** and at time instant/s **T,** below **D** %?"	"(**X**,**Y**)" (scalar/ vector)

Besides the above explained queries and answers the PM can also request parameters related to the propagation model and characteristics, as well as some characteristics of the primary transmitters and their activity. These queries need further evaluation.

5.7 Memory and communication requirements

The REM based policy derivation application requires *moderate* to *high* memory and communication requirements for both the REM part and the policy part. The actual requirements depend on the concrete scenario, environment dynamics, target location area size etc. and need more detailed and careful analysis.

6 Scenario specific REM instantiations

At previous chapters we presented generic examples about the construction, update and usage of REMs. Since all this information must also be stored and processed, we also wish to optimize the amount of information needed to be stored and the needed processing for a given quality of description. Using a distributed sensing system we also wish to control how much information is fused to central places and how much processing is carried out in a distributed manner. Specific application scenarios will help to trim down the complexity of the DREM representation, functionality and maintenance, giving pragmatic DREM instantiations for specific applications. The data representation for the queries and the expected answers will be fully described for each case.

6.1 Intra-operator scenarios

The storing and processing of REM-related data in intra-operator scenarios are bound to restrictions imposed by the 3GPP standards. More specifically, these are the releases before R99 for 2G, releases between R99 and Rel.7 for 3G (UMTS and HSPA), Rel.8 and Rel.9 for LTE; and Rel.10 for LTE-A. Since the focus of the FARAMIR project is on new technologies, we will concentrate on conditions and requirements for LTE and LTE-A, i.e., Rel.8 and beyond. In this section, a synthesis of what exists in those standards concerning REM-related data collection and storage will be given. This will be followed by additional requirements and conditions needed for REM construction and elaboration.

6.1.1 General characteristics and assumptions

In the following, we recall the intra-operator scenarios (or Use Cases – UCs) defined in [1] and listed with appropriate abbreviations for easy further reference in [2]:

UC1 - In-band coverage/capacity improvement by relays (CREL)
UC2 - Femtocell optimization (FCO)
UC3 - System Optimization (SO)
UC4 - Introduction of new technologies through refarming (NTR)
UC5 - Vertical handover (VO)
UC6 - Intra-System Handover (ISHO)

Each UC has different requirements in terms of temporal, spatial and spectral granularities as well as precision. For example, UC4 is an optimization process extended over a very large time-scale (in the order of months or years) whereas UC5 and UC6 needs actions/decisions in the order of (mili)seconds. Therefore, each UC has its own particularities concerning data collection and REM construction *procedures*. However, the data structure, the interfaces between different entities and the data collection queries can be considered more or less similar for all of them. For example, although their temporal procedural requirements are quite different, UC4 and UC5/UC6 needs Received Signal Strength (RSS) measurements to construct coverage REMs for their respective optimization purposes. Therefore, in the rest of this section, these commonalities in data collection and REM construction concerning the intra-operator UCs will be given.

6.1.2 REM architecture

Here, basic elements concerning system architecture of REMs for intra-operator scenarios will be described. The overall LTE Radio Access Network (RAN) architecture, including femtocells (HeNBs) and operator's network management system, is depicted in Figure 7:

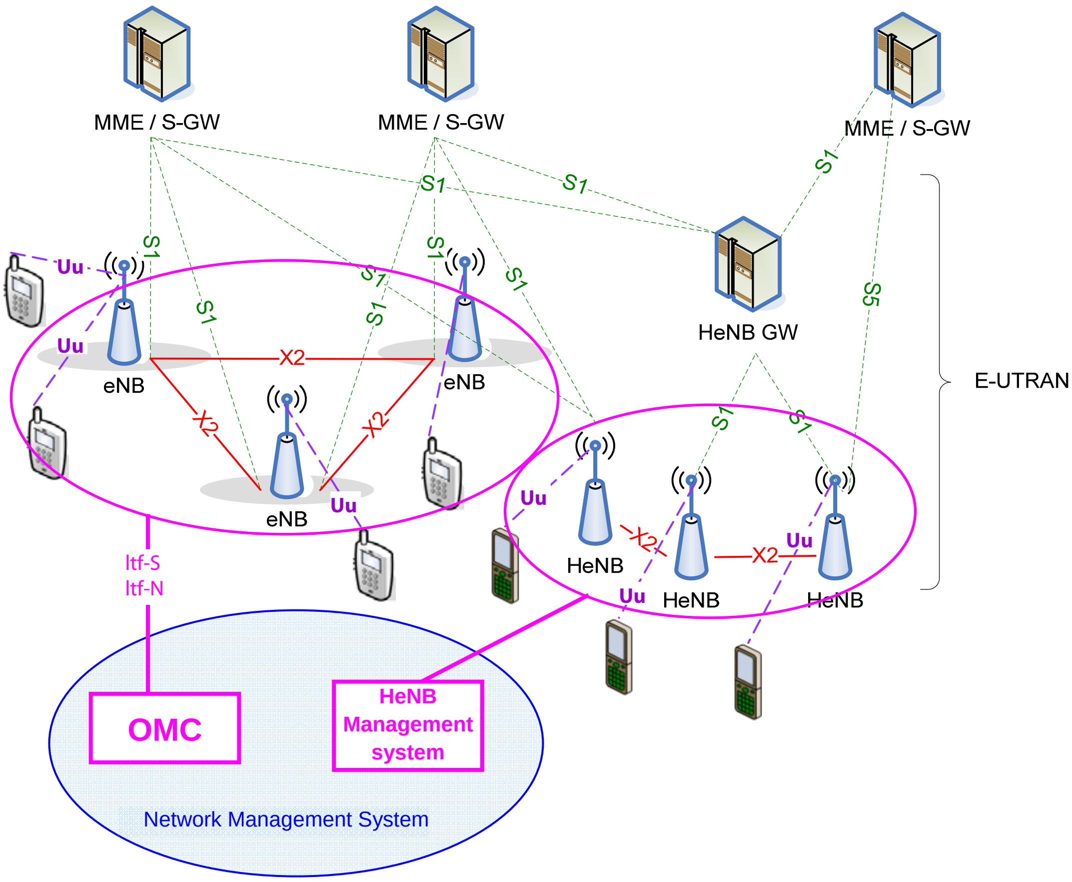


Figure 7: LTE RAN architecture including femtocells (HeNBs) and network management.

For optimization of radio resource utilization in the intra-operator scenarios of D2.2, there must be a layered and distributed REM system architecture, i.e. the functional architecture blocks (MCDs, REM SAs, REM Managers and REM GUIs) must be placed at several nodes (of different hierarchical levels) in the above architecture. Note that in this document, only the architectural aspects concerning REM-related data collection will be covered. The remaining parts concerning the RRM optimization will be treated in the upcoming deliverable D2.4.

6.1.3 Sensing data information modeling

Since intra-operator REM scenarios are based exclusively on the LTE architecture, the sensing data information models are heavily shaped by the information models that are defined by the existing LTE standards. Therefore, we will begin this section by presenting the existing LTE measurement reporting descriptions and data structures. This will be followed by an additional high-level description of sensing data models needed for REM construction.

Physical layer UE measurements:

The UE physical layer measurements that are of interest to the Faramir intra-operator scenarios are the Reference Signal Received Power (RSRP) and the Received Signal Strength Indicator (RSSI) measurements.

RSRP is defined as the linear average over the power contributions (in watts) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth. The UE can make intra-frequency and inter-frequency RSRP measurements in both connected and in idle mode. The number of resource elements within the considered measurement frequency bandwidth and within the measurement period that are used by the UE to determine RSRP is left up to the UE implementation with the limitation that corresponding measurement accuracy requirements have to be fulfilled. The received power per resource element is determined from the energy received during the useful part of the OFDM symbol, excluding the cyclic prefix.

RSSI is the linear average of the total received power (in watts) observed only in OFDM symbols containing reference symbols for antenna port 0, in the measurement bandwidth, over a pre-defined number of resource blocks by the UE from all sources, including co-channel serving and non-serving cells, adjacent channel interference, thermal noise etc.

Physical layer network (E-UTRAN) measurements:

The network physical layer measurements that are of interest to the Faramir intra-operator scenarios are the Uplink Received Interference Power (URIP) and the Uplink Thermal Noise Power (UTNP) measurements.

The URIP measurement includes thermal noise, and covers the bandwidth over one physical resource block of $N_{\mathrm{sc}}^{\mathrm{RB}}$ resource elements where $N_{\mathrm{sc}}^{\mathrm{RB}}$ is the physical resource block size in the frequency domain, expressed as a number of subcarriers [TS 36.211]. The reported value contains a set of URIPs of physical resource blocks for $n_{\mathrm{PRB}} = 0,\ldots,N_{RB}^{UL}-1$ where $N_{\mathrm{RB}}^{\mathrm{UL}}$ is the uplink bandwidth configuration, expressed in multiples of $N_{\mathrm{sc}}^{\mathrm{RB}}$ as defined in [TS 36.211].

UTNP is defined as (N_o x *W*), where N_o denotes the white noise power spectral density on the uplink carrier frequency and $W = N_{RB}^{UL} \cdot N_{sc}^{RB} \cdot \Delta f$ denotes the UL system bandwidth. The measurement is optionally reported together with the URIP measurement and it is determined over the same time period as the URIP measurement.

The UE measurement data used for REM construction is communicated through the *MeasurementReport* message of the *Radio Resource control (RRC) protocol*; which is used for the indication of measurement results. The following ASN.1 description summarizes the internal data structure of the *MeasurementReport* message [3GPP 36.331]:

```
-- ASN1START
MeasurementReport ::=               SEQUENCE {
    criticalExtensions                  CHOICE {
        c1                                  CHOICE{
            measurementReport-r8                MeasurementReport-r8-IEs,
            spare7 NULL,
            spare6 NULL, spare5 NULL, spare4 NULL,
            spare3 NULL, spare2 NULL, spare1 NULL
        },
        criticalExtensionsFuture            SEQUENCE {}
    }
}
MeasurementReport-r8-IEs ::=        SEQUENCE {
    measResults                         MeasResults,
    nonCriticalExtension                MeasurementReport-v8a0-IEs
    OPTIONAL
}
MeasurementReport-v8a0-IEs ::= SEQUENCE {
    lateNonCriticalExtension            OCTET STRING                        OPTIONAL,
    nonCriticalExtension                SEQUENCE {}                         OPTIONAL
}
ASN1STOP
```

The data structure that is required for the RSRP measurements is determined by the associated measurement report mapping between the fields in the *MeasurementReport* message and the real RSRP value. The reporting range of RSRP is defined from -140 dBm to -44 dBm with 1 dB resolution. Table 12 taken from [3GPP 36.133] depicts the mapping of the measured RSRP quantity to the reported value in the *MeasurementReport* message:

Table 12: RSRP measurement report mapping.

Reported value	Measured quantity value	Unit
RSRP_00	RSRP <= -140	dBm
RSRP_01	-140 <= RSRP < -139	dBm
RSRP_02	-139 <= RSRP < -138	dBm
…	…	…
RSRP_95	-46 <= RSRP < -45	dBm
RSRP_96	-45 <= RSRP < -44	dBm
RSRP_97	-44 <= RSRP	dBm

Note that the reported value has 98 values ranging from 0 to 97 (fitting into 7 bits as can be observed from the ASN.1 description above).

For scenario-specific instantiations of the overall REM system architecture, the approach adopted in this section for REM construction will be extended to RRM optimization, taking into account the related mechanisms of the LTE architecture for a selected set of intra-operator scenarios. The necessary requirements for the REM construction and for its utilization for RRM optimization purposes exceed what is currently provided by the LTE standard. Therefore, in the complete architecture work of deliverable D2.4, the limits of what can be achieved with the existing standards will be completed by what is necessary in terms of additional requirements to achieve an efficient REM construction and utilization according to pre-defined RRM optimization objectives determined by the selected intra-operator scenarios.

Using the above information on the existing LTE protocols, interfaces and data structures on physical layer measurements, we can construct the following table (Table 13) that defines the data model:

Table 13: The data model for intra-operator scenarios.

Parameter	**Size**	**Units**	**Comments**
RSRP	vector of 7 bits	[dBm]	measurements
Nature	scalar	[no dimension]	event-triggered or periodic
Cell Id	scalar	[no dimension]	the serving Cell ID of the UE
Time label	scalar	[seconds]	time of the measurement
x-coordinate	scalar	[Latitude]	latitude of the measurement
y-coordinate	scalar	[Longitude]	longitude of the measurement
UE identifier	scalar	[no dimension]	A unique sensor identifier

6.1.4 Propagation modeling

In order to draw coverage maps where power is emitted by a single base station whose location is known, we choose the pragmatic approach of using a simple analytical model in combination with a statistical evaluation through measurements of the shadowing which is by nature a random variable over the space. The analytical path-loss (PL) follows the WINNER model [11]:

$$\mathrm{PL} = \alpha log_{10}(d) + l_0 \tag{4}$$

where d is the distance between the BS and the mobile terminal, and the model parameters α and l_0 are given in Table 14.

Table 14: WINNER model parameter values.

	suburban	urban
α	40.2	35.0
l_0	27.7	38.4

Both cases experience a log-normal shadowing that further modifies the received power. Shadowing is claimed to have a $\sigma = 8dB$ variance and a $\phi = 50m$ correlation distance. When considering a homogeneous terrain topology, which is the case within a BS influence zone, the model parameters $\alpha, l_0, \sigma \mathrm{and} \phi$, can be safely assumed constant. However, it is preferable to evaluate those parameters rather than taking values from literature as they heavily depend on the geographical specificities (*e.g* typical street width, vegetation, flat vs hilly terrain) and the measurements are also impacted by side-effects that modify those values (*e.g* antenna tilting, feeder losses).

It must be noted that this model does not prevent large deviations from this log-linear decay. The degree of these deviations is caracterised by the variance of the shadowing. Hence we make no assumption on the dominance of the linear decay or the shadowing over each other.

We propose the use of the following model for the received power at location i in dBm:

$$p_i = p_0 - \alpha \log_{10}(d_i) + s_i, \tag{5}$$

where p_0 is the emitted power minus the path-loss constant l_0, α is the path loss coefficient, d_i and s_i are respectively the distance in meters and the shadowing in dB scale between the BS and the location of i. We do not include any temporal dependency as we consider that measurement duration is long enough to average out the fast fading effects. Discretizing the 2D space on a rectangular grid, (2) gives us the received power at any point.

Here we assume that the shadowing is a correlated random vector with log-normal distribution and a correlation distance exponentially decaying with the distance, which can be expressed as

$$\mathbb{E}(S_i S_j) = \sigma^2 \exp(-\frac{d_{ij}}{\phi}), \tag{6}$$

where d_{ij} represents the Euclidean distance between the mobile measurements points indexed by i and j.

More advanced models that include further linearly dependent parameters (*e.g* street width) are still possible to introduce at no cost in computation time, however, they would require additional input maps.

It is also possible to use alternative functions for the correlation of the shadowing with additional parameters, although this would increase the computational load for evaluating those latters.

In this model, the parameters p_0, α, σ^2 and ϕ are unknown. However, we do have prior information on what their values might be. For instance, we know that the radiated power must be something around the power at the feeder, α is around 35 in urban areas and σ typically ranges between 8 and $11dB$ for typical outdoor Above RoofTop to Below RoofTop scenarios [12].

6.1.5 Radio element parameter modeling

The basic radio elements of the intra-operator REM scenarios are the LTE network entities (eNBs, HeNBs, RN, MME, HeNB Management system, OMC) and the UEs. Table 15 presents a mapping of REM-related architectural entities (as defined in D2.3) on LTE network entities.

Table 15: functional entities in the LTE architecture for the intra-operator scenarios.

	MCD	**REM SA**	**REM manager**	**REM GUI**
UC1 – CREL	• UE • RN • eNB	• eNB • MME • OMC	• MME • OMC	• OMC
UC2 – FCO	• UE • Femtocell (HeNB) • eNB	• eNB • HeNB GW • eNB	• HeNB Management System • MME • OMC	• OMC
UC3 – SO	• UE • eNB	• eNB • MME	• MME • OMC	• OMC
UC4 – NTR	• UE • eNB	• OMC	• OMC	• OMC
UC5 – VO	• UE • eNB	• eNB • MME	• MME	• MME • OMC
UC6 – ISHO	• UE • eNB	• eNB • MME	• MME	• MME • OMC

RN: Relay Node
MME: Mobility Management Entity
HeNB: Home eNodeB
OMC: Operation and Maintenance Center

Note that the presence of more than one network entity for one REM functional block means that the REM has a layered structure, i.e., different REM blocks with different characteristics (temporal/spectral/spatial granularity levels, update rates etc.) can be found at different hierarchical levels of the LTE network.

6.1.6 Description of query/answers to the REM

As in previous sections, we begin this section by first describing the existing LTE interfaces and protocols that can be readily used for REM construction and that forms the basis for the REM construction queries. This will be followed by a high-level query description.

Interfaces:

The definition of the above mapping in section 6.2.4 between the LTE RAN entities and the REM functional architecture blocks allows us to go one step further to define a similar mapping for the interfaces. Note that currently, the exact interface definitions concerning the OAM system and the HeNB management system do not exist, since 3GPP is currently working on these issues. Therefore, the interface mapping concerning these interfaces will not be exactly defined here. Since this document is focused on REM construction, we will be describing the interface between the MCDs and the REM SA. Therefore, the lack of exact interface definitions concerning the OAM and the HeNB management system does not pose any problem at this point.

Table 16 shows the mapping between the interfaces that are currently defined for LTE and those that are defined in D2.3 for REM functional architecture:

Table 16: REM interfaces vs. E-UTRAN interfaces for the intra-operator scenarios.

	MCD-REM SA interface	**REM SA-REM Manager interface**	**REM Manager-REM GUI interface**
UC1 – CREL	Uu S1-MME Itf-N/Itf-S	S1-MME Itf-N/Itf-S	-
UC2 – FCO	Uu S1-MME	S1-MME Itf-N/Itf-S	-
UC3 – SO	Uu S1-MME	S1-MME Itf-N/Itf-S	-
UC4 – NTR	Uu S1-MME Itf-N/Itf-S	-	-
UC5 – VO	Uu S1-MME	S1-MME	Itf-N/Itf-S
UC6 – ISHO	Uu S1-MME	S1-MME	Itf-N/Itf-S

Protocols:

The mapping of Table 16 allows us to use the already existing protocols defined in the LTE standard. Since the REM-related data concerns only the control plane, we will be only interested in the control plane protocol structure of LTE. Figure 8 recalls the control plane protocol stack defined for LTE:

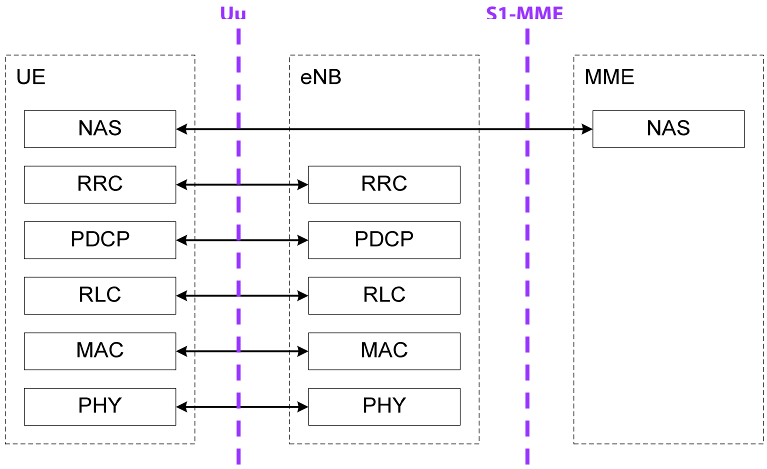


Figure 8: Control-plane protocol stack of LTE [3GPP TS 36.330].

For femtocells, the control-plane interface between the HeNB, the HeNB GW and the core network is provided by the S1-MME interface. The following figures depicts the control-plane protocol stack of the S1-Mme interface in the case of (Figure 9) without HeNB GW and (Figure 10) with HeNB GW.

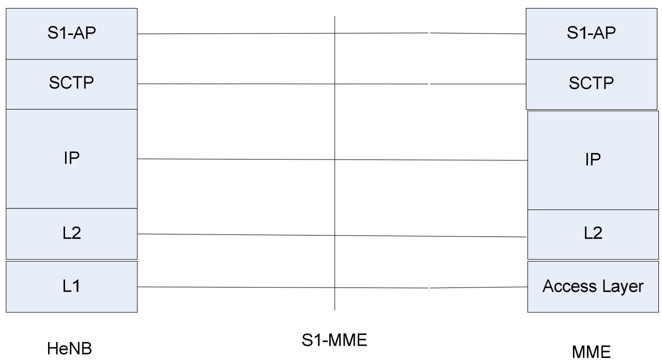


Figure 9: Control plane for S1-MME interface for HeNB to MME without the HeNB GW [3GPP TS 36.300].

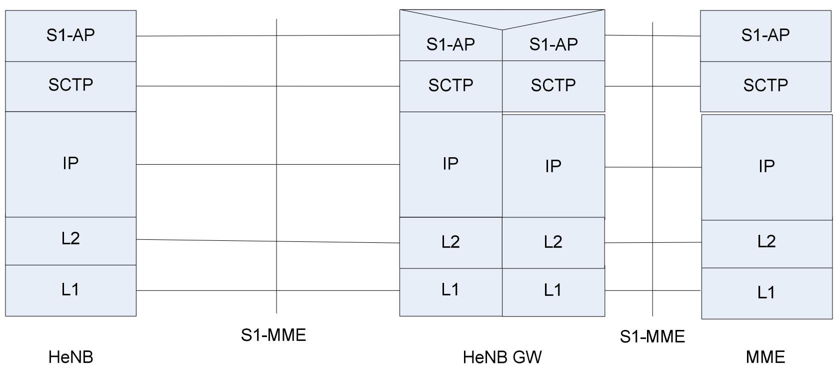


Figure 10: Control plane for S1-MME Interface for HeNB to MME with the HeNB GW [3GPP TS 36.300].

For REM construction purposes, we are concerned with the measurement messages involved in the above protocol stack. For the FARAMIR intra-operator scenarios, those measurements are mainly the physical layer measurements. They are performed by different entities (i.e. by the UEs and by the network) and communicated on different interfaces (Uu for the UE and S1-MME for the network).

The protocol layer that carries these measurement messages is the Radio Resource Control (RRC) protocol layer. RRC protocol layer is responsible from services and functions like the broadcast of system information, paging, establishment/maintenance/release of RRC connections, mobility, QoS management, UE measurement reporting and control of the reporting.

We now give descriptions of different queries needed for REM construction for intra-operator scenarios. Table 17 gives the periodic RSRP measurements. Such measurements are launched by the network (usually the eNB or the HeNB) and executed by the UEs periodically. The period (ΔT) and the start/stop times ($\mathbf{i_{min}}\Delta T$ and $\mathbf{i_{max}}\Delta T$) are determined by the REM manager according to the specific requirements of the optimization at hand.

Table 17: Query for RSRP (periodic measurement).

Id	**Query**	**Answer**
QI-001	"What are the values of RSRPs at locations ($\mathbf{X_i},\mathbf{Y_i}$), at frequency **F** and at time instants $\mathbf{i(\Delta T)}$ with $\mathbf{i_{min}} <= \mathbf{i} <= \mathbf{i_{max}}$?"	"$\mathbf{P_i}$" (7 byte vector) with "Confidence $\mathbf{C_i}$" at each time instant $\mathbf{i(\Delta T)}$

Apart from periodic measurements, RSRP measurements triggered by specific events (e.g. handovers) are also performed by the UEs. Table 18 gives the event-triggered RSRP measurements. Such measurements are launched by the UE to detect certain events (received signal level from the serving/neighboring BS nodes being below and/or above certain thresholds). The set **J** of BS nodes on which the measurements are made and the threshold values **M** are determined by the REM manager according to the specific requirements of the optimization at hand and communicated to the UE.

Table 18: Query for RSRP (event-triggered).

Id	**Query**	**Answer**
QI-001	"What are the values of RSRPs at locations ($\mathbf{X_i},\mathbf{Y_i}$), at frequency **F** and and at time instants $\mathbf{i(\Delta T)}$ as long as RSRP from nodes **J** is greater/less than a value **M**?"	"$\mathbf{P_i}$" (7 byte vector) with "Confidence $\mathbf{C_i}$" at each time instant $\mathbf{i(\Delta T)}$

6.2 Secondary access to TV white space spectrum by (LTE) out-of-band femtocells

In this section we will detail relevant models for the various elements introduced in Section 1, for the particular scenario characterized by "out-of-band femtocells" (Section 3.2.1 in D2.2) operating in "TV White Space" (Section 3.2.5.1 in D2.2). We will present models for radio propagation, transmitter characteristics and sensing data information, that are the immediate consequence of a range of assumptions related to this particular scenario's characteristics.

A first purpose of this Section is to be *as specific as possible* in the formulations of the various models (as opposed to the general formulations covered in earlier Sections in this report), in order to obtain useful and concrete models that can straightforwardly be used for analysis purposes or for the synthesis of processing algorithms on which REM-creation builds.

A second purpose is to adapt the level of complexity of the models to the feasibility and practical applicability of today's known estimation methods and data storage/processing capacity. Such an adaptation will pave the way for immediate implementation in our prototypes. Beyond this, we will also present some additional models whose complexity prevents prototyping with today's technologies, but make for interesting and challenging research problems.

In some instances in what follows, assumptions may seem to be *too* specifically chosen – this is intentional though, for the sake of concreteness and in the spirit of the above purposes.

As a result, the set of assumptions and models in this section characterize a particular REM instantiation for the "Femtocells in TVWS"-scenario.

6.2.1 General characteristics and assumptions

We recapitulate first some of the relevant characteristics of the "Femtocells in TVWS" scenario.

Primarily, we will focus on Europe. Following recent rulings by the US Federal Communications Commission that opened up significant parts of the TV spectrum for unlicensed use in the US, several other countries around the world and particularly in Europe are currently considering similar measures (see, for example, [13], [14] and [15]). In Europe, the availability of TV white spaces in the 470-790 MHz UHF band is of particular interest. This range of frequencies, appreciated for its attractive propagation properties, is what remains of the European UHF TV band after the assignment of the 800 MHz band (790-860 MHz) for other, licensed services (as a part of the harmonized European strategy to use the digital dividend), a process that has taken place or is ongoing in several European countries.

The 470-790 MHz UHF band is, since the sixties partitioned into 40 TV channels, each 8 MHz wide. Most countries have exclusively licensed the major part of this 320 MHz spectrum to TV broadcasters. Notable exceptions are some bands in some countries reserved for military or astronomy purposes. Also, s*ervices ancillary to broadcasting* (SAB) and s*ervices ancillary to programme making* (SAP) (including wireless microphones) are deployed in most countries in this spectrum, but are usually spread widely across the whole band and usually on a secondary basis to use for TV broadcasting. SAB/SAP services typically use interleaved spectrum, but some European states have allocated specific frequency channels or sub-bands on a nationwide basis to these uses. For the sake of simplicity, we will ignore SAB/SAT transmission in our initial models.

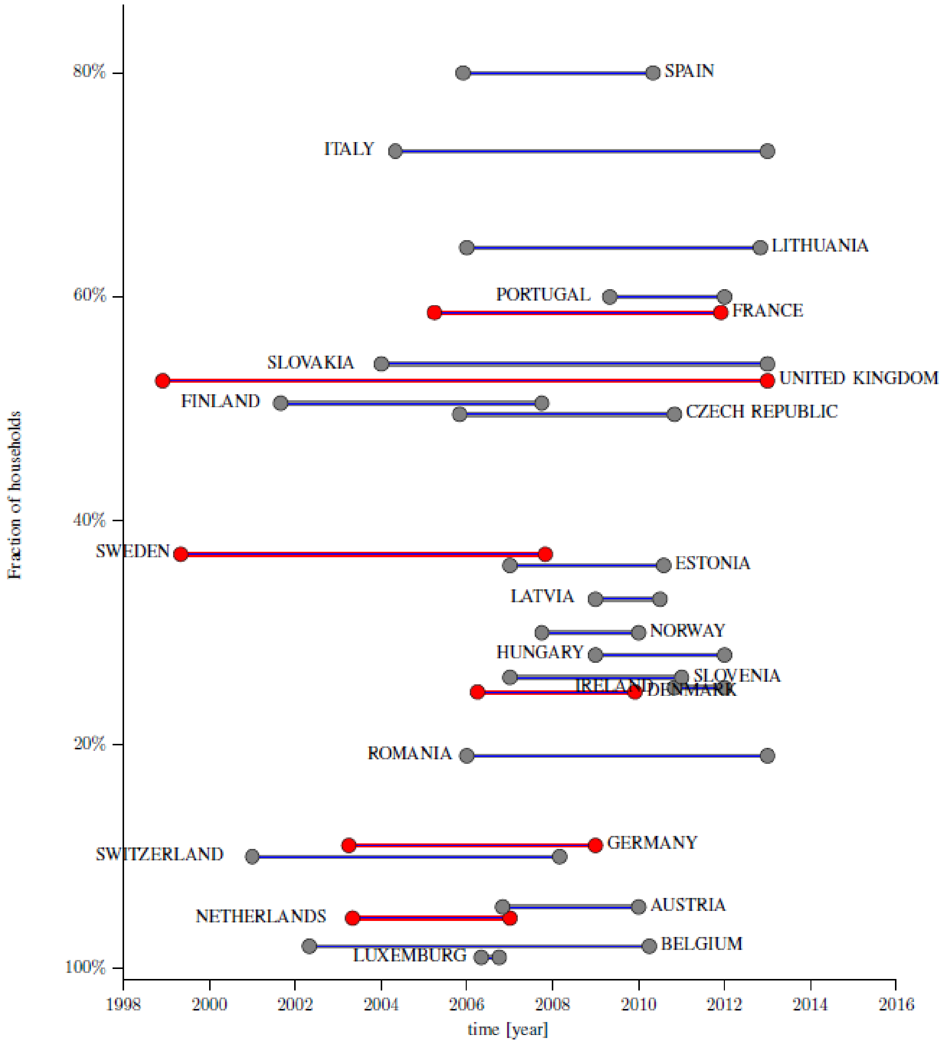


Figure 11: The Analog-to-digital switch over in Europe. Time between first introduction of digital TV transmitter and switch-off of the last analogue transmitter versus the penetration of terrestrial television (the percentage of the households having terrestrial TV as the main TV receiver).

Currently, many European countries are in the process of switching over their TV networks from analog to digital, see Figure 11. While some countries have already completed this transition, others plan to do so in the next couple of years. The current situation will therefore not sustain during the coming years. Rather than focusing on the current primary usage of the TV band, we will model the situation when the switch-over has been completed and only digital DVB-T transmitters remain active. This will be the dominant primary usage situation in most European countries for the decade(s) to come.

While the targeted spectrum is thus primarily used by TV-transmitters our scenario adopts the secondary usage of this band by LTE eNodeB base stations.

Cellular systems, and in particular the 3GPP LTE standard come in two flavors: time-division duplex (TDD) or a frequency-division duplex (FDD). Typically, licenses for the LTE spectrum may come with the regulator's constraint to use either of the two technologies. It has been argued that for the secondary usage the TDD technology is better suited as it would be more flexible in its frequency usage. Deployment of secondary FDD networks would require white spaces to come in *two separate* frequency portions sufficiently separated in frequency to guarantee interference-free operation. This would limit the white-space opportunities of the secondary network and hence reduce its spectral efficiency. In our scenario we will assume a TDD operation of the secondary network.

Regulatory issues for this scenario have by far not been resolved. Hence, in the modeling we will have to anticipate on some typical regulatory scenarios. Firstly and theoretically, the TV spectrum in Europe may be opened up as it has been done in the US: any operator may deploy (certified) secondary equipment in the white spaces. In other words, a very heterogeneous secondary use landscape would emerge. For the sake of simplicity, however, we will in the following model an alternative regulatory scenario where a single network operator owns the *exclusive* rights (in a certain region, in a certain part of the TV band, with a certain maximum power) to deploy secondary transmitters. This assumption will greatly simplify the signal models as it essentially results in the appearance of *only two kinds* of radio signals in our models: primary DVB-T signals and secondary LTE-TDD signals.

The purpose of the REM is twofold: On one hand, it will be used to configure the femtocells on a locally spare TV band while avoiding any interference to the existing TV systems, on the other hand it should provide a record of the femtocells' key transmission parameters (location, power, etc.), in order to optimize the secondary network's operation.

In the light of this purpose, one of the main algorithmic tasks of the REM will be to estimate relevant parameters that characterize *both* the primary TV transmitters *and* the secondary LTE transmitters. In particular we will assume that the location, power, and height of the TV transmitters are not known by the secondary LTE network. In addition we will assume that the secondary network has no knowledge of the location and power of its constituting femtocells.

As one interesting particular alternative, we will consider the case where the LTE network has access to a nationwide database that contains all relevant TV transmitter parameters. In this scenario, the REM's purpose reduces to characterizing the LTE femtocell transmitters and, possibly, only confirming or complementing the characteristics of the TV transmitters.

Related to the sensing devices in this scenario, we will assume that the mobile devices in the secondary LTE network have the capability to do geo-localized measurements. Specifically, we assume the UE's will be able to provide and report measurements of the received signal strength in multiple TV channels, along with an accurate timestamp and location coordinates.

Table 19 summarizes the main general characteristics of this scenario. In the following section we address the radio channel model, the detailed models of the radio transmitters along with the models for the sensor data.

Table 19: Main choices for the data models.

Parameter		**modelling choice**	**alternative choice**
Region		Europe	other regions
Frequency band		470-790 MHz, 8 MHz channels	
Primaries	Service	Terrestrial broadcast television	
	technology	DVB-T	
	rate of change	order of weeks, months	
	REM provides	location, power, height	TV database available
Secondaries	service	cellular data	
	Technology	LTE TDD	
	Duplexing	TDD	FDD
	rate of change	order of hours	
	Regulation	exclusively licensed	shared use
	REM provides	location, power	
Sensors	reside in	UEs	
	Provide	RSS, location, timestamp	
	mobility	0-50 km/h	

6.2.2 REM architecture

In view of the layered hierarchical REM architecture as presented in [2] and reproduced here in Table 20, we consider here the “Operator local REM” architecture that operates on the lowest hierarchical level and represent typically a domestic area of a few blocks. It is the area architecturally covered by the HeNB gateway as illustrated in Figure 7. With this scale of the problem, the aim of the REM is to provide a radio interference field estimate (RIFE) for this region, either by a direct method (essentially an inverse scattering or an interpolation problem) or by an indirect method (first estimating the key transmit parameters that determine the field and then, using a channel model for the region, creating the RIFE).

Table 20: Three-layered REM implementation in macro- and femtocells.

	National	**Operator national REM**	**Operator local REM**
Node locations	X	X	X
Node resource capacities	X	X	X
List of eNBs/ HeNBs		X	X
General user date/price plan		X	X
Location based user service (QoS)		X	X
User behavior/traffic statistics		X	X
Local interference statistics			X

For the particulars of the mapping of the functional entities and interfaces (see Figure 4) onto the architectural blocks and interfaces (as defined in [2]) it suffices here to refer to the description in the previous sections 6.1.1 and 0 for the particular *femtocell optimization* scenario (UC2-FCO), see also Table 15 and Table 16.

6.2.3 Sensing data information modeling

We will base the data modeling on the following assumptions:

1. Sensors are integrated with the LTE system's UE's.
2. Sensors only measure the downlink. There will be no interference from uplink UE transmissions in the same frequency band. Here, we essentially assume a time synchronization mechanism that assures that the measurements only take place in the downlink TDD time slots.
3. Sensors measure the received signal strength. They may either do this by plain energy detection or by the usage of the pilots available in both the primary DVB-T and the secondary LTE signals.
4. Sensors (UE's) know their own locations. This is accomplished by GPS or other location-services provided by the LTE network.

These assumptions lead to the model for a sensor data record as listed in Table 21. Measurements records with the format as indicated in Table 21 are either transmitted periodically to the fusion center/REM manager, or transmitted in response to an explicit measurement request from the fusion center/REM manager. This mechanism allows the REM manager control the total amount of sensing data at any time and TV band.

Table 21: The model of the data reported by the sensors

Parameter	**Size**	**Units**	**Comments**
RSS	vector	[dBm]	measurements
TV-band label	vector	[MHz]	TV bands of the measurement
Time label	scalar	[seconds]	time of the measurement
x-coordinate	scalar	[Latitude]	latitude of the measurement
y-coordinate	scalar	[Longitude]	longitude of the measurement
Sensor label	scalar	[no dimension]	An unique sensor identifier

6.2.4 Propagation modeling

In this section we will investigate models that describe the propagation of our primary and secondary transmitters (TV and LTE transmitters, respectively) to the receiving antennas of the sensor devices (typically residing in the LTE UEs). Since we assume that the sensors only report the strength of the signals they receive, we will only be interested here in the modeling of the *received power* as a function of the power emitted by the transmitters. In other words, we will ignore any radio channel modeling that relates to the signal's phase, often referred to as *coherent* channel model information. Since any such coherent information will be ignored or lost in our sensor receivers (by assumption) we do not incorporate these channel aspects in our models.

Since the assignment of the frequencies 470-790 MHz to broadcasting TV half a century ago, radio propagation models for these frequencies have been subject of extensive measurements and research. Propagation in this band is well-understood and a number of modeling approaches dominate the literature. We characterize in the following the pathloss, the shadow fading, the multipath and the fast fading properties in relation to the general scenario assumptions stated in the previous section.

While the free-space attenuation between isotropic antennas is characterized by $P_r = \lambda^2(4\pi)^{-2}{d_{rt}}^{-2}P_t$, where λ is the wavelength and d_{rt} is the distance between the transmitter and the receiver, a simple, widely established and useful pathloss model is characterized by

$$P_r \sim {d_{rt}}^{-\alpha}P_t, \tag{7}$$

where $\alpha > 2$ is the path-loss coefficient. Figure 12 illustrates the pathloss characteristics as compiled by the ITU-R ([16], [17]) empirically constructed from large measurement campaigns. These results are statistical, average results that predict the pathloss and whose values essentially are available through large tables and a set of interpolation/extrapolation rules. While the ITU-R channel models are suitable and accurate for simulation, evaluation and planning purposes, the simple closed-form model (7) is in many cases better suited for analysis purposes and mathematical manipulation.

A second effect (and typically independent of the path loss) relevant to the scenario at hand is the shadow fading. In many state-of-the-art contributions on radio environment mapping this effect is ignored, not because the significance of this impairment is underestimated but, mainly because its incorporation in the models typically makes for much more difficult research problems. The classical model for shadow fading is

$$P_r \sim G_{rt}P_t, \tag{8}$$

where G_{rt} is a random scalar variable taken from a log-normal distribution characterizing the shadow fading loss between a transmitter and a receiver. A typical value for the variance of $10\log_{10} G_{rt}$ is 8dB. In particular the outdoor-to-indoor loss of the signal's power is covered by this statistical model. The shadow-fading, characterizing a radio link of a particular transmitter-receiver pair is often simply modeled as spatially uncorrelated, although spatial obstacles typically in the vicinity of the transmitter or the receiver account for its existence, and would justify a spatially correlated model.

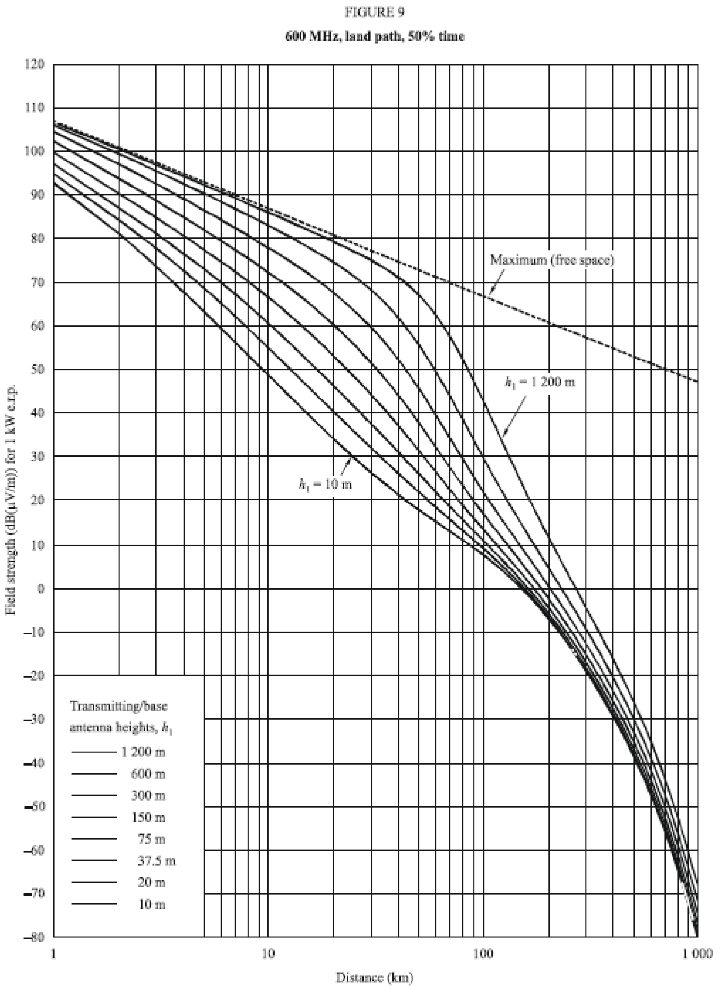


Figure 12: Field strength as a function of the distance to the transmitter for various antenna heights (from [16]).

As a third effect, multipath propagation accounts for additional variations in the received signal power. In order to keep the signal models manageable we ignore the effect of multipath on the received power.

Finally, thermal noise in the receiver accounts for an additional received power in the sensor. In the current scenario, the measurement bandwidth is typically one TV channel of $B = 8$ MHz and hence the thermal noise in this band at 20°C (293.15K) is

$$\sigma_r^2 = kBT = (1.38 \cdot 10^{-23})(8 \cdot 10^6)(293.15) = 3.24 \cdot 10^{-14}\ [\mathrm{W}] = -\ 104.9\ \ [\mathrm{dBm}] \quad (9)$$

Combination of (7), (8) and (9) and realizing that many sources contribute independently to the received power at sensor r, we obtain the signal model accounting for the signals in one TV channel:

$$P_r = C_1 \sum_t G_{rt}^{TV} {d_{rt}}^{-\alpha} P_t^{TV} + C_2 \sum_t G_{rt}^{LTE} {d_{rt}}^{-\alpha} P_t^{LTE} + \sigma_r^2,$$

where C_1 *and* C_2 are scaling constants. Here, the first term represents the appearance of the primary TV transmitters while the second terms accounts for the secondary HeNB transmitters. Despite the relatively simplicity of this model it makes for a number of interesting and challenging problems related to the generation of the radio interference field estimation.

Each measurement P_r represents the received power in a time-frequency-space bin. We assume that each sensor can provide accurate labels accompanying each power measurement, in such a way that there is never any doubt to which time-frequency-space bin a certain measurement refers.

One of the main problems is then to generate an estimated radio interference field to be stored in the REM, from the measurements P_r. The processing to accomplish this typically involves the estimation/prediction of a number of unknowns. The number of transmitters contributing to the received power in the sensors is unknown, the transmit powers and the transmitter locations (needed to identify d_{rt}) are unknown.

Different explicit models appear under certain *additional* assumptions:

1. Typically, the shadow fading loss depends on the physical characteristics in the vicinity of the transmitter and the receiver of a data-link. Hence we can assume that the shadow fading coefficients G_{rt}^{TV} and G_{rt}^{LTE} show a high degree of corrrelation. For instance if the sensor receiver is indoors, it is likely that both G_{rt}^{TV} and G_{rt}^{LTE} contain a power-loss component representing the outdoor-to-indoor radio channel (assuming the other femtocells appear in other buildings in the vicinity of the sensor.)
2. When the secondary system has access to a (national) database with primary transmitter data, the second term (the total received TV power) is to a large extent known. Both d_{rt} and P_t^{TV} are then known from the database and only the shadow fading is unknown. This simplifies the problem considerably.

6.2.5 Radio element parameter modeling

In accordance with the general assumptions in Section 6.2.1, two types of radio elements appear in this scenario:

1. DVB-T transmitters
2. LTE Home eNodeB's

In the following we characterize these elements in more detail and with respect to the particular features relevant to the creation of a REM in this scenario.

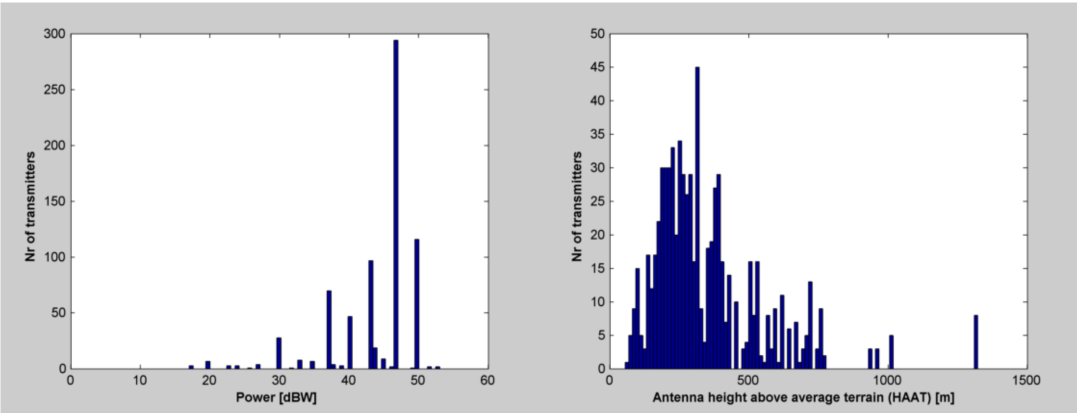
6.2.5.1 DVB-T TV transmitters

The modeling of the radio characteristics of European TV networks can greatly be aided by a proper analysis of *true* data. In fact, may regulators and broadcasters make essential data about their networks publicly available; see [19]-[23] for details. Along with the detailed location coordinates, the transmission power and the antenna heights are disclosed in these databases. In some cases even the antenna's directional patterns are detailed. The availability of this data, allows us to run any simulation of REM construction on true network data, rather than on abstract data models. Table 22 illustrates the number of TV transmitters present in October 2010 in 11 European countries, along with their respective population size and areas. Note that in some countries still a substantial number of analog transmitters is active – in these countries, the switch-over has not yet been completed.

Table 22: Digital broadcast TV network characteristics in 11 European countries

Country	Population [millions]	Area [km²]	Number of TV Transmit.		Modulation
			Analog	Digital	
Czech Republic	10.51	78620	103	318	64 QAM
Germany	81.80	357160	75	731	16 QAM
Luxemburg	0.50	2608	11	3	64 QAM
United Kingdom	62.01	243916	1176	2790	64 QAM
Sweden	9.34	442804	0	1194	64 QAM
Austria	8.38	83888	134	164	16 QAM
The Netherlands	16.58	36996	0	281	64 QAM
Denmark	5.53	42564	32	303	64 QAM
Switzerland	7.78	41408	6	285	64 QAM
Belgium	10.83	30656	20	65	64 QAM
Slovakia	5.42	48420	1096	19	64 QAM

Figure 13 shows the distributions of the power, the height and the locations of these transmitters in Germany. As an example, Figure 13 also illustrates the distribution of the power and the height of the 731 DVB-T transmitters in Germany.



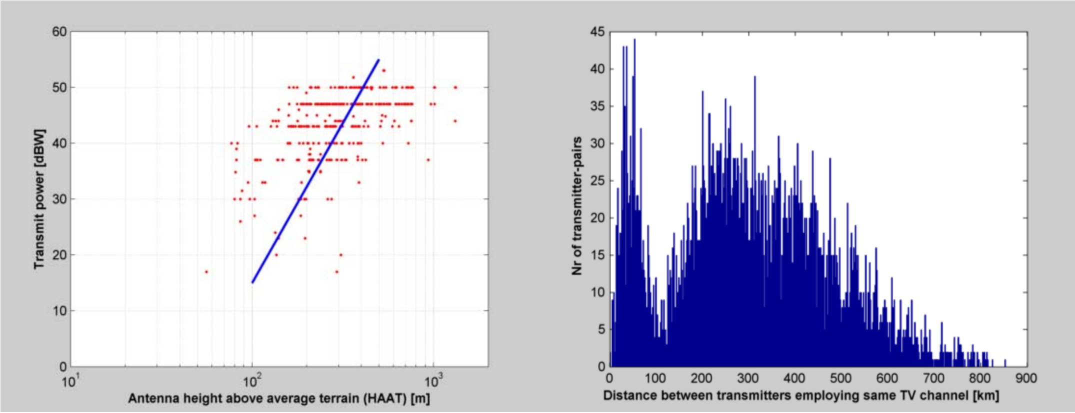


Figure 13: Characteristics of the 731-transmitter German TV network. Top left: distribution of the transmit power. Top right: Distribution of the height above average terrain (HAAT). Bottom left: Transmit power *vs.* height above average terrain (HAAT) of Germany's 731 DVB-T transmitters. Bottom right: Distance spectrum of TV transmitters using same TV channel.

Furthermore, distance spectrum in kilometers between DVB-T transmitters operating the same TV channel is shown. Note in particular the two concentrations of distances. The group of distances up to 100 km typically represents a main, high-power TV tower surrounded by one or few relay stations that operate the same frequency hence accomplishing a local single-frequency network. Such SFN-operation is known in DVB to be feasible for inter-transmitter distances of up to 90 km. The large second cluster representing distances between 100 and 800 km typically illustrates there-use of TV channels in Germany.

Figure 14 illustrates the distribution of the distances to the region where no secondary transmission is allowed for protection reasons. Note the difference between TV channels. Whereas channels 22, 39 and 56 appear densely in whole Germany, channels 31, 51 and 58 allow for large areas where secondary transmission with high powers is allowed and possible.

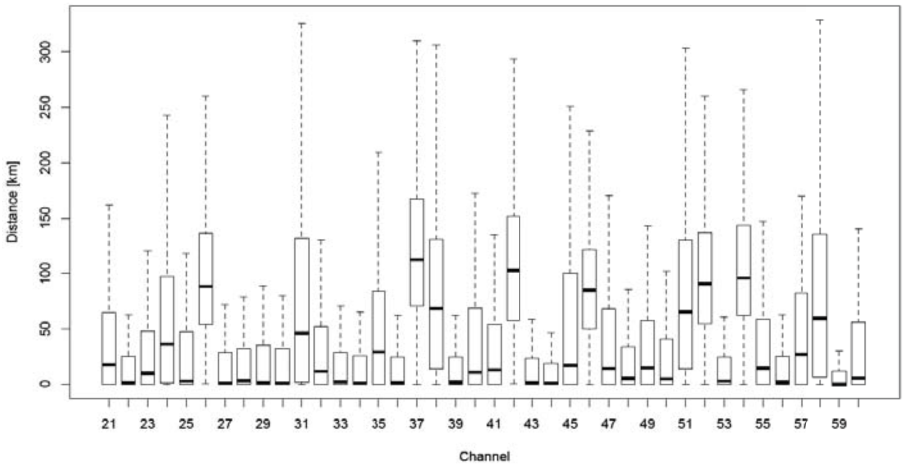


Figure 14: The distribution of distances to the protected area for the European TV channels 21-60 in the 470-790 MHz band in Germany. The three horizontal lines of the box correspond to the 25% quartile, the median and the 75% quartile. The whiskers give the data point at most 1.5 times the inter-quartile distance away from the edge of the box.

We draw the following conclusions:

1. Power and height are correlated. Operators do not deploy TV towers at high relative locations for the deployment of a low-power transmitter, and neither do they install high-power transmitters in low locations.
2. At a certain location and in a certain TV band, typically *very few simultaneous TV transmitters can be sensed*. This is an important observation since it allows for a 'sparsity'-assumption in the TV transmitter modeling. A REM construction algorithm can exploit this assumption as a (Bayesian) prior knowledge in the location estimation process of the REM construction.

As a first note it is understood that the characteristics of the TV transmitters, once installed and started to operate, will typically not change during at least weeks or months. Operators might change the frequency plan every now and then for efficiency reasons, or network maintenance, but will typically avoid to do so too often.

As a second note it is understood that in a sub-scenario, the TV transmitter characteristics are accessible by secondary users in a nation-wide database. In such case, the sensing-based REM construction merely serves as a verification or complement to the information provided by this database. Alternatively the REM construction algorithms may actually exploit the database information in order to improve the estimation performance of the radio element parameters related to the LTE HeNB's.

Finally we briefly comment on the protection of the primary TV receivers. The ITU-R has specified in [24] the required field strength for proper TV reception. In particular, for proper reception, the required field strength must exceed

$$E = 20\log_{10} f - 150.1 + SNR_{req} \quad [dB\mu V/m],$$

where $SNR_{req} = 6.9$ for QPSK-based networks, $SNR_{req} = 13.1$ for 16QAM, and $SNR_{req} = 18.7$ for 64QAM.

6.2.5.2 Secondary transmitters: LTE HeNB's radio characteristics

The sole secondary type of transmitter in this scenario (by assumption) is the out-of-band LTE Home eNodeB. In terms of transmit power, a Home eNodeB is much like a static UE. For example, while the maximum transmit power of a 3G handset is 21dBm (125 mW), the maximum transmit power of a UMTS femtocell is 10-17dBm (10-50 mW). In contrast to the handheld devices, the femtocell base station typically does not move.

Most of today's scenarios rely on a mass market for a deployment of femtocells in the end-customer's home. While there are scenarios where femtocells are envisaged to cover small outdoor hotspot, it seems reasonable to here make the firm assumption that femtocells operate indoors. When mass market deployment becomes reality the spatial distribution of these base stations will be determined by the distribution of the population's residences.

Because of the low power of the HeNB, it is likely that sensors must be in the immediate vicinity of the HeNB in order to distinguish its presence from the thermal noise floor. In other words, it is likely that any given sensor will only measure a small number of simultaneous femtocells in the same TV channel. Hence we make a similar assumption here as we did for the TV transmitters: At a certain location and in a certain TV band, typically *very few simultaneous HeNodeB's can be sensed*.

Rate of change of the characterizing parameters (location, frequency) for HeNB's is in order of hours, depending on the rate with which the operator allows re-configuration of the femtocells.

6.2.6 Description of query/answers to the REM

A user of the REM in this scenario typically will need the REM to give answers related to the radio interference field at a certain time and location and in a certain TV channel (frequency). In the most straightforward form, we will require the REM to answer a query of the form QP-001 in Table 23. Here, the REM user expects the REM to provide an estimate of the interference field in one single time-frequency-space bin:

$$\hat{P} = f(X, Y, F, T)$$

Note also that the REM is expected to provide a quality-label **C**, representing the confidence of this estimate. In this simple form, the variables **X**,**Y**,**F** and **T**, along with the answers **P** and **C** are scalar-valued.

This query represents the information that can be useful to a single secondary device at location (**X**,**Y**) preparing to operate the TV channel C at time T. The information contained in the answer will allow this device to decide whether or not to execute its planned transmission.

More sophisticated queries follow when these values are allowed to be vector-sized or when a query will ask for the *average* field strength in a time-frequency-space *region* as illustrated by QP-002 and QP-003 in Table 23.

Table 23: Queries for the field strength.

Id	**Query**	**Answer**
QP-001	"What is the value of the interference field at location (**X**,**Y**), at frequency **F** and at time **T**?"	"**P**" (scalar) with "Confidence **C**"
QP-002	"What are the values of the interference field at locations (**X**,**Y**), at frequencies **F** and at times **T**?"	"**P**" (vector) with "Confidence **C**"
QP-003	"What is the average value of the interference field at locations ($\mathbf{X_0}<\mathbf{X}<\mathbf{X_1},\mathbf{Y_0}<\mathbf{Y}<\mathbf{Y_1}$), at frequencies $\mathbf{F_0}<\mathbf{F}<\mathbf{F_1}$ and at times $\mathbf{T_0}<\mathbf{T}<\mathbf{T_1}$?"	"**P** " (scalar) with "Confidence **C**"

A secondary REM user may also be interested in knowing when the interference field values at certain frequencies or locations will drop below a certain level. This query is relevant when a secondary user wants to know whether or not it should prepare for an evacuation of the operating frequency band.

Table 24: Queries for time.

Id	**Query**	**Answer**
QT-001	"When does the value of the interference field at location (**X**,**Y**) and at frequency **F** drop below **P** dBm?"	"**T**" (scalar) with "Confidence **C**"
QT-002	"When do the values of the interference field at locations (**X**,**Y**) and at frequencies **F** drop below **P** dBm?"	"**T**" (vector) with "Confidence **C**"
QT-003	"When does the average value of the interference field at locations ($\mathbf{X_0}<\mathbf{X}<\mathbf{X_1},\mathbf{Y_0}<\mathbf{Y}<\mathbf{Y_1}$), at frequencies $\mathbf{F_0}<\mathbf{F}<\mathbf{F_1}$ drop below **P** dBm?"	"**T**" (scalar) with "Confidence **C**"

A third class of queries deal with the quest for useful TV channels. A secondary user may want to identify the TV frequency channels that are candidates for being used. This is typically relevant at start-up, but also for maintaining an up-to-date list of potential evacuation channels in case primaries show up in its operating channel.

Table 25: Queries for frequency.

Id	Query	Answer
QF-001	"At which frequencies is the value of the interference field, at location (**X**,**Y**) and at time **T,** below **P** dBm?"	"**F**" (scalar) with "Confidence **C**"
QF-002	"At which frequencies is the value of the interference field, at locations (**X**,**Y**) and at times **T,** below **P** dBm?"	"**F**" (vector) with "Confidence **C**"
QF-003	"When does the average value of the interference field at locations ($\mathbf{X_0}$<**X**<$\mathbf{X_1}$,$\mathbf{Y_0}$<**Y**<$\mathbf{Y_1}$), and at times $\mathbf{T_0}$<**T**<$\mathbf{T_1}$ drop below **P** dBm?"	"**F**" (scalar) with "Confidence **C**"

Finally, for completeness, a fourth class of queries collects the possible locations where secondary transmission is possible. This class is of less relevance than the previous classes but may be interesting for mobile secondary users.

Table 26: Queries for location.

Id	Query	Answer
QL-001	"At which locations (**X**,**Y**) is the value of the interference field, at frequency **F** and at time **T,** below **P** dBm?"	"(**X**,**Y**)" (scalars) with "Confidence **C**"
QL-002	"At which locations (**X**,**Y**) is the value of the interference field, at frequencies **F** and at times **T,** below **P** dBm?"	"(**X**,**Y**)" (vectors) with "Confidence **C**"
QL-003	"At which locations (**X**,**Y**) is the average value of the interference field, at frequencies $\mathbf{F_0}$<**F**<$\mathbf{F_1}$ and at times $\mathbf{T_0}$<**T**<$\mathbf{T_1}$ below **P** dBm?"	"(**X**,**Y**)" (scalars) with "Confidence **C**"

6.3 Non-coordinated spectrum access between PUs and SUs

This section presents the elements that need to be modelled and stored in the REM in the context of the scenarios belonging to the group *Non-coordinated Spectrum Access between PUs and SUs* introduced in the Deliverable D2.2 [1], taking also into consideration the RRM optimisation problems that were raised in Deliverable D5.1 [25] related with these scenarios.

6.3.1 General characteristics and assumptions

The group *Non-coordinated Spectrum Access between PUs and SUs* introduced in the Deliverable 2.2 [1] is characterised by cognitive radio (CR) networks coexisting with heterogeneous primary user networks that from a general perspective may exhibit different spectral features in terms of bandwidth, allowed interference or activity patterns. There is no coordination between PU and CR networks. Therefore, CR users access the spectrum in an opportunistic manner depending on the information contained in the REM.

This group of scenarios characterises from a general perspective a wide set of different applications, as described in [1], ranging from the out-of-band femtocells being a generalisation of the scenario presented in Section 6.3 without making any specific assumption neither on the particular band nor the technology to be used, the home networks, smart metering and smart grids.

The particular REM information to be stored and/or computed is tightly associated to the particular needs of the targeted RRM optimisation problems, as identified in Deliverable D5.1 [25]. In the following, the RRM problems applicable in the scenario considered here are very briefly summarised, prior to the identification of the associated REM parameters:

- Cognitive (out-of-band) femtocells: In this problem, several coexisting cognitive femtocell networks share the spectrum to provide wireless services to their associated wireless terminals without direct cooperation among them. Additionally, several PU networks with different bandwidth and coverage areas may coexist with these femtocells based on overlay spectrum sharing approach, where each cognitive femtocell has a pool of available frequency bands. The optimization problem targets the allocation of channels and power to the involved femtocells to ensure the QoS requirements of the CR users. Details of this optimization problem can be found in [26] in Sections 4.2.3 (for the general case) and 4.2.4 (for the particular case in which spectrum is in the TVWS and femtocells operate with LTE).

- Cognitive RRM exploiting heterogeneous PU types: This problem assumes CR networks accessing the spectrum in an opportunistic manner and considers the flexibility offered by the existence of heterogeneous PUs with different spectral features to be exploited in the RRM optimization. The keys point is to exploit the opportunities provided by the heterogeneity of the PUs, in order to perform the assignment of resources to the secondary users that minimizes the difference between the total available capacity and the total CR achievable data rates, thus achieving an efficient use of the available resources. Details of this problem can be found in Section 4.3.2 of [26].

- Spectrum Selection based on PU transmission patterns: This optimization problem focuses on exploiting the time dimension information, and in particular advanced statistics capturing the activity/inactivity periods of the PU behavior, to decide the appropriate channels to allocate a SU communication. The target is to perform the allocation so that the spectrum handover rate is minimized. Details of this problem can be found in Section 4.3.3 of [26].

6.3.2 REM architecture

The baseline deployment architecture for these scenarios was described in Deliverable 2.3 section 5.4 [2], following the FARAMIR sub-architecture defined for the REM. In particular, in this scenario a

CR centralized entity that coordinates the resource allocation for CR users in accordance with their QoS requirements and the characterisation of the PU users is assumed. The PU networks are classified into different types based on their spectral features. This determines the amount of the available capacity for the CR users.

The network architecture, as shown in Figure 15, is composed of CR users and a CR centralized entity. The CR users have two functionalities: sensing functionality, to detect any available resources not used by PUs, and user data communication functionality to transmit user data. In turn, the CR centralized entity is responsible of collecting sensing data and coordinating the radio resource management (RRM) based on the information from the REM, performing the allocation of resources to the CR users. Following the FARAMIR sub-architecture for the REM, it is composed of two elements: the REM SA that stores sensing measurements and the data computed by the REM Manager based on these measurements, and the REM Manager that has the data elaboration functionality for processing the measurement data to construct the REM.

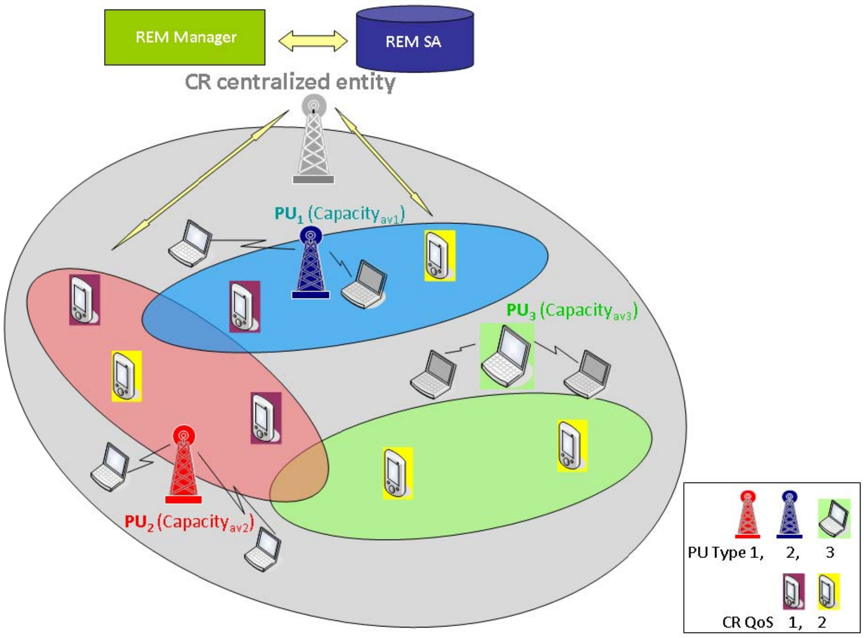


Figure 15: Architecture for Non-coordinated Spectrum Access between PUs and SUs.

In accordance with the REM model discussed previously in this deliverable, in the following, a list of the REM information parameters that are needed for one or several of the optimisation problems associated to this scenario is provided.

6.3.3 Sensing data information modeling

Some of the different contents of the REM will be obtained from measurements carried out by MCDs in accordance with the REM sub-architecture defined in FARAMIR. Each sensor will collect measurements at a specific geographical location. Depending on the specific problem to consider different types of information can be provided by these sensors:

- Received Signal Strength (RSS) measurements: These correspond to the power level received over a certain bandwidth in a specific frequency. The combination of RSS measurements from different sensors can be used to derive other parameters stored in the REM, such as the position and radiation pattern of the transmitters, as well as the propagation model characteristics, using methodologies like the one presented in [26].

- Signal detection measurements: This corresponds to a binary indication of whether a signal is present or not in a given band. Classical energy detection can be used for this purpose. The processing of this information over different frequencies and times allows building the statistics to characterize the PU activity that are described in previous section.

- Cyclostationary feature detection: This detection allows to identify not only the activity over a primary band but also to extract specific PU signal features such as the maximum of the autocorrelation function and the interval time in which this maximum is detected. These elements allow computing aspects such as guard interval length, symbol duration, and subcarrier spacing in case of OFDM signals that can serve to classify heterogeneous PUs and correspondingly to associate to each PU different allowed interference levels.

Table 27 summarizes the model of the data reported by the sensors based on the above considerations. Like in previous sub-sections, the list is exhaustive and can be particularized depending on the considered optimization problem and the type of sensing carried out.

Table 27: The model of the data reported by the sensors.

Parameter	**Size**	**Units**	**Comments**
Sensor label	scalar	[no dimension]	A unique sensor identifier
x-coordinate	scalar	[Latitude]	latitude of the measurement
y-coordinate	scalar	[Longitude]	longitude of the measurement
Frequency band	vector	[MHz]	Bands of the measurement
Time label	scalar	[s]	Time of the measurement
RSS	vector	[dBm]	Measurements for each band
Signal presence indicator	vector	[no dimension]	In case of energy detection, for each band it takes the value 1 if the signal is detected and 0 otherwise

Cyclostationarity features	vector of duples	[no dimension, s]	In case of cyclostationarity detection for each band it gives two values: the maximum of the autocorrelation function and the time instant in which this occurs.

6.3.4 Propagation modeling

An adequate characterization of the propagation conditions is required in this scenario mainly for two reasons. It should enable on the one hand the estimation of the interference that can be generated to the primary users and on the other hand to decide whether the communication between CR users is feasible or not depending on the propagation losses in their link. Propagation modeling is in particular used by the RRM optimization problems "cognitive (out-of-band) femtocells" and "Cognitive RRM exploiting heterogeneous PU types" described previously in Section 6.3.1.

The characterization of the propagation model will typically be given by the path loss exponent and the losses at 1m. Also some metric to characterize the shadowing effects (e.g. standard deviation and shadowing decorrelation distance) can be included. This characterization should be given for the area of interest where the CR network operates.

Table 28 summarizes the list of parameters to characterize the propagation model in a given geographical area and/or frequency.

Table 28: Summary of propagation model parameters.

Parameter	**Size**	**Units**	**Comments**
Path loss exponent	Scalar	[no dimension]	Value of α in the classical propagation model expression: $L(dB)=Lo+10\alpha \log d(m)$
Loss at 1m	Scalar	[dB]	Value of Lo in the classical propagation model expression: $L(dB)=Lo+10\alpha \log d(m)$
Shadowing standard deviation	Scalar	[dB]	Standard deviation of the shadowing process
Shadowing decorrelation distance	Scalar	[m]	Decorrelation distance of the shadowing process

6.3.5 Radio element parameter modeling

The radio elements associated to this scenario are the PU and the SU transmitters and receivers. Focusing on the specific optimization problems summarized in Section 6.3.1, the following information needs to be stored in the REM to model these transmitters:

- Transmitter characterization: This includes a list of general features to be used to characterize a primary and/or secondary transmitter. For instance, in the case of the "cognitive (out-of-band) femtocells" optimization problem this list is associated to the different femtocells that belong to an interfering set (as defined below). The associated features are:
    - position
    - radiation pattern
    - transmitted power
- Interfering set: It corresponds to the set of femtocells within the interference range of a given femtocell for a given interference threshold. This information can be computed by the REM manager upon request of the RRM for the "cognitive (out-of-band) femtocells" optimization problem.
- Available frequency bands: This information refers to the frequencies that are available for establishing the CR communication, including both the central frequencies and the bandwidths based on PU usage. This is applicable to the three optimization problems mentioned above. The information on these bands will be obtained from the frequencies used by the PU transmitters.
- PU Allowed Interference levels: It is the maximum interference power that can be tolerated by the PU receiver when sharing the spectrum with a CR user. It is used for the adaptation of the CR transmission power in the "cognitive RRM exploiting heterogeneous PU types" optimization problem.
- Characterization of the PU activity in each available channel: It corresponds to statistics reflecting the activity (ON) and inactivity (OFF) periods to be used in the optimization problems "Cognitive RRM exploiting heterogeneous PU types" and "Spectrum Selection based on PU transmission patterns". Statistics will be associated to a certain geographical area. The list of statistics to be considered includes the following ones (see section 4.3.3 of [25] for details):
    - Average value of *ON* and *OFF* periods.
    - Variance of ON and OFF periods.
    - Duty Cycle

- o Empirical pdf (probability density function) of ON and OFF periods
- o The conditional probability of observing a certain duration of the OFF period given a certain duration of the last ON period was observed.
- o A measure of dependence level between successive ON/OFF periods (see [25])
- o Conditional mean of OFF given the last observed outcome of ON

- Allowed Interference threshold: it is the maximum interference power density that can be tolerated by the CR wireless receiver for a given QoS requirement, to be used in the "cognitive (out-of-band) femtocells" optimization problem
- QoS requirements of the CR terminals: It corresponds to the minimum data rate required by the CR terminals, and is applicable to the three previously mentioned optimization problems.

Based on the above considerations, Table 29 lists a summary of the characteristics of the different considered radio elements that need to be included and/or computed in the REM. Information regarding the type of information element is provided in each case. Note that the list is exhaustive, and that not all the elements may be necessary in all the considered optimization problems. Note also that the list is subject to refinements once more detail in the development of the solutions for the problems is available.

It is worth mentioning that the elements of the list in Table 29 can be combined/filtered to get additional information elements such as the Interfering set, that will be obtained based on the set of femtocells within the interference range of a given femtocell for a given interference threshold, as used in the "cognitive (out-of-band) femtocells" optimization problem. In this way, this type of additional information does not need to be stored permanently but can be computed on a per request basis.

Table 29: Summary of modelled radio element parameters.

Parameter		**Size**	**Units**	**Comments**
Transmitter characterization		Vector of structures with the elements indicated below per transmitter		
	Label	Scalar	[no dimension]	Identifier of the transmitter

	Transmitter position [x-coordinate,y-coordinate]	Vector (dimension 2)	[Latitude, Longitude]	Position of each transmitter (e.g. femtocells) including latitude and longitude coordinates
	Radiation pattern	Vector (dimension 360/Δ)	[dB]	Transmitter radiation pattern in steps of Δ degrees (e.g. 10º). Note that direction is implicit in this list of values as the angle with the maximum associated value.
	Transmitted power	Scalar	[dBm]	
	Frequency band	Scalar	N/A	Label of the frequency band used by the transmitter
Interfering set		Vector	[no dimension]	Labels of the transmitters within a given interference range.
Available frequency bands and associated characteristics		Vector of structures with the elements indicated below per frequency band		
	Label	Scalar	[no dimension]	Identifier of the frequency band
	Central frequency	Scalar	[MHz]	Central frequency of the considered band
	Bandwidth	Scalar	[MHz]	Total bandwidth available in the band
	Geographical area	Vector	[Latitude, Longitude]	Limits of the geographical area where the information of a certain band is applicable.
	PU Allowed Interference level	Scalar	[dBm]	Maximum interference power that can be tolerated by the PU receiver in each frequency band.
	Average value of ON period	Scalar	[s]	Average duration of activity periods in the considered band
	Average value of OFF period	Scalar	[s]	Average duration of inactivity periods in the considered band

	Variance of ON period	Scalar	[s^2]	Variance of activity periods in the considered band
	Variance of OFF period	Scalar	[s^2]	Variance of inactivity periods in the considered band
	Duty Cycle	Scalar	[no dimension]	Duty Cycle in the considered band measured as the ratio of activity time with respect to total time in a certain interval.
	Pdf of ON period	Vector (dimension N)	[no dimension]	Probability density function of the activity periods in the considered band. The dimension N corresponds to the number of intervals in the pdf.
	Pdf of OFF period	Vector (dimension N)	[no dimension]	Probability density function of the inactivity periods in the considered band. The dimension N corresponds to the number of intervals in the pdf.
	Conditional pdf of OFF period given the last ON period	Matrix (dimension NxN)	[no dimension]	Conditional pdf between consecutive activity and inactivity periods in the considered band.
	Dependence level between successive ON/OFF periods	Scalar	[no dimension]	Value between 0 and 1 indicating how dependent are successive ON and OFF period (0: independent, 1: fully dependent).
	Conditional mean of OFF period given the last observed ON period	Vector (dimension N)	[s]	Average of the OFF period duration conditioned to the previous ON period duration
Allowed Interference threshold for CR users		Scalar	[dBm/Hz]	Maximum interference power density that can be tolerated by the CR wireless receiver
QoS requirement of CR users		Scalar	[b/s]	Minimum data rate required by the CR terminals

6.3.6 Description of query/answers to the REM

During the resource allocation process to the CR users, the cognitive RRM will interact with the REM Manager in order to get the required information in each case. For that purpose, the protocols and interfaces defined in [2] will be used. In particular, the message exchanges to request the different REM data to the REM Manager are based on the FDATA_REQ and FDATA_RSP messages described in Section 3.2.3 of [2]. This allows considering a general query/answer model composed of two different messages:

- FDATA_REQ: It will contain the identification of the REM information element that is being requested (among those listed in the tables of previous sub-sections), as well as the associated inputs, if any, to compute or filter it (e.g. geographical position, interference threshold, etc.).
- FDATA_RSP: It will contain the associated response to a previous FDATA_REQ, including the value of the REM information element as indicated in the REM.

It is worth mentioning that, in order to get the associated response, the REM Manager may have to interact with the REM SA or with other elements of the architecture. In turn, the REM SA could require the reception of new measurements from the MCDs.

An example of the interaction with the REM is illustrated in Figure 16, corresponding to the cognitive out-of-band femtocells optimization problem. The process starts when the RRM (that can be either local to one femtocell or global controlling a number of femtocells) needs to decide the adequate frequency and power for operation of a femtocell. In that case, the RRM entity will send a number of FDATA_REQ messages to the REM Manager asking for the available frequency bands, the set of interfering femtocells and their characteristics, and the path loss characterisation. To provide this data, the REM manager can carry out different actions. In some cases, some data will not be associated to measurements but to specific policies, as it would be the case of the interference threshold or the QoS requirements. Then, in case this data is not available at the REM manager, it will be requested to some policy manager. In other cases, data will be related to measurements carried out by MCDs. This will require the interaction with the REM SA to get the raw measurements from the MCDs and perform the corresponding computations (e.g. path loss, discovery of other femtocells, etc.) if not already carried out before. The results will be provided to the RRM entity using FDATA_RSP messages.

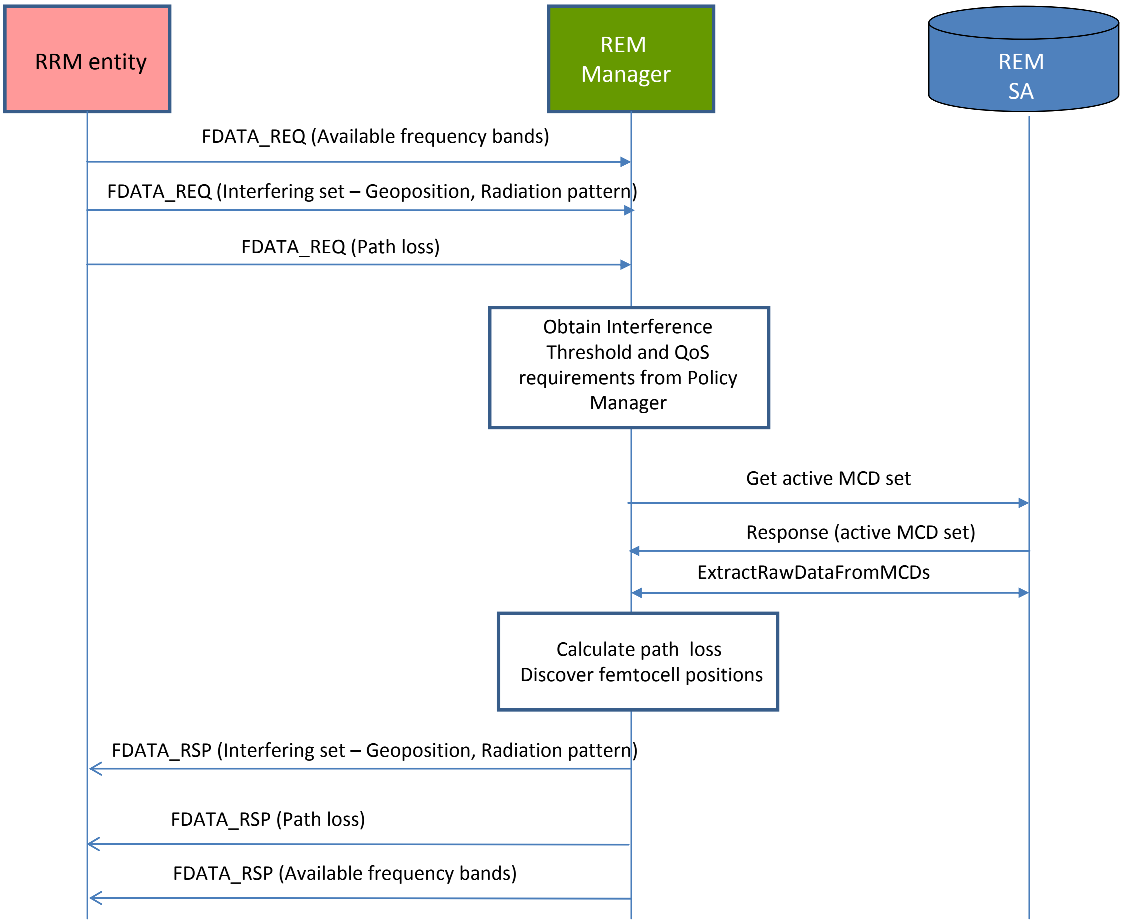


Figure 16: Example of the interactions between RRM, REM Manager and REM SA in the case of cognitive out-of-band femtocells.

7 Conclusions

In this document we provided a detailed description on what information types REMs should contain for each envisioned scenario of interest, presented however as special cases of a broad, generic information-representation-and-flow model. We discussed the model representation of such information, how is to be arranged, indexed and interpreted, and how to be used, all that in a bandwidth-processing economic fashion. Application-Programming Interfaces (APIs) were also discussed especially focussing on requirement on the types of supported queries from the REM in order to pave the way towards pragmatic implementation of such models.

Starting from a generic REM data model description we narrowed the scope to the most challenging part of the design of REM's, namely the dynamic aspect of information gathering and processing, achieved mainly via the deployment and active exploitation of various types of spectrum-assessing (measuring and processing) devices. A more detailed description of the various modeling options of representing such information was then given based on a generic DREM approach. The three main categories of information related to the construction of the DREMs were identified to be

a) the sensed data, directly related to information about the active radio elements;

b) information models that build up knowledge about the radio elements using (a), and

c) methodologies together with appropriate modeling approaches to reconstruct the Radio Interference Field using (b).

Closing the generic DREM description, the crucial application of policy derivation was described in a generic way that could fit a large number of specific scenarios. Furthermore, since any potential implementation will relate to some specific scenario of interest, we delineated a number of typical scenarios and demonstrated a systematic mapping of the broad architecture and information process to each such case, identifying all the related components that comprise it. In each such case, a thorough description of the information data modeling, gathering, exchanging and processing was detailed in a way as to validate the proposed general framework.

While the present document develops many of the key aspects of the information and reference models for generic and extendible radio environment maps, more work is needed towards the final architecture and implementation designs especially related to development of the concrete data representations for the related interfaces and storage solutions. Our intention is to use the present deliverable as a living document that will be extended over time as this work continues. Snapshots of this evolving documentation will be also then used in subsequent design documents on architectural and implementation levels whenever specification of the information models used are needed.

Glossary and Definitions

Term	*Description*
3GPP	3rd Generation Partnership Project
AoA	Angle of Arrival
BS	Base Station
CoRaL	Cognitive Radio Language
CR	Cognitive Radio
CSMA	Carrier Sense Multiple Access
DREM	Dynamic Radio Environmental Map
DSA	Dynamic Spectrum Access
eNodeB	evolved Node B
EPC	Evolved Packet Core
FFT	Fast Fourier Transform
GPS	Global Positioning System
GSM	Global System for Mobile communications
GUI	Graphical User Interface
GW	GateWay
HDR	High Data Rate
HeNB	Home eNodeB
HSPA	High Speed Packet Access
LTE	Long Term Evolution
LTE-TDD	LTE – Time Division Duplex
MCD	Measurement Capable Device
MCS	Modulation and Coding Scheme

Term	*Description*
MME/S-GW	Mobility Management Entity / Serving GateWay
O&M	Operation & Maintenance
PC	Personal Computer
PCD	Policy controlled Cognitive radio Device
PDP	Policy Decision Point
PE	Policy Engine
PEP	Policy Enforcing Point
PI	Policy Interface
PM	Policy Manager
PR	Policy Reasoner
PS	Policy Server
PU	Primary User
REM	Radio Environmental Map
REM SA	REM data Storage and Acquisition unit
RF	Radio Frequency
RFU	RF Unit
RRM	Radio Resource Management
RSSI	Received Signal Strength Indicator
SINR	Signal-to-Interference-and-Noise Ratio
SNR	Signal-to-Noise Ratio
SoA	State-of-the-Art
SU	Secondary User
ToA	Time Of Arrival

Term	*Description*
TVWS	TV White Space

References

[1] FARAMIR Deliverable D2.2:"Scenario Definitions", http://www.ict-faramir.eu/

[2] FARAMIR Deliverable D2.3 "Preliminary System Architecture", http://www.ict-faramir.eu/

[3] FARAMIR Deliverable D6.1. "Prototype Requirement Analysis", http://www.ict-faramir.eu/

[4] Youping Zhao, "Enabling Cognitive Radios through. Radio Environment Maps", Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University, May 2007.

[5] C. Botteron, "A statistical analysis of the performance of radio location techniques," Ph.D dissertation, Dept. Elec. and Comp. Eng., Univ. of Calgary, Alberta, 2003.

[6] F. Perez Fontan and P. Marino Espineira, "Modeling the Wireless Propagation Channel" Willey, 2008.

[7] IST-WINNER II Deliverable D1.1.1 v1.0, "WINNER II Interim Channel Models", December 2006.

[8] D. Denkovski, V. Pavlovska, V. Atanasovski and L. Gavrilovska, "Novel Policy Reasoning Architecture for Cognitive Radio Environments," *IEEE GLOBECOM2010*, Miami, FL, USA, December 2010.

[9] D. Elenius et al., "CoRaL–Policy Language and Reasoning Techniques for Spectrum Policies," *8th IEEE International Workshop on Policies for Distributed Systems and Networks*, Washington, DC, USA, 2007.

[10] XG Prolog Policy Engine. Available at: http://xg.csl.sri.com/prolog.php.

[11] Daniel S. Baum and others. Final Report on Link Level and System Level Channel Models. Technical report, IST WINNER, 2005.

[12] Gamini Senarath and al. Multi-hop Relay System Evaluation Methodology. 2007.

[13] US Federal Communications Commission, "Second Report and Order and Memorandum Opinion and Order, in the Matter of Unlicensed Operation in the TV Broadcast Bands", Tech. Report 08-260, Nov. 2008.

[14] Ofcom, "Implementing Geolocation", Consultation, 2010.

[15] Infocomm Development Authority of Singapore, "Trial of White Space Technology Accessing VHF and UHF Bands in Singapore", Technical Report, 2010.

[16] ITU-R, "Method for point-to-area predictions for terrestrial services in the frequency range 30MHz to 300 MHz", International Telecommunication Union, Geneva, Recommendation BT.1368-8, 2009, Recommendation P.1546-4, October 2009.

[17] ITU-R, "Calculation of free-space attenuation", International Telecommunication Union, Geneva, Recommendation P.525-2, 1978-1982-1994.

[18] http://www.bundesnetzagentur.de/cln_1912/DE/Sachgebiete/Telekommunikation/RegulierungTelekommunikation/Frequenzordnung/Rundfunk/Rundfunk_Basepage.html

[19] http://appl.at-ez.nl/dav/index.html

[20] http://www.teleoff.gov.sk/index.php?ID=377

[21] http://www.pts.se/sv/Dokument/Rapporter/Radio/2008

[22] http://www.teracom.se/Sandarinformation/Hitta_ratt_tv_mast

[23] http://stakeholders.ofcom.org.uk/broadcasting/guidance/tech-guidance

[24] ITU-R, "Planning Criteria for digital terrestrial television services in the VHF/UHF bands", International Telecommunication Union, Geneva, Recommendation BT.1368-8, 2009.

[25] FARAMIR Deliverable D5.1 "Conceptual Framework for enabling Measurement-based Mechanisms".

[26] Liliana Bolea, Jordi Pérez-Romero, Ramón Agustí, Oriol Sallent, "Context Discovery Mechanisms for Cognitive Radio", IEEE Vehicular Technology Conference in Spring (VTC-Spring), May, 2011.