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

FARAMIR

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Final System Architecture

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Abstract:

This document describes the final FARAMIR architecture which includes the system-level architectural description of the REM-related entities, the capabilities of those entities and the nature of communication between those entities. This architectural work is performed for a selected set of FARAMIR scenarios among those of D2.2 and for specific Radio Resource Management (RRM) Optimization tasks defined for those scenarios in D5.1.

Keywords: Radio Environmental Maps, Final system architecture

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1 Introduction

One of the main goals of the FARAMIR project is to conceive, develop and demonstrate future wireless cognitive systems which are environment-aware and capable of autonomously optimizing their operations using this environment awareness. The cognitive tool that provides the environment awareness and thus allows this capability is called as Radio Environmental Maps (REMs). FARAMIR project works not only on advanced methods of constructing realistic REMs, but also on a ***"focused technology development"*** based on REMs, which can be commercially exploited. To achieve the latter, FARAMIR has measurable and targeted technology goals, whose embodiment can be found in the prototyped project innovations.

One of such essential project goals is to develop and demonstrate reference architectures and functional entities related to REMs on concrete real-world applications showing their real-world value in radio resource optimization. For this purpose, several scenarios have been selected among the multitude of scenarios defined in the beginning of the project [1], for which a detailed system architecture work has been carried out. This detailed architecture work takes the generic functional architecture of REMs defined and developed in D2.3 [2] to detailed and ready-to-implement *system architectures* for these selected scenarios.

This deliverable presents this system architecture work for four FARAMIR scenarios:

1. In-band femtocell optimization,
2. LTE in TV WhiteSpaces (TVWS),
3. Non-coordinated spectrum access between Primary Users (PUs) and Secondary Users (SUs)
4. Ad-Hoc networks

The main motivations behind the choice of these four scenarios among the others can be listed as follows: 1) they offer different deployment architectures; other uses cases are minor variations of these four types (in other words, the functionality and interface requirements are covered by these four scenarios), 2) these scenarios makes good compelling reasons and demonstrate the (practical) usage of REMs, 3) The deployment scenarios are considered along the exploitation capabilities of the individual partners.

For each scenario, first, an explanatory description and the related optimization problem is given. This is followed by a short description of functional and operational system requirements. Then, the mapping of the generic functional REM architecture blocks defined in D2.3 on the physical network entities is described, followed by a detailed description of the involved interfaces, with protocol definitions and the related Message Sequence Charts (MSCs). Finally, the associated information and data models are given. The specificity of any scenario with respect to system architecture (such as the use of a dedicated sensor network for the in-band femtocell optimization) is also taken into account.

Common to all scenarios, data integrity, reliability and security issues are also addressed in the final section, focusing mainly on the following three points:

1. Given that the measurements are imperfect, how to assure reliability?
2. What kind of security issues is relevant for each scenario and how to deal with them? Note however that, since security is not the focus of the project, the aim of this point is rather to raise the issue than to propose solutions.
3. How to handle malfunctioning measurement devices and other components?

A statistical point of view is adopted for the above points, where robust statistics are proposed.

Note that the system architecture definition is the key component in implementing a real system. Therefore, the system architecture work reported on in this deliverable constitutes the basis for the ongoing prototyping work of the project as well.

2 FARAMIR functional architecture

This section will be a brief overview of the FARAMIR functional architecture which was described in detail in deliverables D2.3 (cf. Figure 1) and (regarding the used data model) D4.1. The final system architecture will be based on this functional architecture through mapping of the functional architecture blocks on network entities and defining the communication between those entities for each pre-selected scenario and the associated Radio Resource Management (RRM) optimization task.

The preliminary FARAMIR functional architecture, described in D2.3, defined the main functional blocks and interfaces required for REM construction. Namely, the REM functional architecture defines four REM related important blocks:

1. **Measurement Capable Devices (MCDs)**, which represent the network elements capable of performing spectrum related measurements. The MCDs in a system architecture viewpoint can refer to mobile terminals (capable of extracting the Received Signal Strength Indication, RSSI), dedicated spectrum sensing devices etc. The MCDs should be capable of performing geo-location and spectrum measurements.

2. **REM data Storage and Acquisition unit (REM SA)** is the main storage in the FARAMIR functional architecture. It stores and manages the measurement data coming from the MCDs, as well as the processed data by the REM Manager. The REM SA supports the storage, representation and queries based on a rich data model, which has been described in detail in deliverable D4.1, and will be further enriched towards deliverable D4.3 (with precise specification of the required elements for the key scenarios being defined in the present document). Examples of the elements in the data model include:

    - Transmitter types and configurations (can be manually added to the storage or identified by feature detection technique by the MCDs)
        - This includes the used technology, allowable interference levels, transmission power, used frequencies, and so on.

    - Transmitter locations (can be manually added to the storage or localized using transmitter localization techniques)
        - Locations as individual points in a given coordinate system
        - Support of probabilistic localization representation in selected areas
        - Region representation support

    - Radio interference fields (estimated empirically or modelled)
        - Basis function representation
        - Image/pixel based representation

    - Service areas (estimated empirically by distributed measurements or modelled using known transmitter locations and propagation models)

        - Binary pixel images
        - Representation in terms of polygons
        - Probability distributions for coverage over regions

    - Propagation models (can be manually added or estimated online)
        - Defined in terms of function parameters
        - Associated with location regions
        - Terrain data representation for, e.g., the Longley-Rice model

    - Activity information (activity periods, duty cycle, on-off models etc.), received signal strength spatial distribution (empirically estimated with distributed measurements or analytically using propagation, shadowing and fading models)

The REM Storage can be implemented in a monolithic fashion, or be hierarchically distributed over the network. The local REM data can be replicated using specific replication policies into a global REM Storage.

3. **REM Manager** is the functional block in charge of requesting measurements, extracting and processing the data from the REM SA. Namely the construction of REM data can refer to empirical estimation or modelling based on predefined knowledge (as previously described).

4. **REM User** represents potential beneficiaries from the REM data

    - The functional architecture described in D2.3 limited the "REM User" entity only on a Graphical User Interface (GUI) functionality, i.e. real-time presentation of the REM data. This was subsequently extended to allow integration towards RRM functions and other applications of REM data.

    - The REM User in general can refer to other resource management entities, such as RRMs or Policy Managers (PMs) that can benefit on the REM knowledge, in optimization and management of the secondary system into efficient spectrum usage.

Three important interfaces exist in the FARAMIR functional architecture:

1. **MCD - REM SA interface**, handling the communication between the MCDs and the REM SA in the functional architecture. This interface is used to handle control traffic required for the registration/de-registration of the MCDs in the REM SA, the configuration/re-configuration of the MCDs, and measurement requesting. In the data plane this interface transfers measurement data from the MCDs associated to the geo-location and time of collection.

2. **REM SA – REM Manager interface**, managing the interactions between the referred entities. Via this interface the REM Manager can extract data from the REM SA, such as raw

measurements, static PU information, active MCDs information etc., to perform the required REM calculations. In the opposite direction this interface handles the restitution of processed REM data into the REM SA. Through this interface, the REM Manager can also initiate MCDs reconfiguration and new measurements if required.

3. **REM Manager – REM User interface**, which enables the practical usage of the REM data. This interface provides the REM User with ability to initiate the processing and gather the processed REM data from the REM Manager. This REM data can refer to spatial radio interference fields, primary user locations, spectrum activity patterns, time and spatial statistics, etc. If the REM User refers to RRM or PM functional block, the processed REM data can be used to facilitate efficient spectrum management by the referred.

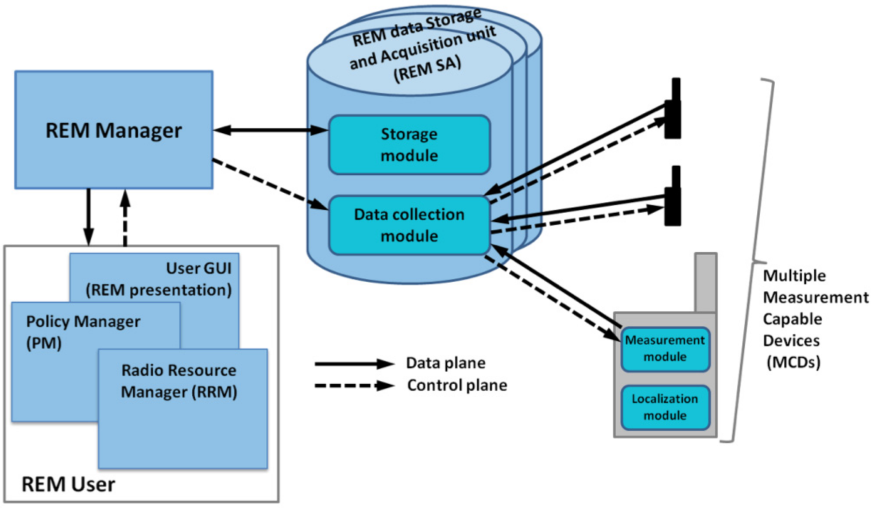


Figure 1: FARAMIR functional archtecture [1].

The FARAMIR functional architecture should also include the possibility of hierarchical organization, i.e. having different instances of REMs at different hierarchical levels with different spatial and temporal characteristics. Figure 2 presents such a hierarchically organized REM architecture. The data from the local REM Storages is replicated on a global REM Storage, to provide a wider REM coverage.

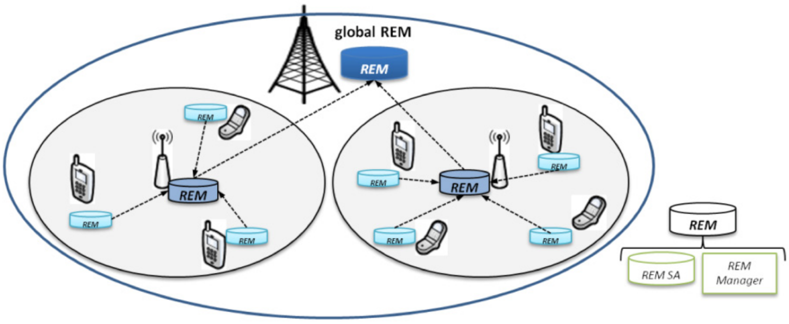


Figure 2: REM hierarchy.

On the level of the functional architecture, there are no particular restrictions on how it is mapped onto the high-level system architecture within a particular realization. However, in most systems (as we shall see in the next section when specific system architectures are discussed) the mapping would follow the classical Control plane – Data plane division of the target system architecture in a very natural manner (these control and data planes should not be confused with the REM architecture planes discussed above). This typical system architecture is illustrated in the Figure 3 below.

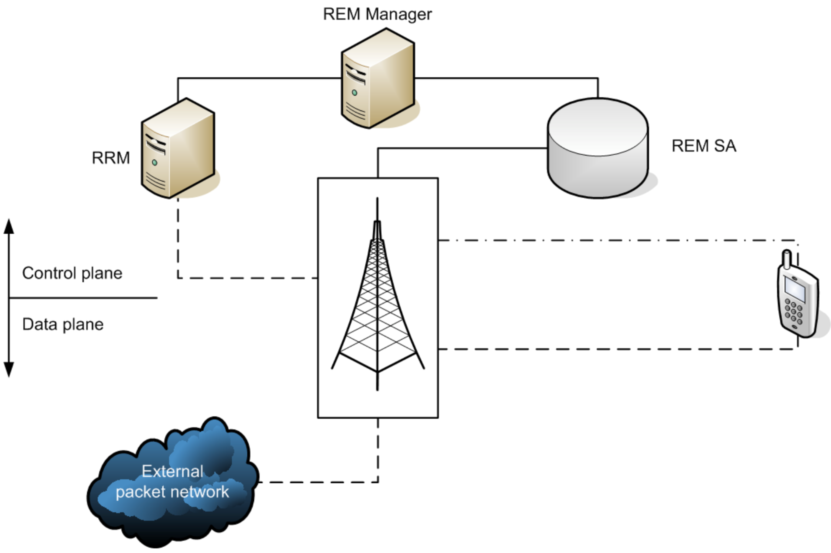


Figure 3: Example of a mapping of the functional architecture to the control and data planes of a particular communications system. The nature of the interfaces indicated by different line styles are discussed in the text.

From the figure we see that there is a natural mapping of the REM functionality towards the control plane (and management plane in case of more complex system architectures), although the actual flow of measurement data might still follow through data plane. The different line styles used in the figure correspond to different types of interfaces in the system. The solid lines map directly on the three key interfaces discussed above, where as the dashed lines are completely system specific. The dot-dashed line between the terminal and the base station is somewhat of a special case, since the REM-SA – MCD would often be at least in part realised through that interface. Often this can be accomplished directly by exploiting a suitable measurement interface already present in the targeted system, whereas in simpler architectures (such as legacy Wi-Fi technologies) there might be need for implementing parts of this interface through application layer mechanisms and using the usual data plane protocols for communications.

Finally, we note that the access to the different interfaces and the functionality offered through those will also be highly specific to the targeted scenario and system architecture. For example, in most cellular network applications the interfaces would only be accessible from entities residing within the operator network itself. Only if explicit agreements have been made, or situation such as roaming occurs, would instances of these interfaces be accessible and used between different stakeholders. In security critical applications even more strict limitations might be in place, together with strong authentication, authorization and accounting mechanisms. At the other end of the spectrum are scenarios of open access type. If the REM functionality is provided by, for example, a national regulator, the REM Manager – REM User interface might very well be at least partially open for all stakeholders.

3 FARAMIR system architectures

The specific set of functions that have to be achieved by the functional architecture blocks of Figure 1 are determined by the functional and operational requirements imposed by the particular REM application scenario and the associated RRM optimization. Depending on the REM application and the associated RRM optimization task at hand, the functional blocks of Figure 1 can be implemented in different physical network entities. It may also happen that more than one functional block are grouped in a single physical network entity. In any case, these entities exchange data whose nature and characteristics need to be well-defined. For this purpose, an *information architecture* must be specified, defining what information has to be provided and in what format, so that the functions defined in the functional architecture can be achieved. The *physical architecture* has to meet both the functional architecture and the information architectures. Other constraints from the real world also have impact on the physical architecture as cost, performance, security, scalability, stability, robustness, regulation, traffic, operator preferences determined by high-level strategies etc.

It is important to note that there is not a unique way of building a system architecture, so many possible architectures for a specific application may exist. From that aspect, the blocks in Figure 1 act as the fundamental building blocks of any possible implementation of final FARAMIR architectures each of which are tailored according to the specific requirements of the scenario and the associated RRM optimization.

3.1 FARAMIR system architecture design guidelines

In this chapter we provide the mapping of the FARAMIR functional architecture towards specific implementation or system architectures, targeting the key REM application scenarios identified in the deliverable D2.2. However, before focusing on the specific system architecture designs, we shall first outline the basic design guidelines that have been adopted in developing these from the general functional architecture. We believe these guidelines to be of independent value, providing guidance in applying the FARAMIR approach to new scenarios as well.

First issue to be considered in any system architecture design in this context is the expected application of radio environmental information. Typical examples of application scenarios, outlined in detail in D2.2, include optimization of the way radio resources are utilized, diagnostics of the network coverage and performance, as well as development of radio environmental awareness for purposes such as monitoring compliance to spectrum access policies, and understanding better the overall spectrum usage in a region. Each of these imposes different boundary conditions and objectives on which kinds of information should be obtained from REMs, where that information should be accessible, and also how accurate and up to date that information should be both in spatial and temporal domains. From these considerations, and by carefully studying the possible deployment architectures and constraints imposed on those by the scenario at hand, much of the REM design flows out naturally. In particular, the necessary components of the data model, as well as the radio environmental inputs that need to be collected are found naturally this way.

Regarding constraints on the possible deployment architectures, for many of the foreseen application scenarios a well-defined physical architecture is already in place. This is especially so in network operator scenarios, in which extensive network deployments already exist, implementations of the various individual network elements typically following the 3GPP standards. In such cases the derived system architecture for REM applications should respect those pre-existing architecture to the extent possible, unless, for example, performance considerations make that impossible and the gains from extending or even violating the existing architecture can be convincingly demonstrated. This implies two issues that should be considered in the system architecture design. First, there should be a clear mapping between the REM architecture blocks introduced in detail in the previous chapter, and the already present architectural entities in the scenario-specific network architectures. Second, existing architecture already often provide rich frameworks for information transfer and exchange between their architectural elements. The design of specific realizations of the interfaces present in the functional architecture can thus often be greatly simplified. The existing interfaces and data model should also be critically considered in terms of their sufficiency for the incorporation of the REM system architecture. For example, there are usually limitations on the accuracy of information that can be conveyed due to use of fixed representations, and in some cases possible signaling payloads are rather short, resulting in potentially very high signaling overheads for transport of large data items. Also the hierarchical or layered structures for REM data processing and collection should be considered in this context.

Finally, realization and implementation of any specific REM system architecture has also potential implications for the actual physical network deployments. For example, in scenarios in which the existing transceivers in the network are too sparse for accurate REM construction, should sufficient benefits from REMs be expected, deployment of additional spectrum sensor networks might turn out to be appropriate. Deployment of such sensor networks might also be appropriate for reasons going beyond simple performance considerations. For example, public bodies, regulators, and licensed primary users in various spectrum sharing scenarios could utilize them for pure monitoring purposes, for observing regulatory compliance, or, finally, for monitoring the compliance of possible secondary users to agreed upon spectrum access conditions. Many such scenarios would benefit from measurements obtained using a network that does not directly belong to any of the other stakeholder involved. Therefore, issues such as deployment of additional measurement capable devices in a given deployment architecture should be considered not only from performance point of view and in terms of functional requirements, but also in terms of possible non-functional requirements imposed on REM system architectures in such scenarios.

The presentation of the concrete system and deployment architectures in the subsequent sections follows the above discussion. For each of the scenarios considered following issues are discussed in detail and the corresponding architectural details specified:

1. First, short description of the scenario and the associated RRM optimization problem are given. While discussed also in earlier deliverables D2.2 and D5.1, key aspects of both are summarized here for completeness.

2. The overall functional and operational (system) requirements imposed by the optimization problem are outlined, and their implications to the concrete REM deployment architecture and data model are discussed.

3. The physical architecture definition is given by mapping of the overall functional and operational (system) requirements on the specific physical network entities. As discussed above the complexity and restrictiveness of this step depends heavily on the constraints imposed by the already present communications architecture.

4. Mapping of the functional REM architectural blocks on the physical architecture is given, together with the rational for choosing precisely the mapping chosen in the text. Where appropriate, alternatives are also discussed for the made choices.

5. Construction of the information architecture for the architecture is carried out using the requirements concerning the data model elements exchanged between different entities as well as the characteristics (temporal, spatial granularity etc.) of these information items.

6. Finally, protocol definitions through Message Sequence Charts (MSCs) as well as concrete data representation specifications are given for the various interfaces from the functional architecture that are present in the given system architecture.

The level of detail for each of these discussion points will vary somewhat from one system architecture to another, mainly depending on the types of technologies already present in the corresponding networks. For example, in intra-operator scenarios substantial constraints are present from existing network deployments that should be respected, whereas for tactical and ad hoc networks much greater flexibility can be afforded in terms of architecture design.

3.2 In-band femtocell optimization

One of the key scenarios chosen for system architecture development is the "Self-Configuration and Self-Optimization of Femtocells" (scenario 2.2.1 of [1]) where the aim is to use REMs in performing self-configuration and self-optimization of femtocells. Note that our focus is on LTE femtocells, i.e. femtocells that use the LTE air-interface and are denoted as Home eNBs or HeNBs for short in 3GPP terminology. Therefore, 3G femtocells are out of the scope of this work, and “femtocells” will mean LTE femtocells in the sequel. Nevertheless, a glimpse of an extension of the proposed REM system architecture for LTE femtocells on a multi-technology setting (including 3G and LTE) will be given. Since this is one of the core scenarios considered in the project, we shall give a very detailed presentation of the resulting system architecture for this particular case, and slightly more simplified versions for the later scenarios.

3.2.1 The description of the scenario and the optimization problem

Femtocells (Home eNBs or HeNBs in 3GPP terminology) are very small base stations that are located in customers' premises. They are plug-and-play devices whose installation and mode of operation is completely under the control of the customers. Hence, the operator does not have any control on the deployment, nor on the rate of change of the femtocell networks. Being deprived of the initial dimensioning/planning as well as the conventional optimization processes, the operator is obliged to benefit from self-configuration, self-optimization and self-healing features of femtocells. Most important of these features are related to interference management between neighbouring femtocells and between femto- and macrocells. Particularly, issues like transmission parameter optimization, neighbour list definition, admission/congestion control optimization, femto-femto and femto-macro mobility management are very important problems that need efficient solutions. We have identified REMs as effective enablers in enhancing the self-x functionalities of the femtocells by endowing them with environmental awareness. Thus, this scenario constitutes as one of the scenarios on which a final FARAMIR system architecture will be developed.

Among many optimization problems cited above, we have chosen to focus on the problem of coverage and capacity optimization of femtocells. The optimization scenario is presented as follows: A femtocell is powered up. Initially, the optimum value of the transmit power is not known. If the transmit power is too low, the femtocell may not cover the whole area that it is supposed to provide service to. If the transmit power is too high, the femtocell will probably cause interference to the neighbouring femtocells. Furthermore, if the femtocell shares the same spectrum with the macrocell network, interference to the neighbouring macrocell must also be considered. Hence, an optimum value of the transmit power should be set in order to compromise between coverage and interference.

REMs can provide the necessary environmental RF information to find the optimum transmit power. The exact coverage need of the powered-up femtocell and the coverage of its neighbouring femtocells in terms of geographic area can be retrieved from the REM. It can also provide the statistical information on the propagation medium so that the optimum transmit power value can be calculated using a realistic propagation model.

The first level of information that may be assumed to be included in a REM is related to static topographic knowledge. For example the location of the network elements (HeNBs, eNBs, UEs) can be used for distance-based power control in order to reduce the generated interference. The key in this procedure is the exact knowledge of the locations, along with the buildings' characteristics (layout, wall penetration loss, inter-site distance, etc.). While the eNBs' locations are usually known and fixed, the HeNBs exact position depends on user's preferences thus making it unpredictable. The use of a dynamic REM with updated information of the location and the activation status of the FAPs would result in more accurate power control decisions.

This information could be collected from a separate sensing network or from the femtocell network itself (base stations as well as user terminals) based on the cellular network topologies (triangulation) or other localization techniques. In each case, this information could be stored in a database at the macrocell level and updated at a relatively slow rate (every hour, twice a day, etc.).

Other power control strategies assume the knowledge of the path loss models in the coverage area of the femtocell. According to these schemes, and when the femtocell detects a Macro User Equipment (MUE), it uses these models to adjust its transmission power accordingly to reduce its interference to the MUE. The femtocell can detect the MUE by listening to the uplink control channels or by using other sensing techniques to locate the MUE signal source; then this information can be stored in a local REM located within the femtocell base station.

Measurement based approaches can also benefit from the use of REMs. In the above-mentioned setup, where the location of the femtocells and the Femto User Equipments (FUEs) has been estimated and stored in REMs, the RSSI and Signal-to-Interference-plus-Noise-Ratio (SINR) measurements from one network element (femtocell or UE) can be used to estimate these in nearby positions. Again these measurements could update a local database (at femtocell or macrocell level), and could be used by an optimization algorithm.

In all these approaches the key characteristic is the use of a REM at various levels. The main difference with traditional approaches is that the information behind the optimization algorithm is not only related to Channel State Information (CSI) measurements made by the user terminals, but it involves accessing the REM databases at various levels, where the information is collected using a combination of available techniques (sensing networks, localization techniques, etc.).

3.2.2 Functional and operational (system) requirements

From the scenario description presented above, the following functional and operational system requirements can be drawn:

1. MCDs have the capability to perform geo-localized measurements on coverage and capacity indicators. These indicators are typically received reference (pilot) signal power for coverage, and the experienced average throughput for capacity.

2. MCDs have the capability to perform geo-localized measurements regardless of their context (indoor-outdoor).

3. MCDs have the capability to perform geo-localized measurements within the frequency bands over which the femtocell network operates (intra-frequency measurements).

4. MCDs have the capability to report the geo-localized measurements with sufficient precision. This precision is determined by the technical performance requirements of the RRM task at hand.

5. Femtocells have the geo-localization capability (they know their own geo-locations).
6. Femtocells can communicate with the REM functional entities.
7. MCDs have the sufficient processing power (battery lifetime) to perform the required tasks (perform/report geo-localized measurements with the required rate, communicate with the REM SA entity).
8. REM functional entities communicate with the operator domain entities (located at the Operation and Maintenance Center, OMC) for Radio Resource Management (RRM) and optimization purposes.
9. The operator must have complete control over the automated RRM and optimization processes in relation with REMs. This implies the capability of powering down or turning off REM-driven RRM/optimization tasks.
10. The operator must have complete control over the REM construction process. This implies discarding or prioritizing certain measurements, zones and/or MCDs, as well as the choice of models and statistical measures for the sake of security, reliability and robustness.

Note that in indoor environments where the current GPS capabilities are lacking the required precision, some assistance from the nearby access points could be foreseen i.e. RF footprint, triangulation etc.

3.2.3 Mapping of the functional REM architecture blocks on the physical network entities

The system architecture of the REM-based femtocell transmit power optimization requires mapping of the REM functional architecture of Figure 1 to the HeNB (femtocell) logical architecture defined by 3GPP and depicted in Figure 4 [3]:

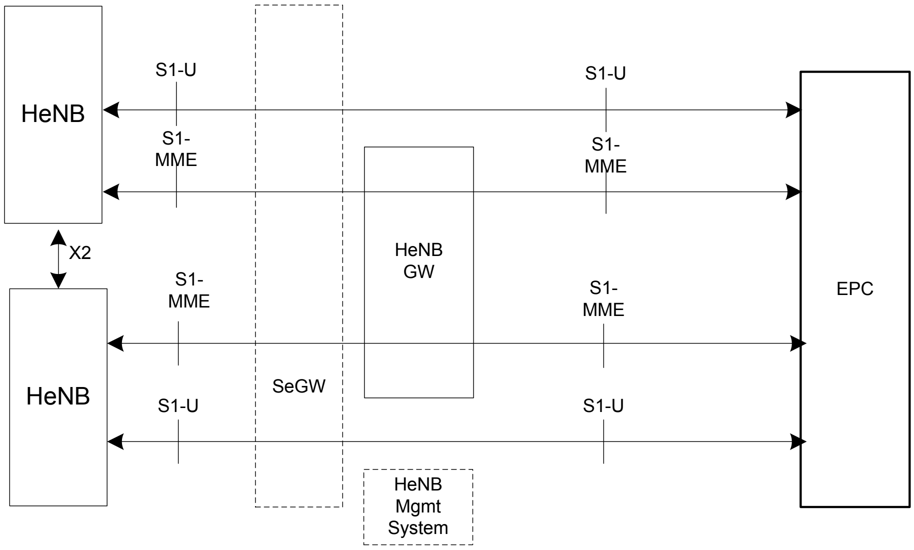
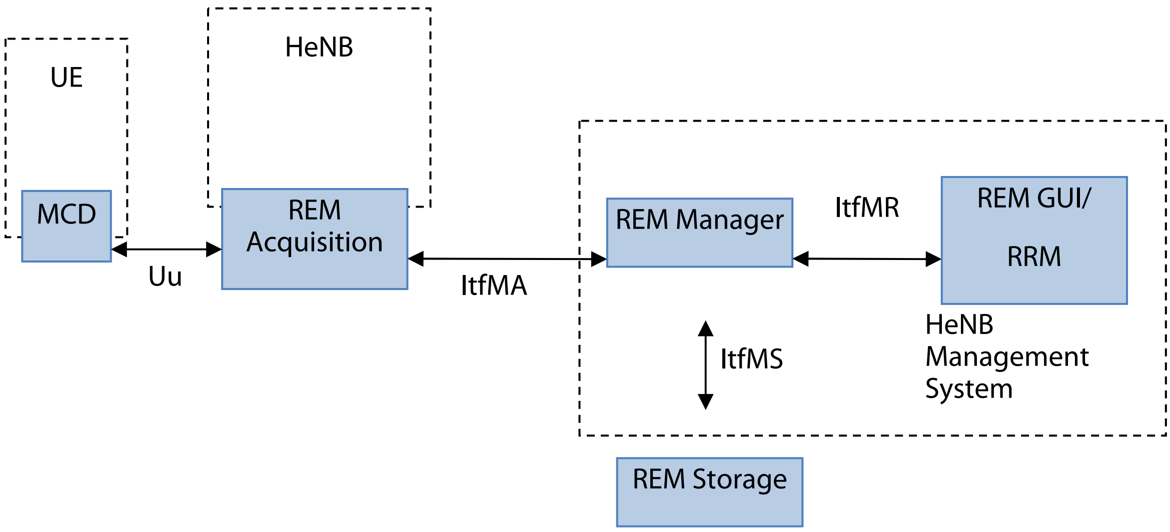


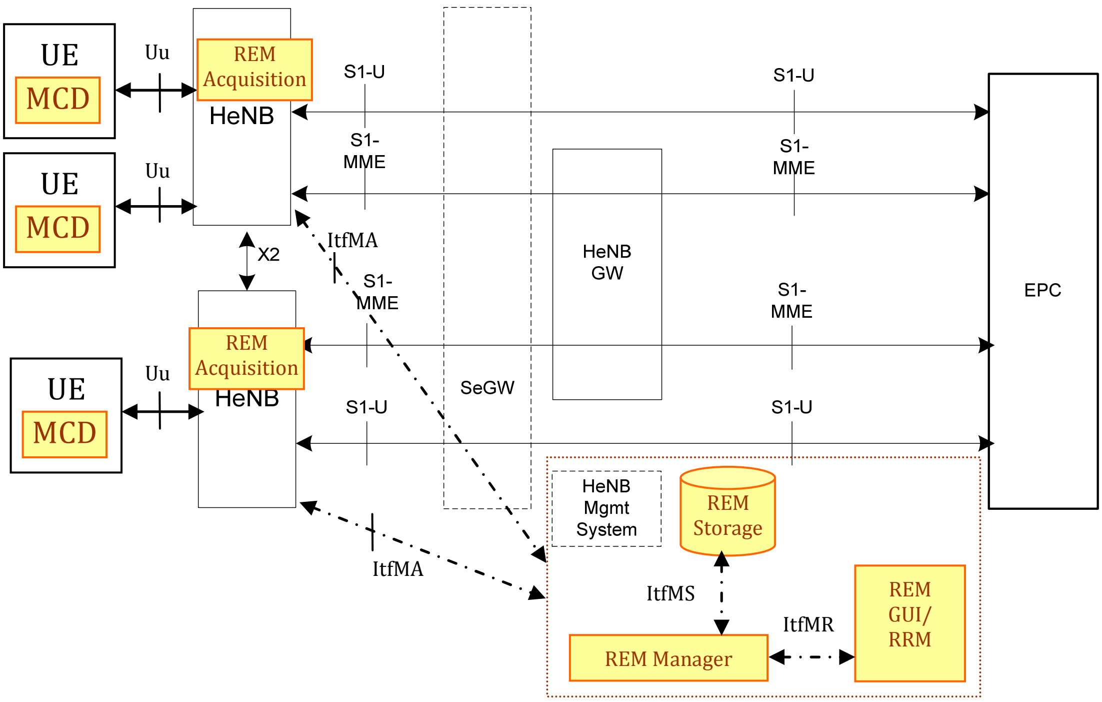
Figure 4: HeNB logical architecture [3].

Note that since the REM system architecture will be developed based on the related 3GPP architecture in the sequel, the 3GPP notation "HeNB" will be used instead of "femtocell" starting from this point on.

The following figure depicts the proposed mapping with the resulting logical architecture; and the discussion that follows explains the reasoning behind:



(a)



(b)

Figure 5: (a) The mapping of logical network entities onto functional architectural blocks and

(b) the resulting logical architecture.

The MCDs will be the UEs (including both macrocell and femtocell UEs) which report their measurements to the network together with the geo-location information. The capability of MCDs to report their geo-location information with sufficient precision is an important requirement for having a reliable REM. Another requirement concerning MCDs is related to the battery lifetime. Since geo-location information consumes power, MCDs must have enough power supply to perform geo-localized measurements and to report them to the network.

Since optimization of the transmit power is based on a compromise between coverage and interference between neighbouring femtocells, the REM must have a relatively global view of the Radio Frequency (RF) environment. Therefore, it is preferable to place it above the HeNB level, so that it can cover more than one neighbouring HeNB coverage areas. It is also preferable to have the REM in the operator domain to compensate the lack of operator control in femtocell placement. Therefore, the HeNB Management System (HeNB Mgmt System in Figure 4 and Figure 5) is an appropriate choice for the REM placement. However, it is better to have a separation of the REM SA sub-entities, namely the REM Acquisition unit and the REM Storage unit; since the

Acquisition module which is supposed to communicate with the MCDs (UEs) is naturally placed at the HeNB. As for the REM GUI/RRM block, it is preferable to place it also inside the operator domain (i.e. the HeNB MS) for the same reasons as the REM Manager and Storage.

3.2.4 Extension to a multi-technology setting

The extension of the mapping proposed in the above section to a multi-RAT environment is depicted in Figure 6. Such a scenario can be foreseen essentially for load balancing purposes in order to adapt to spatial and temporal variations in traffic demand. The mobility between two RATs can be carried out in two different ways:

1. **Legacy inter-RAT mobility**, where multi-mode UE terminals perform inter-RAT mobility by switching from one RAT to the other. In this scenario, the frequency bands of the individual RATs do not change. REMs can provide precise information on when and where to perform legacy inter-RAT handovers, possibly decreasing the necessity to carry out intensive inter-RAT measurements by the UEs.

2. **Dynamic Spectrum Allocation (DS-Allocation)**, where the frequency bands allocated to different RATs of an operator are dynamically modified according to the changing traffic needs. This is accomplished through reconfigurable base stations and UE terminals; and REMs can provide information on when, where and how to optimize the amount of spectrum resources allocated to each technology.

Figure 6 assumes a 3G-LTE multi-RAT environment for illustration purposes. The functional REM architecture blocks are mapped onto the corresponding network nodes in each RAT, i.e.,

1. MCDs onto UEs with 3G and LTE capabilities, but also onto multi-mode (3G+LTE) UE terminals

2. REM Acquisition onto HeNBs for LTE and HNBs for 3G

3. REM Storage onto HeNB Management System for LTE and onto HNB Management System for 3G

4. REM Manager onto HeNB Management System for LTE and onto HNB Management System for 3G

5. REM GUI/RRM onto HeNB Management System for LTE and onto HNB Management System for 3G.

Note that a link between the two management systems (HeNB Management System and HNB Management System) must be present to coordinate between the mobility optimization tasks.

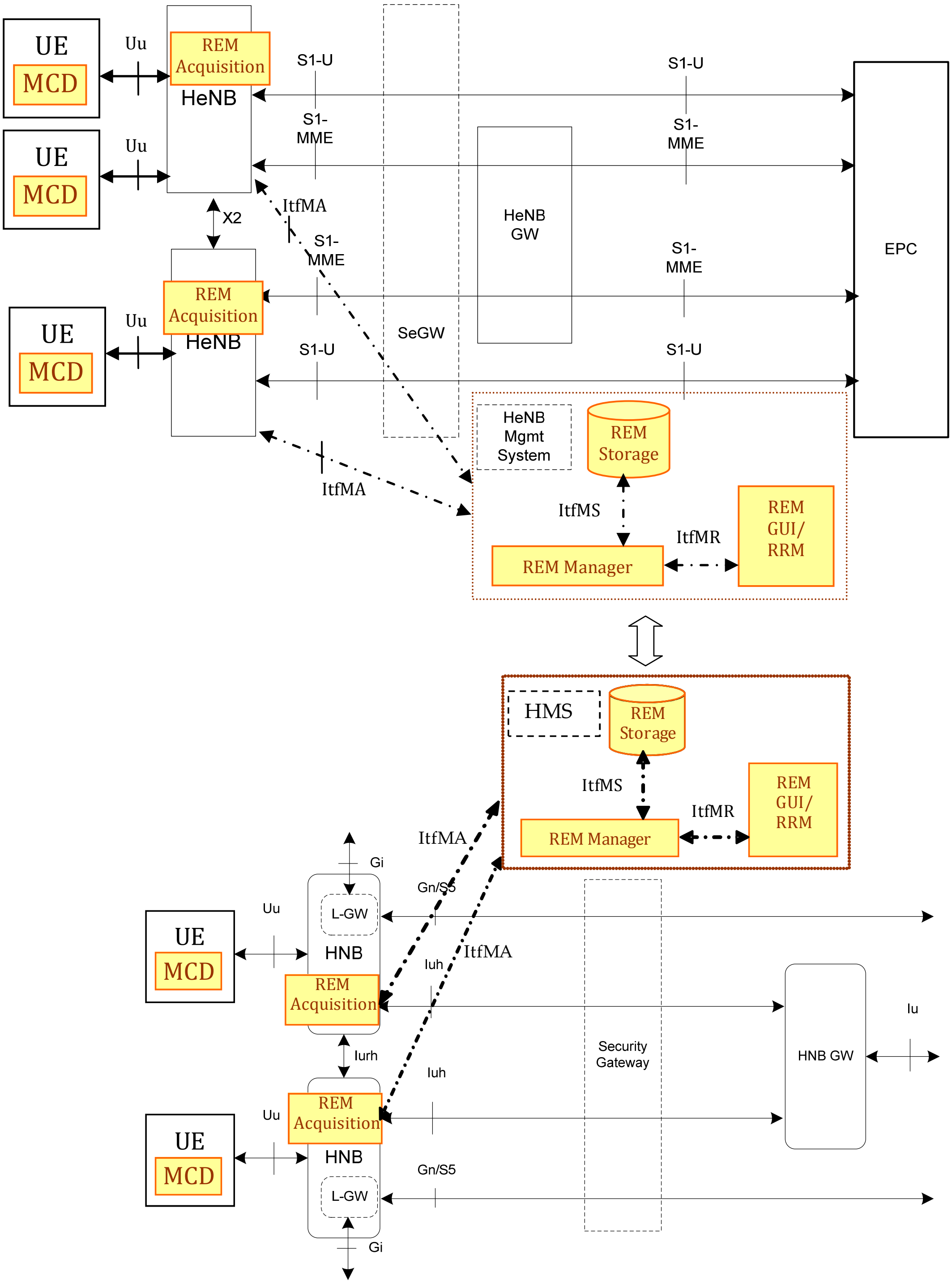


Figure 6: The mapping of logical network entities onto functional architectural blocks for a multi-RAT (3G-LTE) setting.

3.2.5 Interfaces

With the mapping proposed above, the MCD-REM Acquisition interface is mapped to the Uu air interface standardized in LTE. The REM Acquisition-REM Manager interface is mapped to the HeNB-HeNB MS interface (denoted here as IftMA) which is also standardized in LTE as a *Type 1* interface [4], [5], [6]. This interface lies between the Element Management System (EMS) of the control plane and the Network Management system (NMS) of the Operation & Maintenance Center (OMC) of the Management Plane. Finally, the REM Manager-REM Storage and the REM Manager-REM GUI/RRM interfaces (denoted respectively as ItfMS and ItfMR) do not map to any existing standardized interfaces, since they are totally internal within the HeNB MS, and therefore not subject to standardization (i.e. they are proprietary). The existing protocols for measurement reporting over the Uu air interface can serve to a large extent for REM construction purposes, with possibly some small additions to accomplish the required REM functionalities. As for the other two interfaces, since their LTE counterparts are not standardized, they can be defined with more degrees of freedom.

MCD-REM Acquisition interface (Uu air interface of LTE): This interface is used to transmit the registration/deregistration, measurement (re)configuration, measurement request, ACK/NACK messages on the REM control plane and measurement data itself on the (REM) data plane.

REM Acquisition-REM Manager interface IftMA (HeNB-HeNB MS interface): This interface is used by the REM Manager to communicate its control messages (measurement request, measurement (re)configuration, measurement capability request, ACK/NACK) to the REM Acquisition to be transferred to the MCDs. On the other hand, REM Acquisition uses this interface to forward measurement data on the (REM) data plane as well as some control data (registration/deregistration, ACK/NACK messages, measurement capability responses) coming from the MCDs to the REM Manager.

REM Manager-REM Storage interface IftMS (internal/proprietary interface): This interface carries the REM control plane messages from REM Manager to REM Storage such as read/write measurements, ACK/NACK messages, and REM control plane messages (such as ACK/NACK) together with (REM) data plane measurements from REM Storage to REM Manager.

REM Manager-REM GUI/RRM interface IftMR (internal/proprietary interface): This interface carries the REM control plane messages from REM GUI/RRM to REM Manager such as data configuration, data request, ACK/NACK messages, as well as REM control plane ACK/NACK messages and (REM) data plane measurements from REM Manager to REM GUI/RRM.

Note that the term (REM) data plane measurements refer to the raw measurement data as well as the processed REM data.

3.2.6 Protocols and Message Sequence Charts (MSCs)

The protocol messages over the interfaces presented in the previous section rely on the LTE control plane rather than the user plane, since we are only concerned with the measurement data and with the related control messages which are exclusively communicated on the LTE control plane. Therefore, in defining the REM-related protocols, we'll make use of some of the existing LTE measurement reporting procedures that can be of use for REM construction. However, the existing measurement reporting in LTE does not fully meet the REM construction requirements. Hence, we'll complement the LTE measurement reporting protocol with custom made messages tailored for REMs.

MCD-REM Acquisition protocol

The MCD-REM Acquisition protocol is realized through the existing control plane protocol stack over the Uu interface in the LTE standard that exists between the UE and the HeNB (cf. Figure 7).

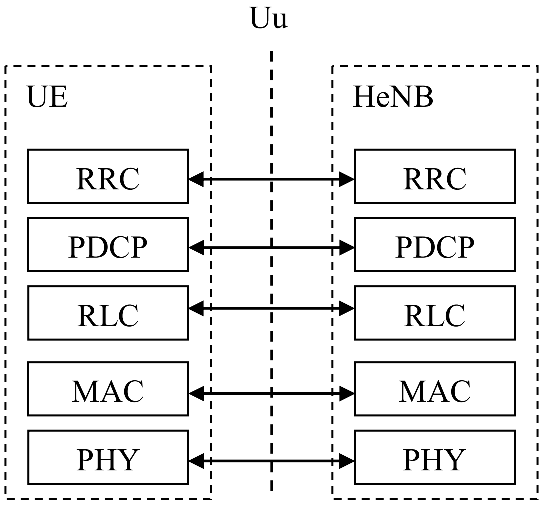


Figure 7: The protocol stack for the Uu interface in the LTE standard.

For REM construction purposes, we are concerned with the *measurement reporting messages* involved in the above protocol stack. 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, Quality of Service (QoS) management, UE measurement reporting and control of the reporting.

The general measurement reporting procedure of the RRC protocol over the Uu interface is carried out as follows: for a specific measurement, the network transmits to the User Equipment (UE) a *RRCConnectionReconfiguration* message whose aim is to setup, modify and/or release measurements among others. This message includes the *measConfig* field (or Information Element, IE, in the 3GPP terminology) that allows the UE to perform the measurement configuration procedure. Upon reception of the *measConfig*, the UE performs radio measurements determined by the requested measurement types/quantities for each cell and for each frequency indicated in the *measConfig*. Note that the measurement types (or measurement/reporting quantities) are the indicators/metrics that are used for performing network (optimization, monitoring, troubleshooting) tasks. A detailed description of these measurement types/quantities will be given in the next section.

When the reporting criteria are fulfilled, the UE replies back to the network with a *MeasurementReport* message that includes the *measID* and the measurement results (*measResult*). For idle mode, the measurement information elements are broadcasted in the System Information. The details of the *measResult* Information Element (IE) will be described in the next section.

The measurement reporting carried out by UEs can be of 3 different modes: 1) periodic reporting, 2) event-based (event-triggered) reporting, 3) logged reporting (recording in an offline manner). The first one concerns UEs at connected mode: they perform on-line periodic reporting without any logging mechanism. The second one concerns both connected mode and idle mode mobiles: the measurement reporting is triggered by a pre-defined event (a certain metric being greater than or lower than a threshold, or an alarm-type event like a Radio Link Failure –RLF). The reporting may be periodic or logged, depending on the type of trigger. If the trigger is an event that does not cause a complete or substantial loss of communication, periodic reporting is feasible. Otherwise, logged reporting is mandatory. This is the case when a RLF occurs: upon RLF, the mobile terminal starts logging measurements; and it reports the logged measurements to the network when the connection is re-established. The third mode applies when the mobile does not have an active communication with the network (either due to a failure as mentioned above, or when it is in idle mode where it does not have an active communication with the network but is still connected). Note that the third mode has been introduced recently within a new feature of LTE-Advanced (Rel.10), called as *Minimization of Drive Tests* (MDTs) [7].

The REM control messages defining the MCD-REM Acquisition protocol are: the registration/de-registration, measurement (re)configuration, measurement request and ACK/NACK messages. The registration/de-registration of a particular MCD can be performed by a query sent from the REM Manager to the Home Subscriber Service (HSS). HSS is a network entity which contains user profiles, performs authentication and authorization of the user, and can provide information about the physical location of the MCD. The deregistration process is initiated by a message sent by the REM Manager, which is transferred to the related UE and is acknowledged by the UE. The measurement capability information of each MCD in terms of supported RATs is communicated to the (H)eNB via *UECapabilityEnquiry* and *UECapabilityInformation* messages exchanged between the UE and the (H)eNB [3]. This information is kept at the (H)eNB as long as the UE stays connected. The UE radio access capabilities are also stored at the MME via a *UERadioAccessCapabilityInformation* message sent from the (H)eNB to the MME via S1-AP signaling [3]. Note that the (H)eNB may also acquire the UE capabilities after a handover completion, which are then uploaded to the MME. For REM construction purposes, it is more practical to use the information stored in the (H)eNB since REM Acquisition is co-located with the (H)eNB and there is no REM functional block located at the MME for the considered femtocell optimization scenario. Thus, the need for creating a new REM-related interface (that involves the MME) is avoided. Note that the radio access capability of a UE determines the frequency bands on which the UE can operate and perform measurements (depending on the geographical zone). The other characteristics of UE measurement capabilities (like types of coding-modulation and MIMO order supported by the UE as well as its battery capacity) can be inferred from the mobile category information that is stored in the (H)eNB.

The MSC describing the registration/deregistration process including the measurement capability information is depicted in Figure 8.

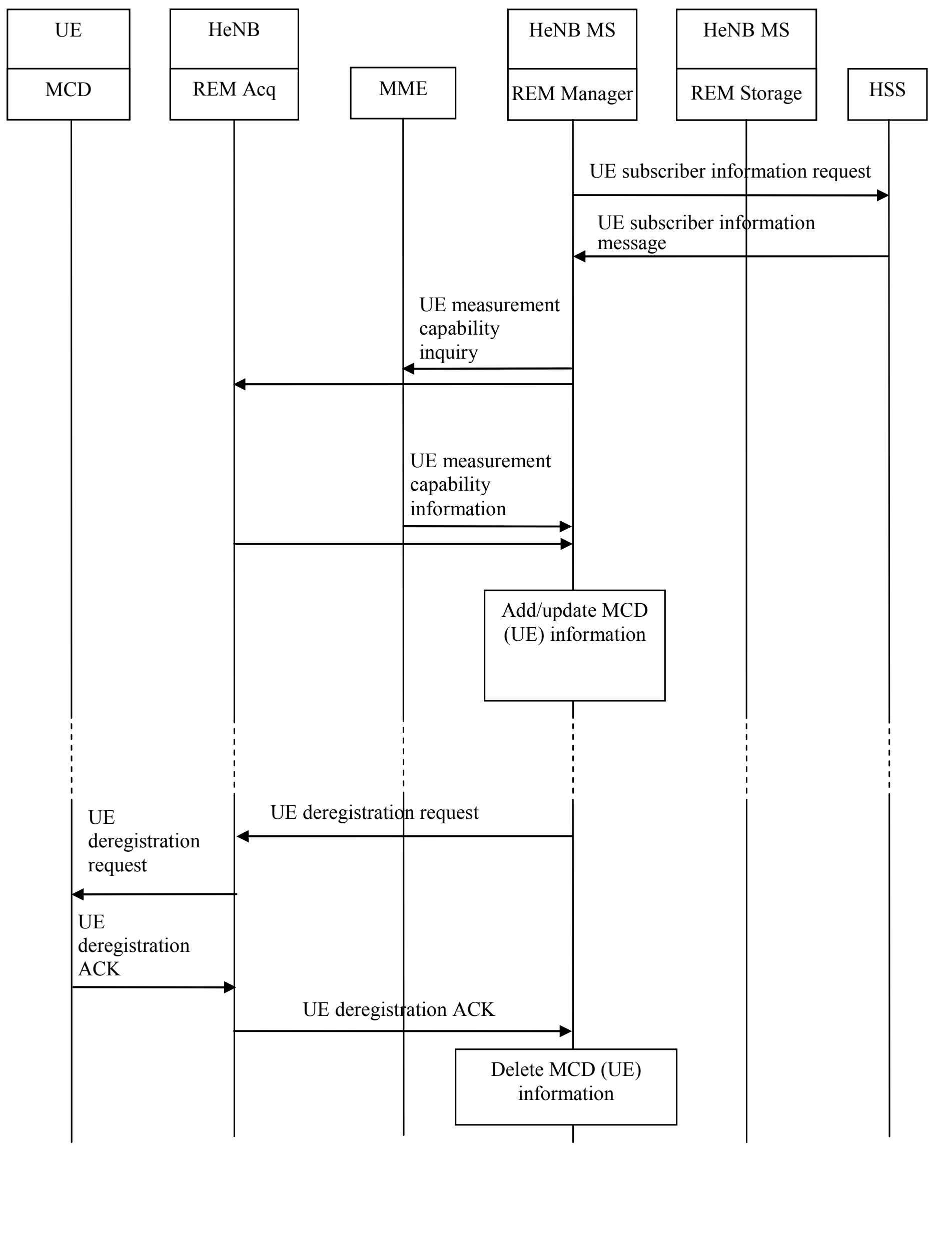


Figure 8: Message sequence chart for registration/deregistration process including measurement capability information.

REMs are populated by measurements coming from the MCDs (UEs) through measurement reports that contain measurement control messages and measurement data itself. These measurements can be classified in different measurement domains, such as intra-frequency (the DL carrier frequency of the serving cell), inter-frequency (frequencies that differ from the DL carrier frequency of the serving cell), inter-RAT (other Radio Access Technologies than the Radio Access Technology of the serving cell) and inter-layer (other layers than the serving cell); and in different measurement types, such as signal strength (Received Signal Received Power, RSRP), signal quality (Received Signal Received Quality, RSRQ) etc. [9].

When deemed necessary by the REM Manager, a measurement configuration/request message is sent to the related MCDs. Each measurement request is associated with a measurement configuration which is communicated to the MCD. This is achieved by a measurement (re)configuration message sent by the REM Manager to the MCD via the REM Acquisition. The existing signaling protocol for measurement reporting in LTE over the air interface which is described above, can be of use for this purpose.

REM Acquisition-REM Manager interface (HeNB-HeNB MS interface) protocol

Although this interface has been standardized in 3GPP as a Type 1 interface, in a great majority of the cases, the HeNB and the HeNB MS belong to the same equipment provider. Therefore, we will assume a single vendor scenario where this interface is a *closed interface*, and thus, take the liberty to define the REM-related messages over this interface, i;e. the messages related to measurement reporting and control.

The REM Acquisition-REM Manager interface carries the following messages:

- From REM Manager to REM Acquisition:
    - Measurement (re-)configuration
    - Measurement request
    - ACK/NACK of received measurements

- From REM Acquisition to REM Manager:
    - ACK/NACK of received (re-)configuration
    - ACK/NACK of received request
    - Measurement report

Since the REM Acquisition acts as a transfer point between the REM Manager and the MCDs, all of the above listed messages exist also on the MCD-REM Acquisition interface. Therefore, we do not need to redefine these messages, but simply reuse their counterparts on the air interface.

REM Manager-REM Storage interface protocol

As with the REM Acquisition-REM Manager interface, REM Manager-REM Storage interface is also not bound to any existing protocol since it is an internal interface that is not subject to standardization but proprietary. This interface basically serves to store raw/processed measurement data by the REM Manager into the REM Storage; and to retrieve REM data from the REM Storage by the REM Manager for RRM and/or for quality check.

The REM Manager-REM Storage interface carries the following messages:

- From REM Manager to REM Storage:
  - Read/write requests for REM data
  - Read/write configurations (including reliability metric)
  - REM data to be stored/written in REM Storage (with the required configuration and reliability)
  - ACK/NACK of read data

- From REM Storage to REM Manager:
  - ACK/NACK of received read/write requests
  - ACK/NACK of received read/write configurations
  - ACK/NACK of written data
  - REM data to be retrieved by REM Manager (with the required configuration and reliability)

Read/write requests and configurations are similar to measurement requests and configurations that exist on the air interface. They contain fields such as frequency band(s), the list of intra-RAT, inter-frequency, inter-RAT, inter-layer neighboring cells (cell IDs), metric (RSRP, RSRQ, etc.), time stamp and location information. REM data to be stored/retrieved also contains these fields, together with the data itself.

Another important attribute of the processed REM data is the *reliability* (or *confidence*) of the prediction used to obtain the processed data. Most often the prediction is carried out by advanced *interpolation* techniques coming from the field of (geo-)spatial statistics; and it is possible to have a quality metric of the interpolation used to carry out the REM data processing. These quality metrics can be higher order statistical moments of the data samples (apart from the averages), like variance (standard deviation), skewness, kurtosis etc., or metrics like entropy, median, mode etc. that describe the data distribution, or even the distribution itself in the form of a histogram. In any case, such a reliability indicator is necessary to judge the quality and the usefulness of the REM data by the RRM/GUI. If the quality is not high enough to be used by the RRM/GUI, extra measurements will be requested by the REM Manager via REM Acquisition from the MCDs.

REM Manager-REM GUI/RRM interface (internal/proprietary interface) protocol

As for the previous 3 interface protocols, the REM Manager-REM GUI/RRM interface is not bound to any existing radio protocols neither, since it is an internal interface that is not subject to standardization but proprietary. This interface carries commands from the RRM/GUI to retrieve REM data for network tasks like optimization, monitoring etc. and the responses as well as the requested REM data from the REM Manager to the RRM/GUI. The messages carried over this interface include:

- From RRM/GUI to REM Manager:
  - Retrieval requests for REM data
  - Data retrieval configurations (including a minimum level of reliability)
  - ACK/NACK for retrieved REM data

- From REM Manager to RRM/GUI:
  - ACK/NACK of received retrieval requests
  - ACK/NACK of received retrieval configurations
  - REM data to be retrieved by RRM/GUI (with the required configuration and reliability)

As a result of the above defined interface protocols, the message sequence charts describing the REM construction and RRM/GUI operations can be summarized in Figure 9 and Figure 10 respectively.

Note that the measurement requests in dashed arrows indicate that these messages are optional. Normally, the triggering conditions are configured in (re)configuration messages and there is no need to re-trigger measurements by separate measurement request messages. Hence, these messages are made optional for providing more flexibility.

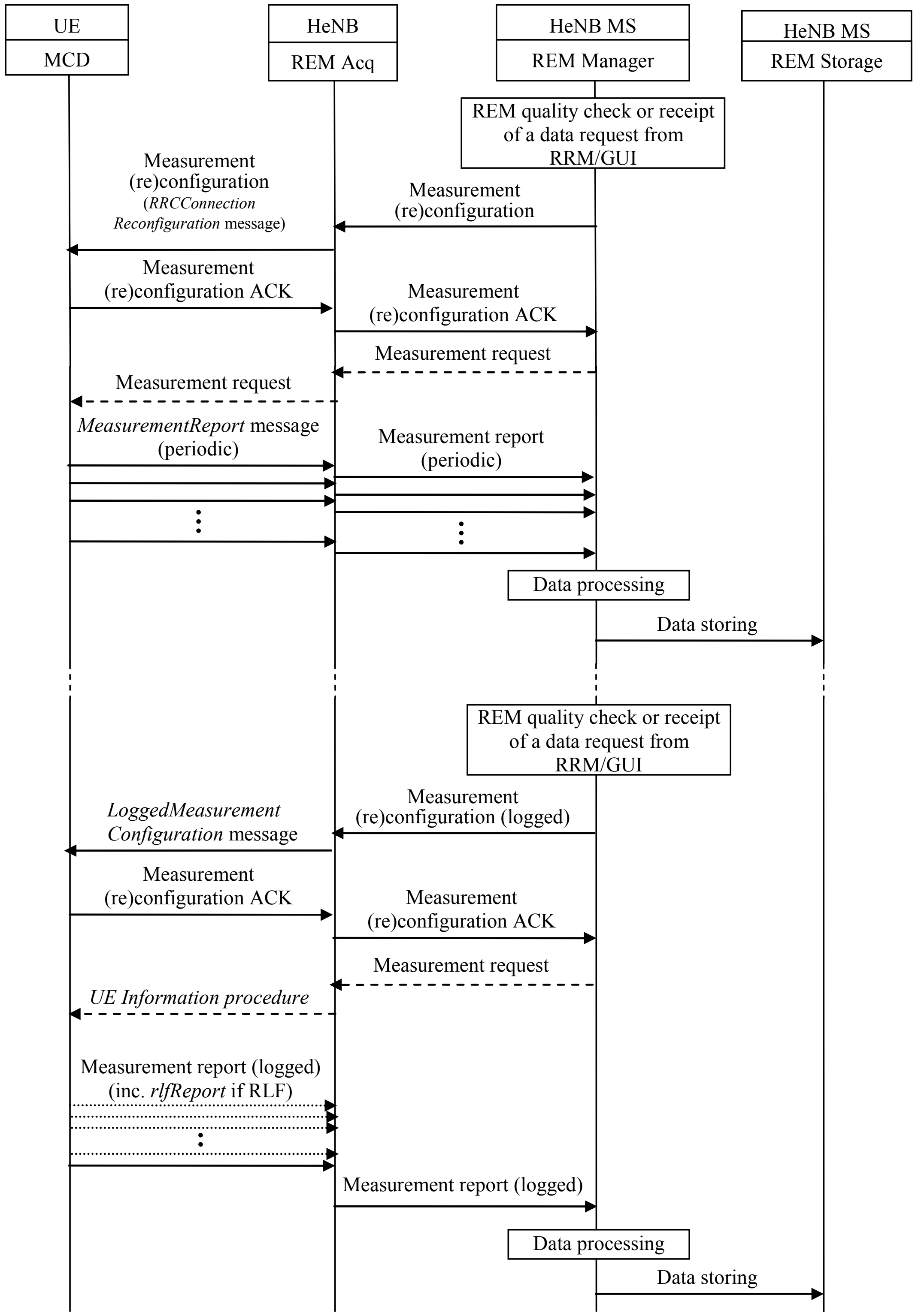


Figure 9: The message sequence chart for REM construction process.

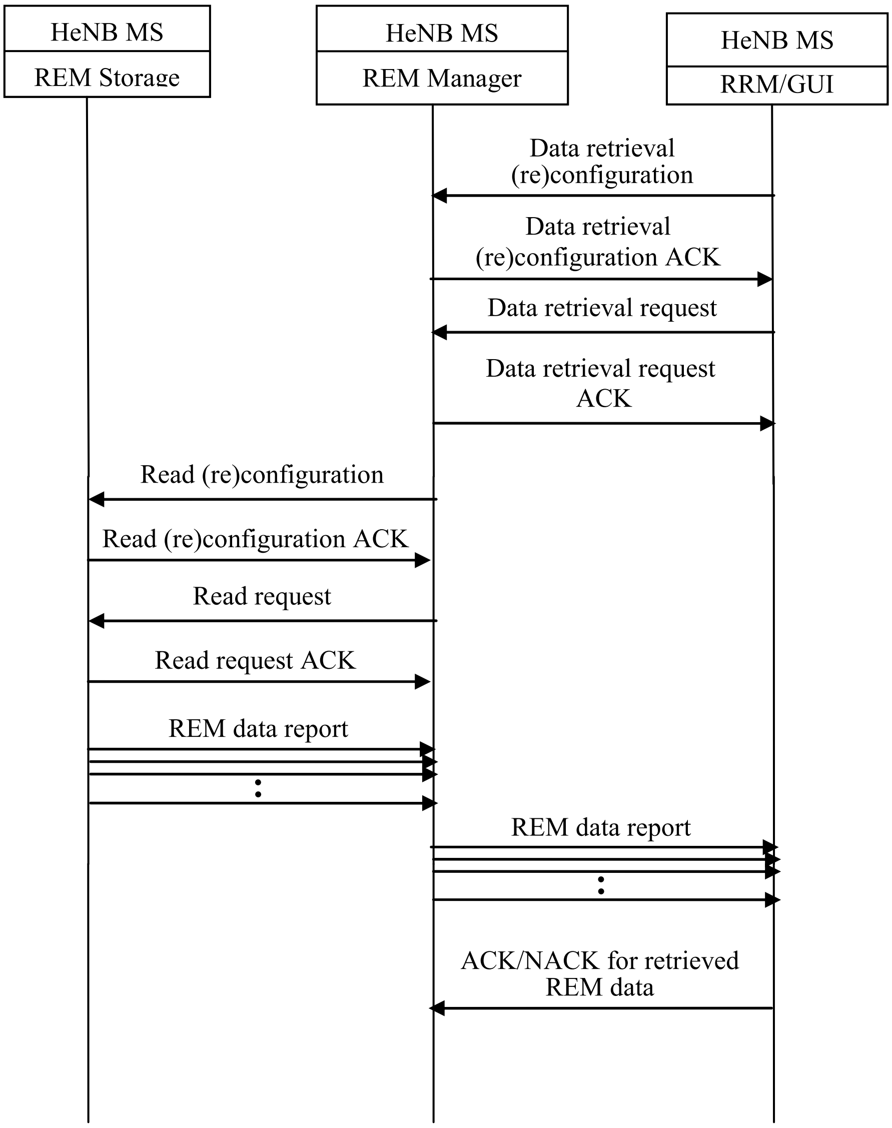


Figure 10: The message sequence chart for RRM/GUI operations.

3.2.7 Information/data models

The information/data model is determined by which type of measurements are made and processed by the REM. In the following, we describe the physical layer measurements reported to higher layers as defined in the LTE standard.

UE measurements

The UE physical layer measurements that are of interest to the femto coverage and capacity optimization scenario are the **Reference Signal Received Power (RSRP)** and the **Received Signal Strength Indicator (RSSI)** measurements.

1. **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.

2. **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.

Network (E-UTRAN) measurements

The network physical layer measurements that are of interest to the femto coverage and capacity optimization scenario are the **Uplink Received Interference Power (URIP)** and the Uplink **Thermal Noise Power (UTNP)** measurements.

1. **URIP** includes thermal noise, and covers the bandwidth over one physical resource block of N_{sc}^{RB} resource elements where N_{sc}^{RB} is the physical resource block size in the frequency domain, expressed as a number of subcarriers [8]. The reported value contains a set of URIPs of physical resource blocks for $n_{PRB} = 0,...,N_{RB}^{UL} - 1$ where N_{RB}^{UL} is the uplink bandwidth configuration, expressed in multiples of N_{sc}^{RB} as defined in [8].

2. **UTNP** is defined as (No x W), where No 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.

Since REM is constructed using geo-localized measurements, distributed across the geographic area of interest, the UE measurements are more of a concern than the network measurements. Nevertheless, the network measurements are complementary to those of the UEs and therefore worth mentioning.

The UE measurement data used for REM construction is communicated over the air interface through the *MeasurementReport* message which is used for the indication of measurement results. In 3GPP, data formats are defined through a specific language, called as Abstract Syntax Notation One (ASN.1), which is a common notation to define data structures in telecommunication and computer networks. Using this notation, it is possible to encode the protocol messages into a stream of bits/bytes that actually circulates on the network interfaces. Due to space restrictions, we will not go into the details of all the above mentioned REM-related protocol messages, but showcase an example message decoding that can be easily applied to other messages. As an example, we have chosen the *MeasurementReport* message on the MDC-REM Acquisition (Uu) interface, since this is the message that carries the geo-localized measurements and therefore is bound to have the most impact on the signaling overhead.

The other REM-related RRC messages on the same interface defined by the LTE standard are:

UECapabilityEnquiry

UECapabilityInformation

RRCConnectionReconfiguration

Example: decoding of the *MeasurementReport* message

In this example, we will start by the high-level RRC message, i.e. *MeasurementReport*, and go down gradually decoding at each step the mandatory fields (IEs) and the fields related to REMs. For this purpose, we will use the ASN.1 descriptions of the messages and the IEs as defined in the 3GPP. To ease the tracking of the nested IEs, a color code is used so that the same IEs at different levels are highlighted by the same color.

The ASN.1 code for the *MeasurementReport* message is shown below [9]:

MeasurementReport message

```
-- 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 *MeasurementReport* message contains a `measurementReport-r8` field which is of type `MeasurementReport-r8-IEs` and which is composed of a sequence of `measResults` and optional extensions (for further releases). The `measResults` IE has the following ASN.1 code [9]:

MeasResults information element

```
-- ASN1START

MeasResults ::=                         SEQUENCE {
    measId                                      MeasId,
    measResultPCell                     SEQUENCE {
        rsrpResult                              RSRP-Range,
        rsrqResult                              RSRQ-Range
    },
    measResultNeighCells                CHOICE {
        measResultListEUTRA                     MeasResultListEUTRA,
        measResultListUTRA                      MeasResultListUTRA,
        measResultListGERAN                         MeasResultListGERAN,
        measResultsCDMA2000                         MeasResultsCDMA2000,
        ...
    }                                                           OPTIONAL,
    ...,
    [[  measResultForECID-r9                MeasResultForECID-r9        OPTIONAL
    ]],
    [[  locationInfo-r10                    LocationInfo-r10            OPTIONAL,
        measResultServFreqList-r10          MeasResultServFreqList-r10  OPTIONAL
    ]]
}

MeasResultListEUTRA ::=                 SEQUENCE (SIZE (1..maxCellReport)) OF MeasResultEUTRA

MeasResultEUTRA ::= SEQUENCE {
    physCellId                              PhysCellId,
    cgi-Info                                SEQUENCE {
        cellGlobalId                            CellGlobalIdEUTRA,
        trackingAreaCode                        TrackingAreaCode,
        plmn-IdentityList                   PLMN-IdentityList2              OPTIONAL
    }                                                                       OPTIONAL,
    measResult                              SEQUENCE {
        rsrpResult                              RSRP-Range                          OPTIONAL,
        rsrqResult                              RSRQ-Range                          OPTIONAL,
        ...,
        [[  additionalSI-Info-r9                AdditionalSI-Info-r9            OPTIONAL
        ]]
    }
}

MeasResultServFreqList-r10 ::=    SEQUENCE (SIZE (1..maxServCell-r10)) OF MeasResultServFreq-r10

MeasResultServFreq-r10 ::=              SEQUENCE {
    servFreqId                              ServCellIndex-r10,
    measResultSCell                         SEQUENCE {
        rsrpResultSCell                         RSRP-Range,
        rsrqResultSCell                         RSRQ-Range
    }                                                                       OPTIONAL,
    measResultBestNeighCell                 SEQUENCE {
        physCellId                              PhysCellId,
        rsrpResultNCell                         RSRP-Range,
        rsrqResultNCell                         RSRQ-Range
    }                                                                       OPTIONAL,
    ...
}

MeasResultListUTRA ::=                  SEQUENCE (SIZE (1..maxCellReport)) OF MeasResultUTRA

MeasResultUTRA ::=  ...
```

```
MeasResultListGERAN ::=                SEQUENCE (SIZE (1..maxCellReport)) OF MeasResultGERAN

MeasResultGERAN ::=...

MeasResultsCDMA2000 ::=                SEQUENCE {
    preRegistrationStatusHRPD          BOOLEAN,
    measResultListCDMA2000                 MeasResultListCDMA2000
}

MeasResultListCDMA2000 ::=             SEQUENCE (SIZE (1..maxCellReport)) OF MeasResultCDMA2000

MeasResultCDMA2000 ::=  ...

MeasResultForECID-r9 ::=        SEQUENCE {
    ue-RxTxTimeDiffResult-r9               INTEGER (0..4095),
    currentSFN-r9                              BIT STRING (SIZE (10))
}

PLMN-IdentityList2 ::=                 SEQUENCE (SIZE (1..5)) OF PLMN-Identity

AdditionalSI-Info-r9 ::=           SEQUENCE {
    csg-MemberStatus-r9                ENUMERATED {member}              OPTIONAL,
    csg-Identity-r9                        CSG-Identity                     OPTIONAL
}

-- ASN1STOP
```

In the above ASN.1 code, the fields for UTRA (3G), GERAN (2G) and CDMA2000 neighboring cell measurements are not shown for brevity purposes. Here, the first level IEs are the:

1. `measId`,
2. `measResultPCell`,
3. `measResultNeighCells`,
4. `measResultForECID-r9` (optional),
5. `locationInfo-r10` and
6. `measResultServfreqList-r10` (optional).

The `measId` IE has the following ASN.1 code [9]:

MeasId information element

```
-- ASN1START

MeasId ::=                          INTEGER (1..maxMeasId)

-- ASN1STOP
```

where `maxMeasId`=32 [9].

The data format of the `measResultPCell` field is defined in the ASN.1 code of `MeasResults` IE. It is a sequence of two fields: `rsrpResult` and `rsrqResult` of types `RSRP-Range` and `RSRQ-Range` respectively. The ASN.1 codes of `RSRP-Range` and `RSRQ-Range` are depicted below [9]:

RSRP-Range information element

```
-- ASN1START
RSRP-Range ::=                    INTEGER(0..97)
-- ASN1STOP
```

RSRQ-Range information element

```
-- ASN1START
RSRQ-Range ::=                    INTEGER(0..34)
-- ASN1STOP
```

meaning that `rsrp-Range` takes integer values between 0 and 97 and `rsrq-Range` takes integer values between 0 and 34.

The data format of the `measResultNeighCells` field is also defined in the ASN.1 code of `MeasResults` IE. It is a list of measurement results performed on the neighboring cells (intra-RAT, inter-RAT etc.) Without loss of generality, we will focus on intra-RAT (LTE or eUTRA) neighbors and perform the decoding only for them. The approach presented here can be readily applied to other types of neighbors as well. Considering only LTE neighbors, the `measResultNeighCells` field is composed of the `measResultListEUTRA` field, whose data format is also defined in the same ASN.1 code: it is a sequence of `MeasResultEUTRA` IEs where the maximum number of reported cells (`maxCellReport`) is equal to 8.

The data format of the `MeasResultEUTRA` IE is described in the same ASN.1 code as the `MeasResults` IE. It consists of the following fields:

1. `physCellId`,
2. `cgi-Info`,
3. `measResult`,
4. `additionalSI-Info-r9` (optional).

The `physCellId` IE has the following ASN.1 code [9]:

PhysCellId information element

```
-- ASN1START
PhysCellId ::=                    INTEGER (0..503)
-- ASN1STOP
```

meaning that the physical cell ID takes on integer values between 0 and 503.

The `cgi-Info` IE consists of 3 fields:

1. `cellGlobalId`,
2. `trackingAreaCode`,
3. `plmn-IdentityList`, (optional)

`cellGlobalId` IE is of type `CellGlobalIdEUTRA` whose ASN.1 structure is given below [9]:

CellGlobalIdEUTRA information element

```
-- ASN1START

CellGlobalIdEUTRA ::=                    SEQUENCE {
    plmn-Identity                            PLMN-Identity,
    cellIdentity                             CellIdentity
}

-- ASN1STOP
```

meaning that it is composed of two fields, `plmn-Identity` and `cellIdentity`.

The `plmn-Identity` IE has the following ASN.1 code [9]:

PLMN-Identity information element

```
-- ASN1START

PLMN-Identity ::=                    SEQUENCE {
    mcc                                  MCC                  OPTIONAL,        -- Cond MCC
    mnc                                  MNC
}

MCC ::=                              SEQUENCE (SIZE (3)) OF
                                         MCC-MNC-Digit

MNC ::=                              SEQUENCE (SIZE (2..3)) OF
                                         MCC-MNC-Digit

MCC-MNC-Digit ::=                    INTEGER (0..9)


-- ASN1STOP
```

meaning that it is composed of two fields, `mcc` (optional) and `mnc`. Furthermore, `mnc` is represented by 2 to 3 integers having values between 0 and 9.

The `cellIdentity` IE has the following ASN.1 code [9]:

CellIdentity information element

```
-- ASN1START

CellIdentity ::=                     BIT STRING (SIZE (28))

-- ASN1STOP
```

meaning that it is a bit string of 28 bits.

The `trackingAreaCode` IE has the following ASN.1 code [9]:

TrackingAreaCode information element

```
-- ASN1START

TrackingAreaCode ::=                BIT STRING (SIZE (16))

-- ASN1STOP
```

meaning that it is a bit string of 16 bits.

The next REM-relevant field in the `MeasResults` IE is the `locationInfo-r10 IE`. It has the following ASN.1 code [9]:

LocationInfo information element

```
-- ASN1START

LocationInfo-r10 ::=    SEQUENCE {
    locationCoordinates-r10                 CHOICE {
        ellipsoid-Point-r10                     OCTET STRING,
        ellipsoidPointWithAltitude-r10          OCTET STRING,
    ...
    },
    horizontalVelocity-r10                  OCTET STRING                OPTIONAL,
    gnss-TOD-msec-r10                       OCTET STRING                OPTIONAL,
    ...
}

-- ASN1STOP
```

meaning that it is a sequence of several different geo-location formats, namely `ellipsoid-Point-r10`, `ellipsoidPointWithAltitude-r10`, `horizontalVelocity-r10` (optional) `and` `gnss-TOD-msec-r10` (optional). All the formats have the same data format, `OCTET STRING`, i.e. a string of 8 bits whose length can take on any value including zero. More precise description of these `OCTET STRING` data types for these location variables/fields can be found in other 3GPP documents, such as [9] (for the former three IEs) and [10] (for the latter IE).

The `ellipsoid-Point-r10` and `ellipsoidPointWithAltitude-r10` IEs have the following descriptions [11] depicted in

Table 1 and Table 2 respectively:

Table 1: Data structure of `ellipsoid-Point`

Information Element/Group name	**Type and Reference**
Latitude sign	Enumerated (North, South)
Degrees Of Latitude	Integer ($0...2^{23}-1$)
Degrees Of Longitude	Integer ($-2^{23}...2^{23}-1$)

Table 2: Data structure of `ellipsoidPointWithAltitude`

Information Element/Group name	**Type and Reference**
Latitude sign	Enumerated (North, South)
Degrees Of Latitude	Integer ($0...2^{23}-1$)
Degrees Of Longitude	Integer ($-2^{23}...2^{23}-1$)
Altitude Direction	Enumerated (Height, Depth)
Altitude	Integer ($0..2^{15}-1$)

Assuming that the enumerated types with 2 values can be decoded by a single bit, the `ellipsoid-Point-r10` IE takes 48 bits and `ellipsoidPointWithAltitude-r10` IE takes 64 bits. In the following, we choose the latter since it contains the more (i.e. the altitude) information.

The following figure (Figure 11) clarifies the top-down approach of decoding the messages and the nested IEs. In this figure, a rough analysis of the size of the messages and the involved IEs is also shown, where maximum sizes of the IEs are considered except the number of reported neighbouring cells, *NCells*, which has a substantial effect on the message size. Therefore, we have adopted a parametric approach, leaving *NCells* as a parameter to adjust.

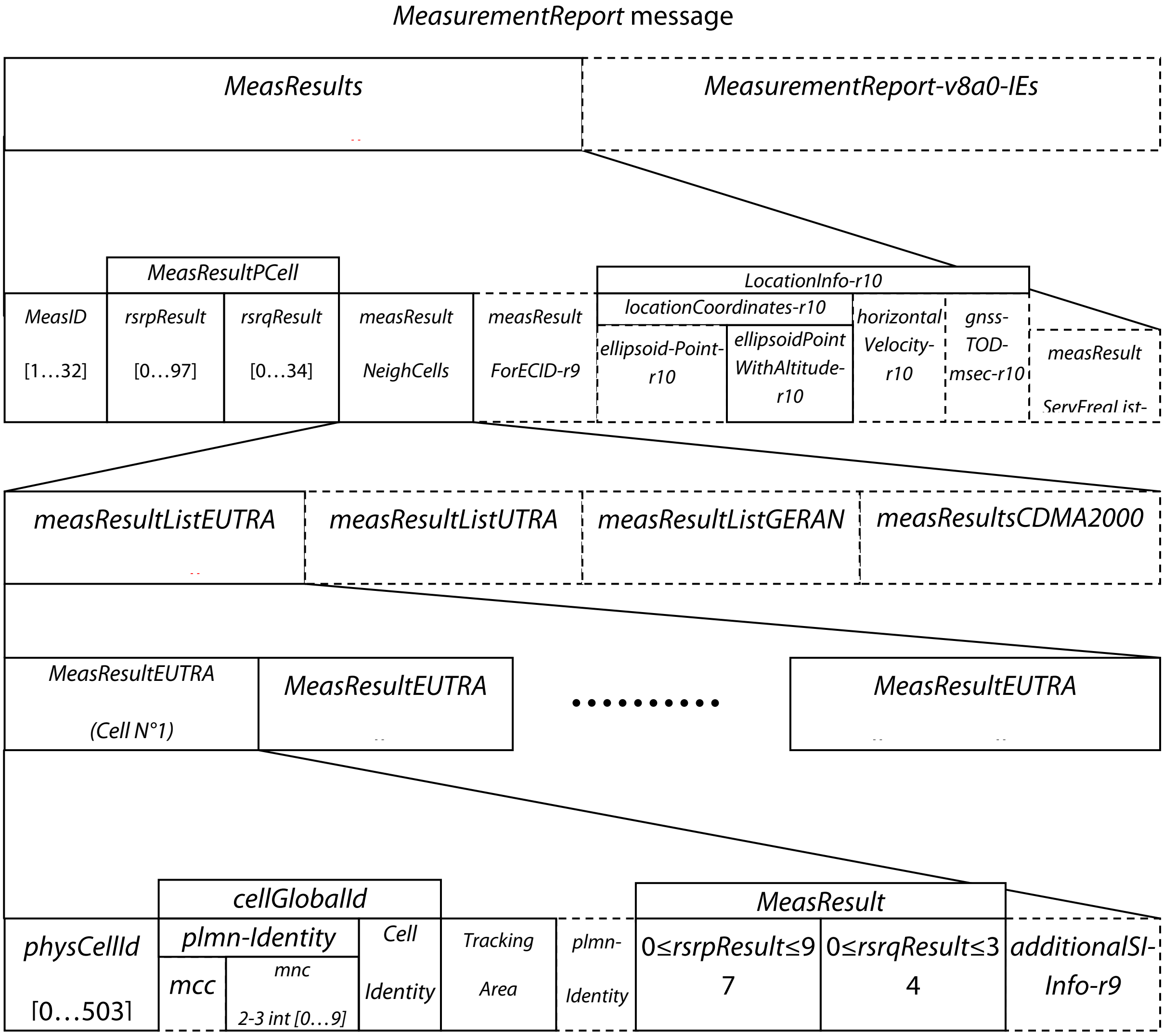


Figure 11: Decoding of the data format for the *MeasurementReport* message.

The detailed architecture work outlined in this section can be used to calculate the signalling cost of constructing, maintaining, updating and using REMs.

3.2.8 Femtocell optimization with a dedicated sensor network

An interesting and viable alternative for having an increased number of observations without increasing the signalling overhead is to make use of a dedicated sensor network which is specifically deployed (by the operator or by third parties) to collect measurements [1]. A dedicated sensor network is crucial for a reliable REM construction, especially in indoor environments, providing a denser distribution of the MCDs. The MCD network should support:

- Heterogeneity, including, for example:

  - MCDs with different characteristics in terms of supported bands, sensitivity, data resolution, resolution bandwidths, sweep time etc.
  - Mutual calibration and synchronization for consistency of the measurement data.

- Different detection types, i.e.:
  - Blind detection such as energy detection, FAR detection, HOS detection etc.
  - Feature detection such as cyclostationarity detection, matched filter detection etc.

- Cooperative sensing

- Localization

The dedicated sensor network allows inspection of different REM related aspects such as estimated RSSI distribution, propagation models, spatio-temporal characteristics of the spectrum activity etc. The calculations are performed by a dedicated REM Manager that stores the REM data into a dedicated REM SA which is either accessed remotely or is organized hierarchically in the network REM system architecture.

Figure 12 depicts an MSC for REM construction based on RRM requirements using a dedicated sensor network. At start-up, the MCD registers into the REM SA and, after a while, a REM data request is sent to the REM Manager by the RRM/GUI block. This initiates the REM Manager to query for MCD reconfiguration and request for the specific measurements. When appropriate amount of raw measurement data is collected for statistical correctness, the REM Manager can calculate the required REM data, which is reported back to the RRM.

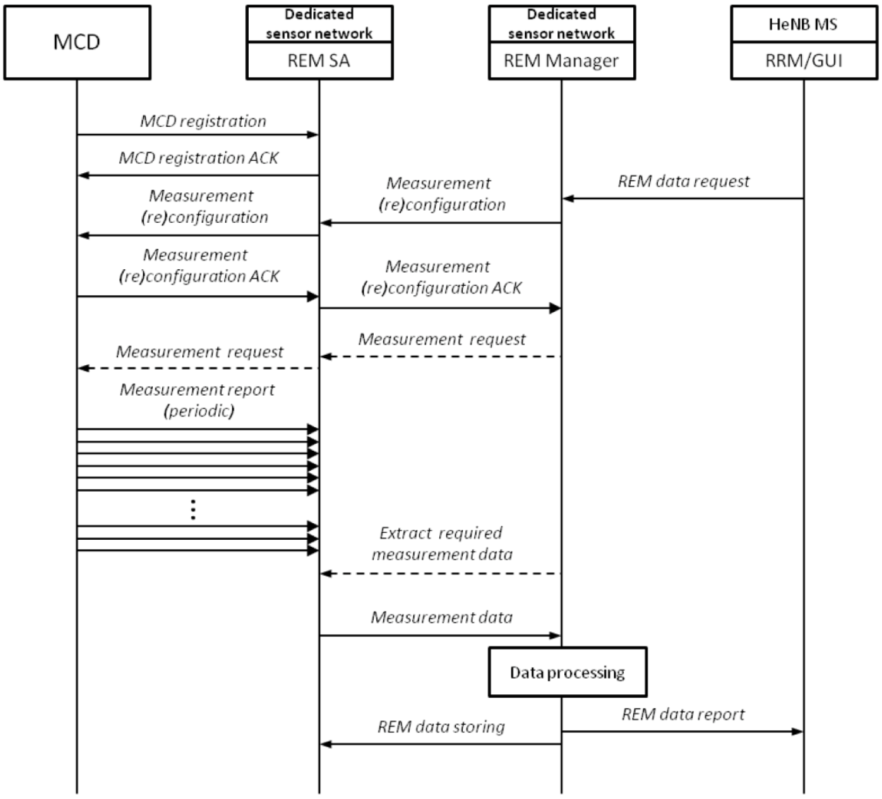


Figure 12: REM construction process based on RRM/GUI query.

3.3 LTE in TVWS scenario

3.3.1 The description of the scenario and the optimization problem

This scenario covers the situation when a femtocell Access Point (AP), or HeNB in 3GPP terminology, is used to increase user throughput in especially dense urban and indoor environment. Further the spectrum used by the HeNB and associated user equipment is TVWS of which usage is allowed by the TV license owners on a secondary basis.

It is envisaged that a femtocell access point or HeNB will be connected to operator's core network through backhaul link such as xDSL, the same as the one used by legacy WiFi access point. Compared with the similar indoor coverage provided by WiFi access point, the LTE femtocell has the following advantages. First it eliminate the need for dual-mode or dual-chipset design for user terminal which can be translated into low manufacture cost and low power consumption as there will be only one LTE baseband and RF chain running within user terminal. Secondly in the paradigm of spectrum agility, one wireless link established between one access point and one user terminal can be desirably moved to another portion of spectrum. If the access on different spectrum portions are carried out by different technologies or chipsets, an inter-system handover is needed, which normally cause longer latency in the service provisioning or even service interruption. On the contrary only inter-frequency handover is needed if both accesses are based on LTE, i.e. LTE macrocell and LTE femtocell. Third, one LTE HeNB will have connection to operator's core network through HeNB Gateway. It will benefit from the cooperation from other neighboring HeNB under the coordination of operator core network, as well as the assistance from knowledge database such as a REM.

The optimization for this scenario is mainly about how to improve user throughput as normally high throughput is the motivation for which the user wants to install a femtocell cell. For many access points, either LTE HeNB or WiFi AP, co-exist in one neighboring area as illustrated in Figure 13, this optimization can be done through spectrum allocation among access points and power setting for the access point transmission.

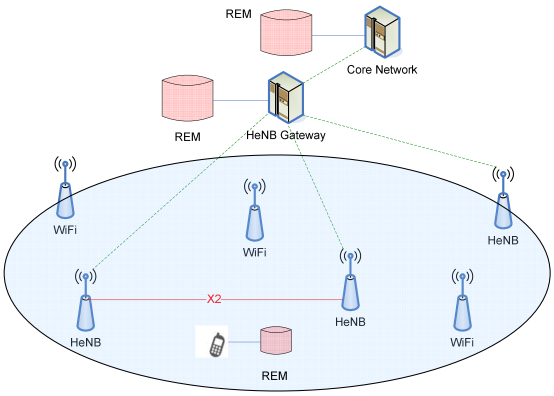


Figure 13: Co-existing of WiFi access points and HeNBs in one neighbouring environment, REMs can be implemented such as they are associated with different network components, in order to support radio resource management and optimization.

3.3.2 Functional and operational (system) requirements

The functional and operational requirements imposed by the spectrum/power optimization problem can be categorized as:

1. Measurement unit requirements
2. Management and decision unit requirements

According to 3GPP standardization, LTE terminals are required to have measurement capabilities to facilitate e.g. inter-RAT mobility where they need to measure the signal strength and the signal quality on pilot channels (or reference signal) of GSM/UMTS/LTE, as well as non-3GPP RATs as CDMA20001x/HRPD, WiMax. The frequency bands of those RATs span from 800/900 MHz to 2.6GHz, while the carrier bandwidth the terminals need to support varies from 200 kHz for GSM, 5MHz for UMTS/WCDMA, to 20MHz for LTE.

In order to make use of TVWS, which spans from 470MHz to 790MHz with channel bandwidth of 8MHz, there are different approaches such as consulting a geo-location database, using sensing technologies or the combination of these two approaches. For the sensing part, it is thus required to have the capability to scan the above TV spectrum to find the usable “white space” in a fast and power efficient manner.

One feasible solution to add TVWS scanning capability to existing 3GPP terminal platform without imposing requirements for major alternation to 3GPP standards is to incorporate standalone sensing module into 3GPP terminal hardware, similar to the incorporation of WiFi module to 3GPP terminals. According to [13], the scanning module can be implemented based on one SDR technology with low power consumption and low cost. The scanning range is from 100MHz to 5GHz which includes TV band, LTE spectrum band and WiFi band. The power consumption is in the range of 50-100mA, which is comparable to or even lower than the power consumption level of current LTE terminal. This sensing can be done quite fast as in order to scan the spectrum ranging from 500MHz to 2.5GHz, it will use 7.6ms. This time is on the same order of magnitude of LTE user plane latency.

Based on the capability of the scanning module (or scanning modules in cooperative scanning set-up), the TVWS can be identified and utilized by LTE downlink or uplink communications. Thus there are requirements on how one available TV channel can be most efficiently utilized. Since 8MHz of TV channel is not a standard channel width for LTE, it is required that LTE base station and terminal shall able to “aggregate” multiple (most likely non-contiguous) TV channels, as well as “squeeze” as many as possible LTE channel into one TV channel. The “narrow” LTE channel bandwidths are 1.4MHz, 3MHz, and 5MHz so there are possibly multiple way of combination. TD-LTE system is more suitable than LTE FDD system for the perspective of this dynamic spectrum usage situation as TD-LTE system can accommodate both downlink and uplink on the same spectrum band.

In 3GPP, Carrier Aggregation, two or more Component Carriers, are aggregated in order to support wider transmission bandwidths. This function can be used to support operation on TVWS by LTE base station and terminals.

The requirement on the network side is the capability on how to collect spectrum scanning results from scanning module (or multiple scanning module). The network needs to decide the size of TVWS and the most efficient method of radio resource management and optimization. It is required that measurements collection, decision making and performance monitoring mechanism shall be established.

3.3.3 Mapping of the functional REM architecture blocks on the physical network entities

Based on the scenario and requirement thereof, the mapping of the functional REM architecture blocks onto physical network entities can be described as follows. First of all, REM is implemented in a layered fashion (Figure 14). For the terminal, the MCD is undertaken by the abovementioned scanning module for spectrum sensing, meanwhile channel power and quality measurement, also seens as part of MCD capability, is done by stardard 3GPP functionalities such as RSRP and RSRQ measurements of LTE terminals. It is also beneficial, for some optimization cases, to make use of termial storage capacity. For example, there can be optimization cases which are only related to local neighbourhood sub-system. Also storage capacity, which is on Gbytes level for modern terminals, can be utilized together with consideration on the storage capacity of femtocell access point, as well as storage capacity of HeNB Gateway.

For HeNB, depending on the network configuration and algorithm implementation, REM Storage and MCD functions can be embeded in HeNB. For example, if one HeNB is equiped with downlink receiver, it can carry out measurements the same as the measurements done by terminals, especially for the small coverage scenario of femtocells.

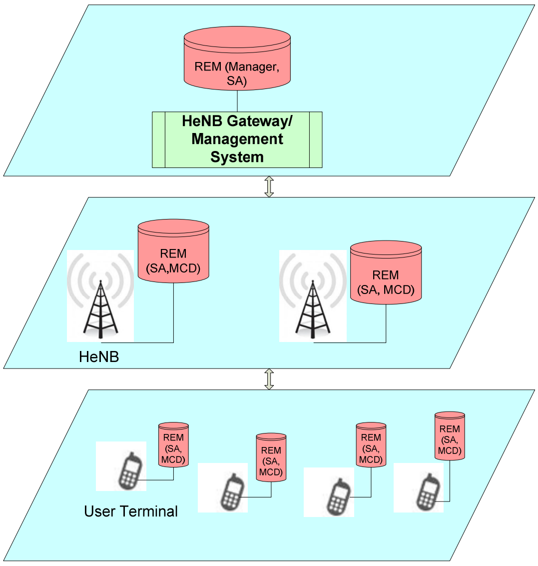


Figure 14: Mapping of REM blocks to network entities in a layered configuration.

The REM Manager is implemented in HeNB Gateway/HeNB management system which can be co-sited with HeNB Gateway. HeNB Gateway will collect measurement by user terminals and measurement by HeNBs and make decision on resource management among neighbouring HeNBs.

3.3.4 Interfaces

The specific interface for this scenario is interface between the scanning module and the terminal as well as HeNB gateway (Figure 15). There shall be one API between scanning module and UE and it is an internal interface. The measurement report of the spectrum by the scanning module shall be transferred to HeNB in the form of NAS (Non-Access Stratum) message.

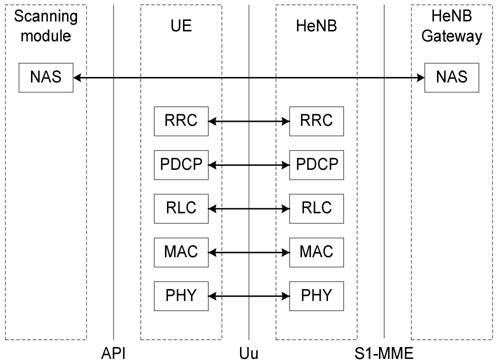


Figure 15: Interfaces for supporting sensing function in user terminal.

3.3.5 Protocols and Message Sequence Charts

Figure 16 illustrates one implementation of message sequence for this scenario. As stated in section 4.3.4, the interface between scanning module and the other part of user terminal (the conventional part of a user terminal) is to be designed as Application Programming Interface (API). The scanning module will be invoked when TVWS scanning is needed. API Measurement Request is sent from REM manager which resides in HeNB Gateway. Such API Massage Request can be piggy-backed on a normal NAS Measurement Request. Similarly API Measurement Response, in which the TVWS scanning results are encoded, is to be piggy-backed on NAS Response and sent back to HeNB Gateway/REM manager.

The protocol between UE and HeNB Gateway will be the same protocols for NAS and/or AS (Access Stratum) establishment, as well as measurement request and response. Besides typical RRC Establishment and S1 Context Setup protocols, for access related (AS) protocol, X2 Context Setup protocols may be needed if there is X2 interface to be established between HeNBs. This could be useful for coordinated/distributed sensing on TVWS, or for the purpose of distributed resource allocation/ optimization algorithms.

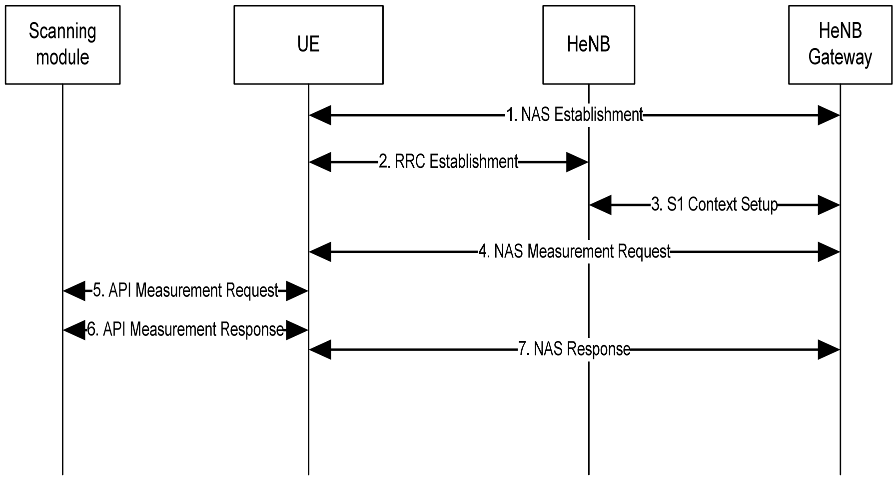


Figure 16: Message flow to support sensing function in user terminal.

3.3.6 Information/data models

This scenario will include the usage of REM hierarchies, i.e. the existing REM SA unit at different levels of the network: at the UE, the HeNB and the HeNB MS. The data replication in the direction UE to HeNB MS would provide a more global REM at the HeNB MS point, which can be used in centralized RRM optimizations, i.e. the allocation of unoccupied bands and transmission power levels to the multiple femtocells of interest.

The REM data used for the femtocell optimization in the LTE in TVWS FARAMIR scenario should include:

- TV transmitter locations and their configuration: this data should exist in the REM database to provide the REM Manager the option to estimate the coverage area of the primary system (TV transmitters) on a larger scale by means of using estimated (or known) propagation models.
- Propagation models estimates: this data is required in order to model the service areas of the primary system, as well as the femtocell coverage.
- Radio Interference Field (RIF) estimation: this data is required to validate the primary system coverage area estimations, as well as to detect the existence of other secondary systems in the tested area (including other operating femtocells).

PUs and SUs interference and localization: this data is required to perform the frequency, bandwidth and transmit power optimization in the femtocells. Similarly as the previous femtocell optimization scenario, the LTE in TVWS scenario might utilize a dedicated sensor network for REM construction purposes. The dedicated sensor network can be also integrated in the REM system hierarchy.

3.4 Non-coordinated spectrum access between PUs and SUs

3.4.1 The description of the scenario and the optimization problem

This section describes the network architecture for *Non-coordinated Spectrum Access between PUs and SUs* scenario that is introduced in the Deliverable 2.2 [1]. In this scenario, there is no direct coordination (i.e. collaboration) between PU networks and cognitive radio networks, also denoted as SU networks, because they are operating different Radio Access Technologies (RATs), i.e., such as legacy RATs. It is assumed that there can be multiple Radio Access Networks (RANs) within a composite wireless network radio environment. Therefore, Cognitive Radio (CR) users access the spectrum of the PU networks in an opportunistic manner which can be optimised using the features provided by the REM such as localized spectral activities (and characteristics) measured by CR users, PU network coverage areas, shared PU resource allocation information, policy information, propagation models and other RF environment information to estimate the available network resources.

Some of the key characteristics that differentiate this scenario from other scenarios are:

1. **Multiple PU and SU networks, operating different RATs:** This gives rise to a likely scenario of many RAT/RANs coexisting in the same locality (i.e. coverage area). If there are multiple RANs and sharing the spectrum between different RANs to optimize radio resource requires knowledge of the available options (i.e. bands and RANs), network performance requirements and RAT characteristics.

2. **Heterogeneity in the MCDs:** In a multi-RAN/RAT scenario, many measurements are RAT specific and hence are not sufficient to determine the complete performance of all available RAT/RAN options. Therefore, RAT specific measurements can be augmented with RAT independent measurements (i.e. such as spectrum occupancy measurements) gathered from various other sources including dedicated sensor networks and spectrum occupancy/allocation databases. The information is likely to be non-homogenous. Consequently, the related interface (i.e. MCD – REM-SA interface) should be described such that it handles this heterogeneity.

As discussed in [1], the scenario *Non-coordinated Spectrum Access between PUs and SUs* is quite general and accepts its instantiation to a number of different scenarios with similar characteristics. This includes different use cases such as out-of-band femtocells, smart meter/smart grid communication networks, home networks, etc. For each of them, different RRM optimization problems may arise depending on the particular aspects of each use case (see [14]). In that respect, in order to cope with the resulting heterogeneity of use cases and optimization problems associated to this scenario, this section will be organised in two main parts. First, a general architecture based on detailing the elements of the FARAMIR functional architecture of section 2 to the characteristics of this scenario will be presented. This will be introduced from a general perspective, without focusing on any specific standard; under the rationality of providing first the main functionalities that the architecture should provide taking into account the degree of generality of the considered scenario and optimization problems. Then, in the second part of the section (see sub-section 3.4.8), the particular mapping of the FARAMIR architecture to IEEE DYSPAN-SC standards [21] will be presented.

In order to present a general architecture valid for the different scenario instantiations and optimization problems, we consider an agile RRM system that can support multiple network operation modes. Each mode is defined by a unique optimization objective of CR network resource utilization. The selection of the operation mode is influenced by the nature of the surrounding radio environment. Figure 17 depicts the overall functional block diagram of this multi-mode RRM system. First various measurements of the RF environment are collected. These measurements are then passed to the *Data Processing and Analysis* stage where various spectral features and statistical properties of the utilized spectrum are extracted. The next stage is the *Resource Allocation Strategy Selection*. The RRM system maintains a number of resource allocation strategies, i.e., Modes that are defined by a unique resource optimization objective and a set of system constraints.

For illustration purposes, we consider in this document a dual-mode RRM system. However, the number of modes can be extended. The first mode (Mode H - Heterogeneous) is suitable for managing CR network resources in the presence of a heterogeneous set of PU networks (in this case heterogeneous assumes the possibility of PUs operating with different RATs). The second mode (Mode D - Dense) is designed to manage the spectral resources in dense CR network deployments.

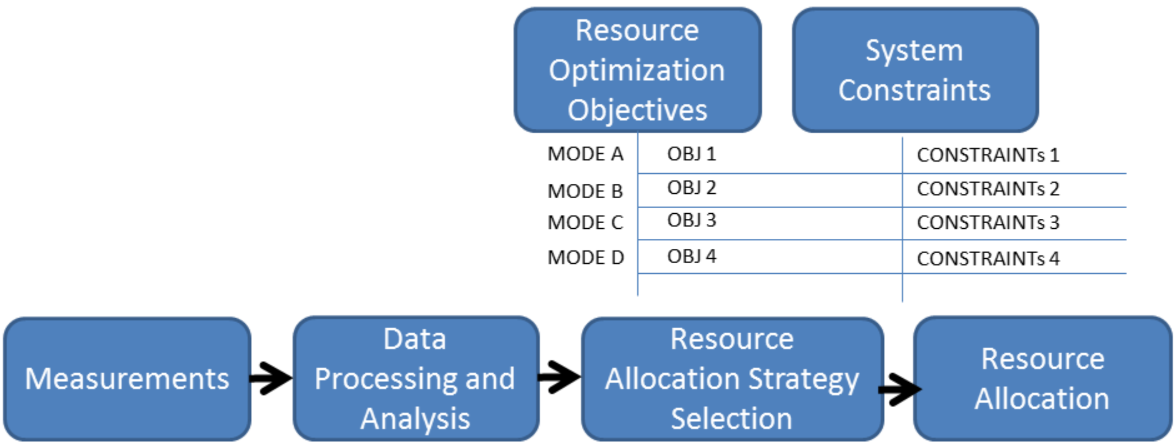


Figure 17: RRM system Functional Block Diagram for
Non-coordinated spectrum access between PUs and SUs Scenarios.

In mode H, RRM takes into account heterogeneous PU networks with different spectral features. By exploiting these features, the RRM system can improve the efficiency of spectrum sharing in CR networks and, thus, enhance their capacity. Unlike conventional RRM systems for CR networks where all PUs' activities are observed as spectral activities of higher access priority to spectral resources, or rely on joint RRM (i.e. in which the devices are supporting multiple RATs and hence can be coordinated), the main merit of mode H is its ability to differentiate and react to different PU activities. Grouping the PU activities into a single abstract utilization category, as is done in conventional RRM systems, removes some PU information about specific features such as bandwidth, allowable interference level and activity pattern, which can be otherwise exploited by the RRM system to improve spectral utilization of the CR network. This mode can be applicable to the optimisation problems "cognitive RRM exploiting heterogeneous PU types" and "spectrum selection based on PU transmission patterns" presented in section 4.3 of deliverable D5.1 [14].

In mode D, RRM aims to minimize the spectral footprint (i.e. the spectrum utilisation per coverage area) of the CR-network to allow dense network deployment. One example of such networks is cognitive femtocell networks. In this mode, a unique resource utilization metric is used i.e., bandwidth-power product (per coverage area). This metric is used to capture the efficiency of spectrum utilization. It is motivated by the fact that communication consumes space [18]. In Cognitive Radio Networks (CRNs), the gain of spectrum sharing comes from the heterogeneity in space consumption of different types of wireless devices with different bandwidth [19]. In this context, a user with large bandwidth demand is allocated first to achieve better utilization. Thanks to its frequency agile features, CRNs are capable of adapting their spectral resource utilization (i.e. bandwidth and transmission power) based on the spectral activity, density and distribution of adjacent PU networks. As a result, CRNs can achieve better utilization of space (i.e., spectral foot-print). This mode can be applicable to the optimisation problem "out-of-band cognitive femtocells" presented in section 4.2.3 of deliverable D5.1 [14].

The CR network considered in this scenario is infrastructure-based with a CR based centralized entity that coordinates the resource allocation for CR users. The network is composed of CR users and a CR centralized entity, which can be located in, e.g., a CR base station or CR-based femtocell. Specifically, the CR centralized entity is responsible for collecting sensing data, constructing REM, and coordinating the RRM. It is composed of:

- The *REM Manager*, which processes the measurements to construct the REM and coordinates the REM construction with other co-existing REM Managers. It also recognizes the surrounding RF environment and selects the appropriate resource allocation mode.

- The *REM SA*, which has the storage and acquisition functionality to acquire sensing data from CR users and to save it as a local database. Also the REM, built by the REM Manager through the data processing, is stored in the REM SA.

The REM information is then used by the CR centralized entity to perform the resource allocation/management functionality. In fact, this entity is responsible for allocating the available resources to CR users efficiently by exploiting the information provided in the REM and based on one of the pre-defined set of resource allocation modes.

In the following, the network architecture used in this scenario is described in details for each operation mode. Figure 18 shows the network architecture in mode H, while Figure 19 illustrates the architecture in mode D. In both modes, the network architecture is centralized and it is assumed that the base station is the CR centralized entity that maintains the REM-SA and REM management functionalities.

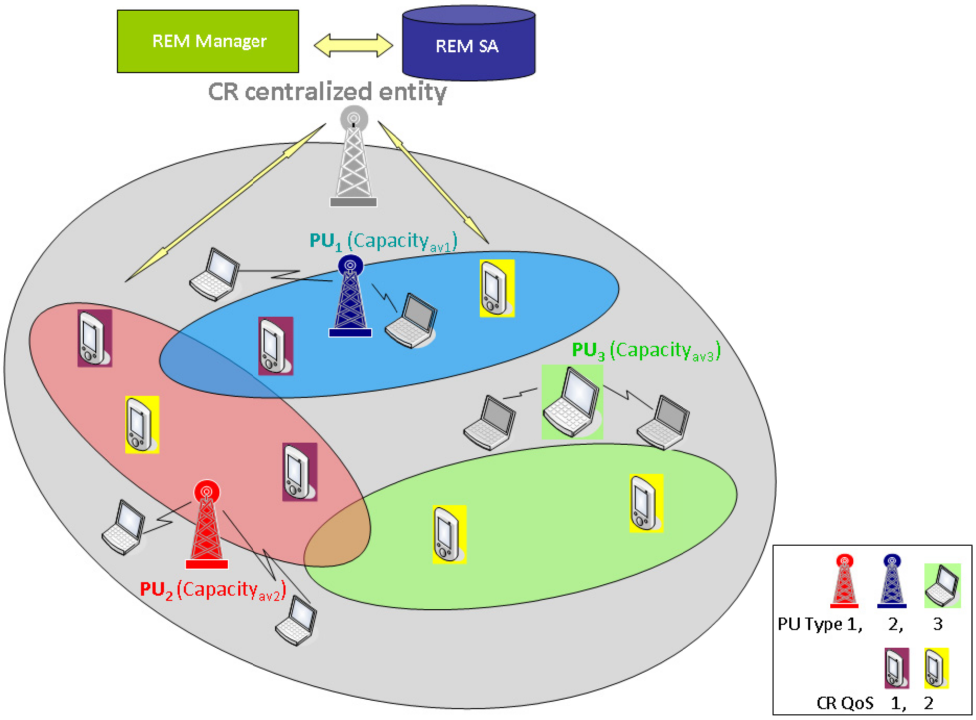


Figure 18: General architecture for the scenario of
Non-coordinated Spectrum Access between PUs and SUs (Mode H).

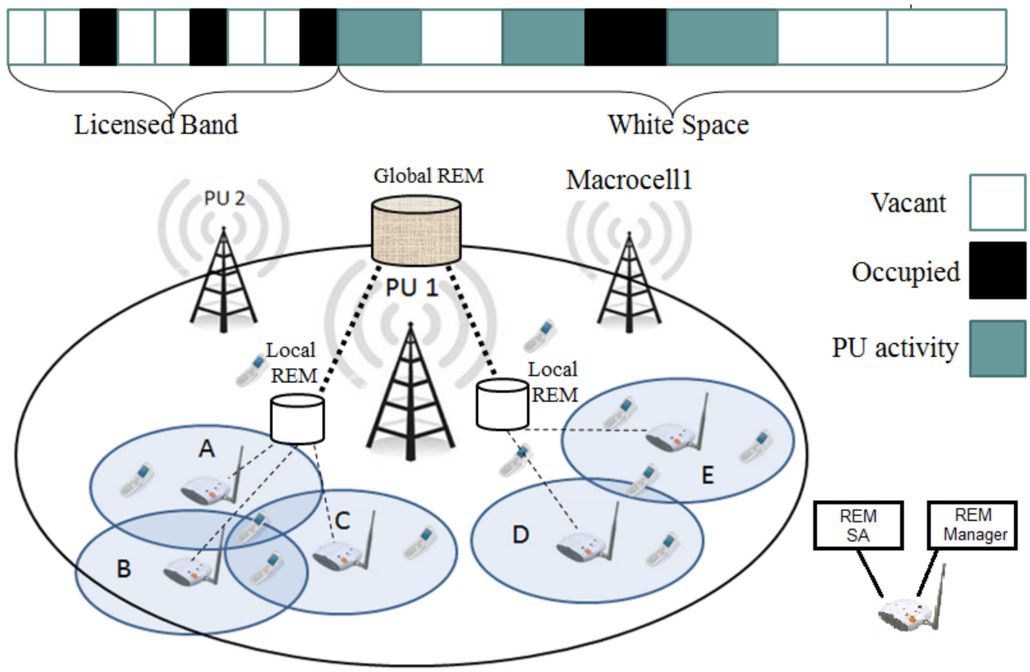


Figure 19: General architecture for the scenario of
Non-coordinated Spectrum Access between PUs and SUs (Mode D).

The scenario illustrated in Figure 18 shows three types of PUs associated to different RATs/frequencies. These PU types form three different clusters of CR users, which can overlap in space as can be seen in Figure 18. Each cluster is identified by the PU type, and the available capacity in a given cluster is determined by the spectral features of the PU type, which are extracted from the REM. Specifically, the measurements obtained by CR users are collected in the REM SA and processed by the REM Manager to detect and classify the existing PU types in the considered geographical area. The detection and classification process [15][16] is outside the scope of this document. After the classification process, the REM Manager updates the REM with the identified PU types and the associated features: bandwidth, allowable interference level and activity pattern. These features are useful for the prediction of the available capacity in a given cluster (such as in terms of aggregate throughput for the network over a suitable time frame). Also, CR users that share the capacity of a cluster can have different QoS. Figure 18 considers two types of CR QoS, named CR QoS 1 and CR QoS 2 respectively.

The network architecture in Figure 19 is comprised of several CR femtocells (A-E) operating in the presence of two primary user networks (PU 1 and PU 2) and a macrocell (Macrocell 1). The shared spectrum is composed of two sets of bands: licensed bands (i.e. bands that are owned by the Macrocell users and are shared with femtocell users on equal access right terms), and white space bands (i.e. bands that are owned by the primary user networks and are shared with femtocell users on opportunistic basis). Each band is divided into a certain number of channels. The bandwidth of channels that belong to different bands can be different. Each channel has two states: vacant or occupied. A third state is used for channels in the white space band in which the PU exhibits a certain discontinuous activity alternating activity and inactivity periods. These states are logged based on relatively frequent sensing and reporting mechanisms to a Radio Environment Map (REM) data base. There are two levels of REMs: Local REM which logs the states of channels in the local area of a femtocell and its interfering set, and Global REM which is responsible of collecting the channel states information from all local REMs and improve the quality of the sensing results using centralized sensing fusion techniques at the global level. The timescale of interest at a local REM level are shorter than the timescales at the global level.

3.4.2 Functional and operational (system) requirements

In the non-coordinated spectrum access scenario between PUs and SUs, the entire management process is based on the CR centralized entity. In the multi-mode RRM system, various sets of functional and operational requirements are considered for each operation mode. However, the CR users in all modes have to be located in the transmission range of the CR centralized entity and vice versa for two reasons:

- To send sensing information to CR centralized entity.
- To receive REM information from the CR centralized entity (e.g., CR clustering information (Mode-H) and power-frequency allocation information).

The following operational requirements have to be arranged. The details of each requirement may vary among different allocation modes depending on the overall network performance objectives:

1. Sensing: The channel quality is estimated by spectrum sensing operation. The sensing operation can be done via a dedicated sensing receiver at the CR-BS or its terminals, or through an external set of wireless sensing networks. We assume that the instant values of spectrum sensing measurements are available at every resource allocation cycle.

2. Limited SU mobility: The channel conditions remain unchanged during the resource allocation cycle.

3. The CR system should be able to know the PU locations and their transmitted power. This information can be obtained from the REM.

In addition to these operational requirements, there are a number of functional requirements at the REM-SA and REM Manager. These requirements are basically a set of measurements and information needed by the processing and allocation algorithms in RRM (e.g., utilized bandwidth, allowed interference, PU location, etc.). They are classified into CRN-related and CR user related information. Further details about the data structure used for these requirements are provided in Section 3.4.6.

3.4.3 Mapping of the functional REM architecture blocks on the physical network entities

As shown in Figure 18 and Figure 19, the network is composed of CR users and a CR centralized entity (assumed to be located in this case in a CR base station). According to this system architecture and the functional REM architecture in Figure 1, the mapping of the functional REM architecture into the physical network entities is shown in Figure 20. In particular, the blue blocks in Figure 20 are the functional entities of Figure 1, while the grey CR Base Station (BS) and the yellow and purple CR users are the CR network entities of Figure 18 and Figure 19. The REM SA block is split in two different functionalities, i.e. the REM Storage and the REM Acquisition, to better illustrate the messages exchange among different functionalities. Moreover, Figure 20 shows the interfaces among the different entities, which will be detailed in the following Section 3.4.4.

The measurement capable devices (MCDs) of Figure 1, which are responsible for acquiring the measurement information from the environment are mapped to the CR users, i. e. the network entities with the sensing functionality. In particular, the CR users utilize feature detection techniques [15] to detect and classify heterogeneous PUs as shown in Figure 18 and Figure 19. This information about different detected PUs is sent to the CR base station through the air interface (*Itf A*). The CR base station is the entity that collects sensing data, constructs REM, and coordinates the radio resource management (RRM). In particular, the BS functionality responsible for collecting the sensing data from CR users is the *REM Acquisition* unit of Figure 1. This unit also sends the registration information from the CR users to the REM Manager and the measurement requests from the REM Manager to the CR users. The interface in charge of communicating between the REM Acquisition and the REM Manager is the REM Manager-REM Acquisition interface (*Itf MA*). The REM Manager is the core functionality of the BS because it is able to build the REM using the sensing data coming from the REM Acquisition unit. The REM is thereby sent to the REM Storage for the saving process and to the REM GUI/RRM for presenting the results and for realizing an efficient RRM. The REM Manager-REM Storage interface (*Itf MS*) is responsible for the exchange of control information, such as read and write messages, and data messages between the REM Manager and the REM Storage, while the REM Manager-REM GUI/RRM interface (*Itf MR*) is in charge of exchanging control and data information between the REM Manager and the REM GUI/RRM in order to obtain an efficient management of the radio resources among CR users.

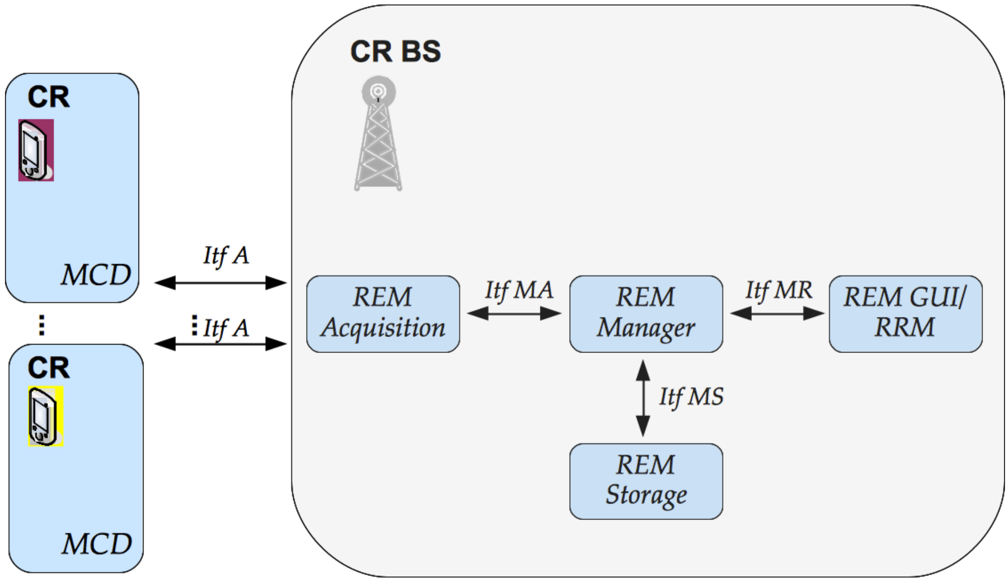


Figure 20: Mapping of the functional REM architecture on the physical network entities for the scenario of Non-coordinated Spectrum Access between PUs and SUs.

3.4.4 Interfaces

The functional entities communicate among them through specific interfaces. Through these interfaces, several types of messages are exchanged. Figure 21 depicts a generic message exchange process between the RRM entities while Figure 22 shows the message exchange in Mode-D. In the following, we describe these interfaces in details.

- The **air interface (*Itf A*)** is the interface between the MCDs, i.e. the CR users, and the REM Acquisition unit. As shown in Figure 21, this interface is used to exchange control messages, i.e. registration messages and measurement requests, and data messages, i.e. raw measurement data from CR users, and measurement report from the REM Manager after the data processing, i. e. the constructed REM.

- The **REM Manager-REM Acquisition interface (*Itf MA*)** is in charge of sending both control and data messages between the REM Acquisition and the REM Manager. Figure 21 and Figure 22 show that these control messages are the registration information that the REM Acquisition receives from the CR users and sends to the REM Manager, and the measurement requests from the REM Manager to the REM Acquisition after the REM quality check. The data messages exchange consists in sending the raw data from the REM Acquisition to the REM Manager for the data processing, and in sending back the built REM, i. e. the measurements report.

- The **REM Manager-REM Storage interface (*Itf MS*)** is responsible for the exchange of control messages between the REM Manager and the REM Storage, e.g. read or write messages, and for the data exchange, e. g. the information of the REM built by the REM Manager and sent to the REM Storage for the saving process.

- The **REM Manager-REM User (GUI/RRM) interface (*Itf MR*)** is used to present the measurement results after the data processing of the REM Manager and to use them for the RRM procedure. As shown in Figure 21, the obtained REM is exploited for the resource allocation among CR users, which consists in two steps: the allocation of CR users to the clusters and the allocation of the resources to the CR users inside the clusters. More details on this process are given in the deliverable D5.1.

3.4.5 Protocols and message sequence charts (MSCs)

The proposed RRM architecture requires specific interactions among its components. This interaction is defined by a number of message exchanging mechanisms. In this section, we describe the generic message exchanges that occur in all modes. Then, we focus on the message exchanging that occurs in Mode-D. The REM-SA deals with two types of messages: the first ones are exchanged with REM Manager through Itf- MS and Itf-MA interfaces, and the other types of messages are exchanged with the CR user through Itf-A interface.

The messages exchanged between REM-SA and CR user are:

- Registration: This message is sent by the CR user to provide CR user-related information such as hardware limitation, minimum reception power limits and data rate requirements. In addition, CR user location is used to identify the sector at which the CR user will be served.

- Measurement Request: Before every resource allocation cycle, the REM manage polls a set of CR measurements through a measurement request message with specific measurement types such as interference and locations.

- Measurement Response: This message is the CR user response to the measurement request message.

- Configuration: This message is sent by the REM Manager to assign the CR user with the allocated resource.

Similarly, the messages exchanged between REM Manager and REM SA are:

- Update: This message is provided by the REM-SA upon changes occur in their database contents or as a response to some report messages. Unlike the measurement response message, the update message is not always a response to the update message.

- Report: The report message is sent by the REM Manager to trigger some processing tasks such as PU activity estimation or activity threshold calculation.

As shown in Figure 18 and Figure 19, CR users send their sensing information to the CR centralized entity, i.e. the CR Base Station (BS), which then correlates between the various measurements to build the REM that is exploited for the RRM procedure. Figure 21 illustrates the generic message exchange during any mode among the components of the multi-mode RRM system. In Figure 22, the message exchange in the particular case of Mode-D is provided. However, in both figures, the REM Acquisition and the REM Storage functionalities are merged together in the REM SA module.

The CR users send their registration information to the REM SA. In particular, only the REM Acquisition functionality of the REM SA is involved in this step, which sends the received registration information to the REM Manager to updates the number of CR users involved. At this step, the REM Manager reads the stored information in the REM Storage through the *Itf MS* interface and carries out the REM quality check to evaluate the need of new measurements. Thus, if it is necessary, the REM Manager requires new measurements to the REM Acquisition through the *Itf MA* interface, which collects the sensing data from CR users through the *Itf A* interface. In particular, the REM Acquisition sends the measurements requests to the CR users first, and then it receives the obtained measurements from them. After that, the REM Acquisition forwards these findings to the REM Manager through the *Itf MA* interface, which processes the data to build/update the REM. In particular, the REM Manager extracts the features of heterogeneous PUs from the sensing data, and uses these features to build the REM and to calculate the available capacity for CR users. This information is essential for the RRM process, which is the final goal of the proposed framework. After the data processing, the obtained data are stored in the REM Storage through the *Itf MS* interface and are sent to the CR users by the REM Acquisition through the *Itf A*. At this point, the CR users can adapt their transmission parameters accordingly, as explained in the deliverable D5.1, and the RRM procedure is carried out through the *Itf MR* interface. It should be noted that the resource allocation (bandwidth and power allocation) is performed in the REM Manager. This allocation is done jointly or decomposed into multiple stages as detailed in D5.1.

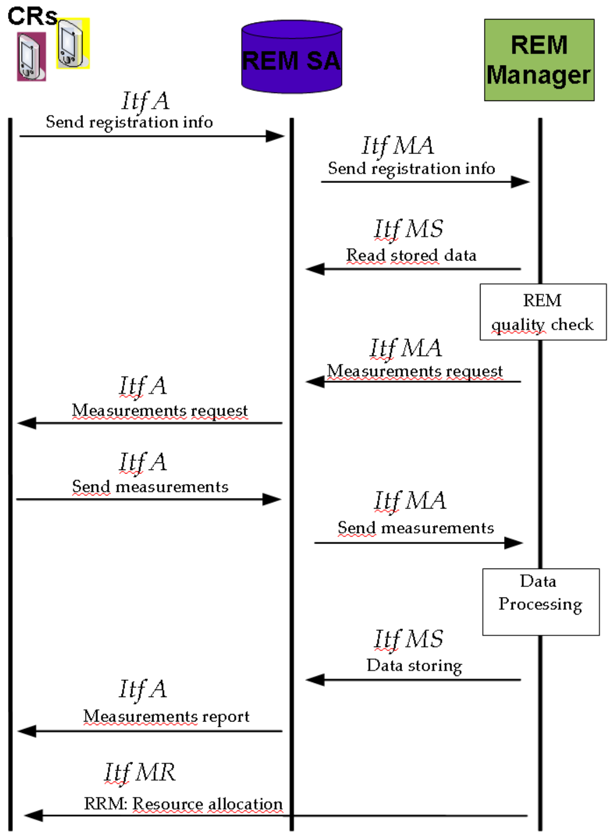


Figure 21: Generic Message Sequence Charts for the scenario of Non-coordinated spectrum access between PUs and SUs.

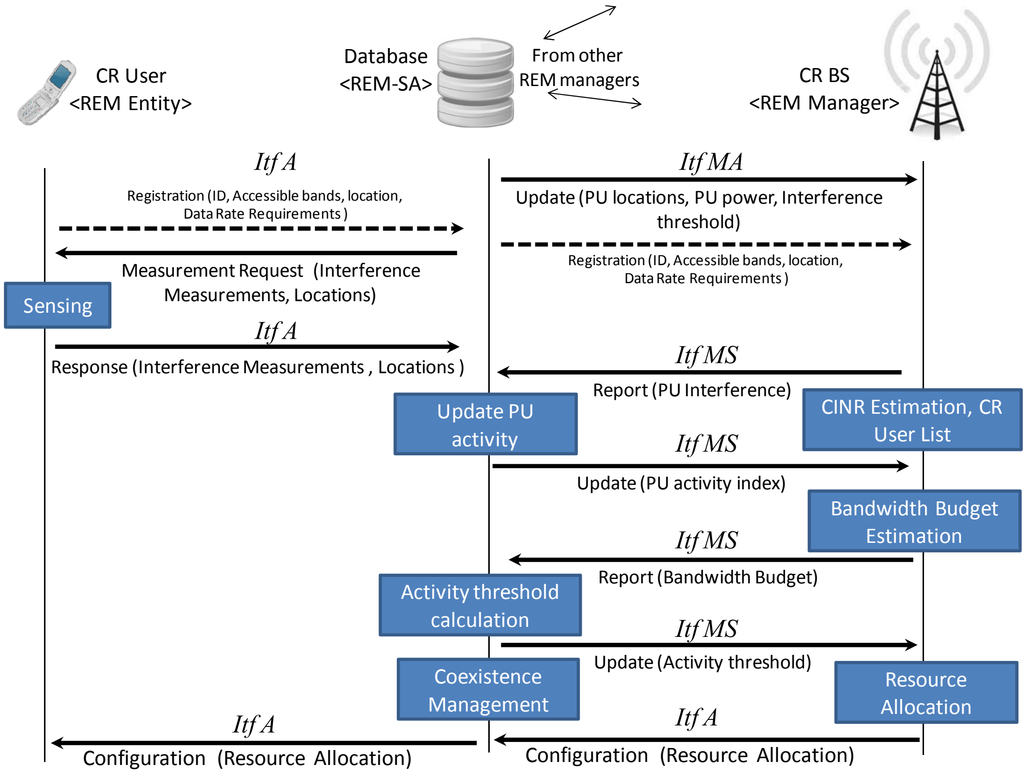


Figure 22: Message Sequence Charts for the scenario running under Mode-D.

3.4.6 Information/data models

The REM SA stores sensing data plus other useful information that depends on every specific mode (or optimisation problem) considered. Here a non-exhaustive list, for the optimisation problems presented in D5.1 is given. Specifically, the REM SA stores three types of information:

SU-Related Information:

- **CR user channel measurements:** These measurements are needed to estimate the channel quality at each user.
- **CR user locations:** The frequency of reporting this information depends on the CR user velocity and the dynamics of the environment. It is required to estimate the channel gain between the CR-BS and CR user as well as updating the CR user list for each sector.
- **CR accessible bands:** Due to the hardware limitation of mobile devices, the accessible bandwidth for each CR user might not be as wide as it is in the CR-BS. Hence, a list of the accessible channels is maintained to be considered during the channel assignment stage. This information is provided once during the registration process of the CR user.

- **Data rate requirements:** This information is obtained during the registration process of the CR user and in the measurement response message in case the CR application has changed its rate requirements. The data rate requirements are necessary to estimate the total bandwidth budget at the CR-BS.

- **Hardware specific limitation parameters** such as the accessible channels, minimum received power, and data rate requirements. The processing load on the mobile device is focused on estimating the interference level at each channel as well as localization functions.

PU-Related Information:

- **PU locations:** The PU transmitter locations are required by the CRN to identify the list of PU networks that can be subject to the CRN interference. In particular, the distance is required to estimate the channel gains between PU and SU nodes.

- **Transmission power:** This information is needed in addition to location to estimate the channel gains.

- **Interference threshold:** this is the maximum tolerable interference level for PU operation measured in power units (e.g. dBm, mW).

- **PU activity index (Mode-D):** This index is maintained at the REM SA based on CR sensing measurements and PU transmission schedule information (if available). Based on accuracy of these measurements and the history of previous interference event, an optimum threshold can be determined. If the activity index exceeds that threshold, the interference power constraint is activated for the next allocation cycle.

CRN-Related Information:

- **Adjacent CRNs:** REM-SA plays a fundamental role in managing the coexistence of multiple CRNs. Since the global level REM-SA has access to the resource allocations of coexisting CRNs, it can coordinate an orthogonal channel assignment among them. This is achieved by selecting an optimum pool of channels for each CRN based on the bandwidth budget requirement and channel conditions at each CRN. Hence, the proposed framework can be extended into multi-cell scenario through appropriate coordination at the REM-SA. This is particularly useful for femtocell applications.

- **Bandwidth budget:** This is the total bandwidth (e.g. total number of channels) that is required by a CR-BS based on the requirements of the users to be served.

- **CR channel sensing measurements:** These measurements are necessary to build and update the PU activity index, and to determine the proper PU activity threshold accordingly.

- **CR supported number of sectors:** This depends on the CR-BS hardware and is required during the channel assignment stage.

- **CR power and channel allocations:** The results of the resource allocation framework are maintained to be updated iteratively at each allocation cycle.

- **Mode-Specific processed features:** In mode-H, for example, the data stored in the REM are the features of heterogeneous PUs and the propagation features. Specifically, after receiving the sensing information about the detected and classified PUs, the REM Manager extracts the PU features, which will be used in the RRM procedure to efficiently allocate radio resources among CR users. The values of these features are specified in different PU standards. In the following these PU features are summarized as:

    - PU Allowed Interference levels (to calculate the available capacities and to adapt the CR transmission power)
    - PU Activity patterns (to calculate the available capacities and to adapt the CR transmission time)
    - PU bandwidth (to calculate the available capacities and to adapt the CR bandwidth)
    - Propagation features, such as propagation factor, (to calculate the CR transmission power)

  These PU features stored in the REM are used in the Cognitive RRM framework [15], detailed in deliverable D5.1, to coordinate the sharing of radio resources among CR users. Specifically, the CR centralized entity calculates the amount of available capacity based on the PU features extracted from the REM. A cluster of CR users that share the same available capacity is formed based on the influencing PU type. Once CR users are grouped into clusters, the CR centralized entity uses REM information to allocate the resources to the CR users in the clusters, in terms of transmission power, time and bandwidth.

3.4.7 Policy Management in Non-coordinated spectrum access between PUs and SUs

One possible instantiation of the REM User is a Policy Manager (PM). This REM instantiation yields an interconnected FARAMIR REM architecture and a policy system for cognitive network management, which can be used in the Non-coordinated spectrum access between PUs and SUs FARAMIR scenario.

Figure 23 shows that REM hierarchy can be also utilized in this scenario. Local policies can be derived based on the local REM information and global policies can be derived based on the REM data stored in global REM Storage. These local and global policies can enable distributed and centralized policy management, where higher importance and priority is given to the global policies.

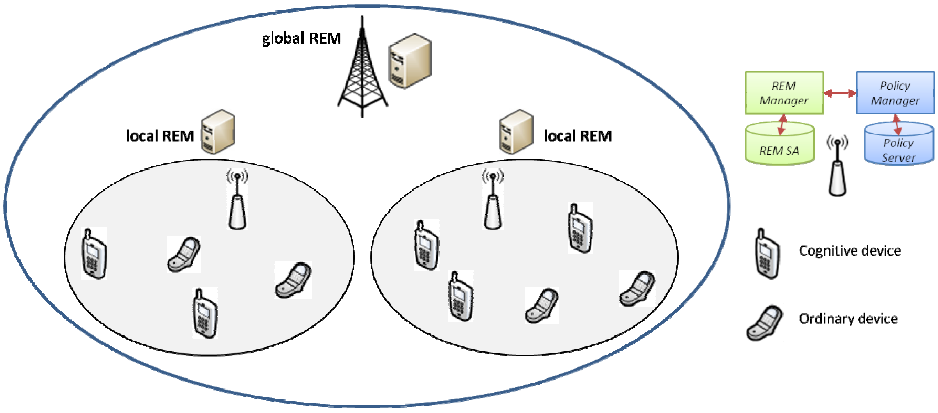


Figure 23: Policy and REM facilitated system architecture for
Non-coordinated spectrum access between PUs and SUs.

Several possible instantiations of terminals can be used in this scenario (Figure 24), i.e.:

- **Policy controlled Cognitive Device (PCD)** – cognitive device that is sensing capable and capable of policy reasoning and policy enforcing. Thus, this radio can be used as MCD and as a CR device. This device can perform autonomous policy reasoning due to the possession of a Policy Engine (PE).

- **Ordinary Cognitive Device (OCD)** – cognitive device that is sensing capable and policy enforcing capable. Thus, this radio can be used as MCD and as a CR device. This device has to use the reasoning capabilities of a remote PE-enabled device.

- **Non-Cognitive Device (NCD)** – ordinary device without cognitive capabilities. This device can be only used as an MCD with limited capabilities, i.e. can measure only its technology specific channels.

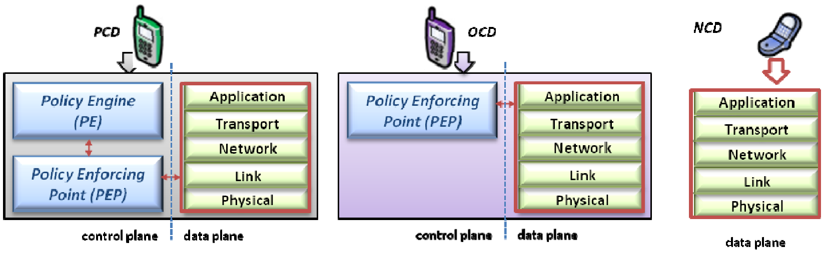


Figure 24: Terminal types from policy aspect.

3.4.7.1 Information/data models

The spectrum access/ sharing policies derivation of the PM can be performed based on the following REM inputs handled by the REM Manager – REM user interface:

- PU information:
  - PU technology information: tolerable interference levels, bandwidth, transmission power, MAC protocol and scheduling, base station locations, etc.
  - The estimated (modeled) radio interference field, the estimated (known) PU locations and the estimated (known) propagation models.
  - The estimated PU spectrum occupancy at frequency bands/time/space, as well as the estimations of the PU activity patterns.

- SU information:
  - The SUs capabilities in terms of the supported bands for operation, power limitations, noise levels, interference thresholds etc.
  - The estimated (known) SUs locations and the measured mutual SU interference.
  - The communication requirements of the SUs.

3.4.8 Architecture Mapping based on IEEE DYSPAN-SC

In this section, we present the analysis of deployment and network mapping for the non-coordinated spectrum access between PUs and SUs scenarios based on existing standard IEEE DYSPAN-SC. We propose that IEEE DYSPAN-SC standards [22]-[24] offer a suitable deployment option for these particular scenarios, in which a heterogeneous network environment exists. The heterogeneous wireless network environment is characterised by multiple RANs, with multiple RATs, multiple radio interfaces and multiple terminals that are operated by the same or different operators in a combined manner.

We discuss the relevance of the IEEE 1900.4-2009 standard [22] with respect to managing the resources within multiple RANs operating different RATs. Also, we consider extending the same analysis towards white space resource management and consider the IEEE 1900.4a-2011 architecture [23]. In the DYSPAN-SC, WG6 has recently published IEEE 1900.6-2011 standard [24] that describes RAT independent spectrum sensing interfaces and data structures. This standard and the newly approved amendment project P1900.6a that targets protocol message sequences are very relevant to the FARAMIR architecture interface design considerations.

The IEEE DYSPAN-SC family of standards abstract information and data models (including policies) at a RAT/RAN technology independent level to facilitate management of resources within multi-RAT and multi-RAN environments. In addition they abstract spectrum resources such as channels and frequency bands with sufficient flexibility and extendibility to permit exploitation within dynamic spectrum access (cognitive radio) scenarios.

3.4.8.1 Coordinating Composite Wireless Networks

An overview of the IEEE 1900.4-2009 standard and its relevance to the FARAMIR architecture and possible network mapping is presented.

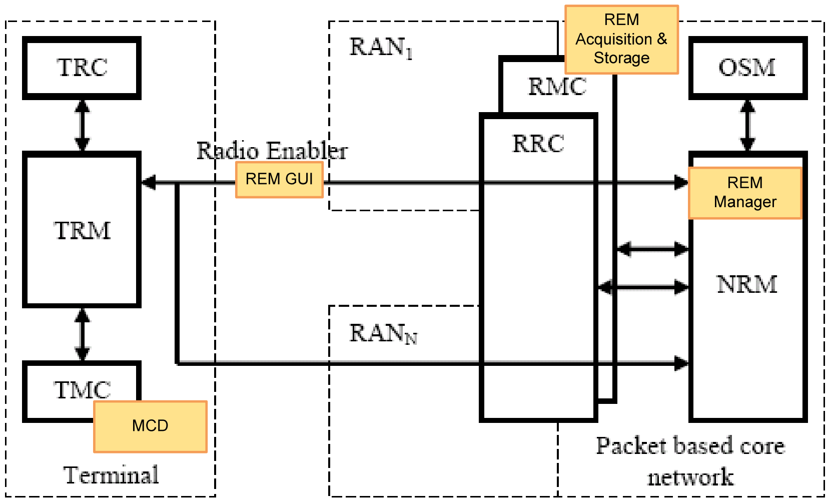
The standard defines the building blocks comprising (i) Network Reconfiguration Manager (NRM), (ii) Terminal Reconfiguration Manager (TRM), and (iii) the information to be exchanged between the building blocks, for enabling coordinated network-device distributed decision making that will aid in the optimization of radio resource usage, including spectrum access control, in heterogeneous (multi-RAT and RAN) wireless access networks.

The purpose of IEEE 1900.4-2009 standard is to improve overall composite capacity and quality of service of wireless systems in a multiple RAT environment, by defining an appropriate system architecture and protocols that will facilitate the optimization of radio resource usage, in particular, by exploiting information exchanged between network and mobile terminals, whether or not they support multiple simultaneous links and dynamic spectrum access.

Operator Spectrum Manager (OSM) may help the operator or regulator/meta-operator to coordinate the assignment of spectrum to the different operators in order to optimize radio resource usage within Composite Wireless Networks (CWN). This entity permits the assignment of spectrum but does not define how this spectrum is utilised and the interface is not itself standardised (i.e. it is operator or regulator dependent).

OSMs generate spectrum assignment policies expressing the regulatory framework and operators objectives for spectrum usage optimization. The OSMs provide these spectrum assignment policies to the corresponding NRMs. The NRMs analyze spectrum assignment policies and available context information and dynamically derive the spectrum and terminal level (i.e. TRM) policies and RAN configurations that are then enforced to optimise the resource utilisation.

Figure 25 illustrates the mapping of FARAMIR entities to IEEE 1900.4 network elements. In this mapping, the policy is received within NRM (from OSM) to permit the NRM to determine the appropriate frequencies and RATs to allocate to the CWN. The NRM (which can utilise the REM Manager function) can then decide on which RAT and frequencies to utilise within the limitation of the OSM policy. The NRM then configures the CWN and issues policies to the TRMs to perform resource selection. The RAN Measurement Collector (RMC) and its functionalities have similarities to REM Storage and Acquisition (REM-SA) entity. In Figure 26 the mapping of FARAMIR functionalities to IEEE 1900.4 functional architecture further emphasis the suitability of deploying of heterogeneous networks.



TRM – Terminal Reconfiguration Manager
TRC – Terminal Reconfiguration Controller
TMC – Terminal Measurement Collector
OSM – Operator Spectrum Manager
NRM – Network Reconfiguration Manager
RRC – RAN Reconfiguration Controller
RMC – RAN Measurement Collector
RAN – radio access network

Figure 25: Mapping of the FARAMIR functional entities to IEEE 1900.4 system architecture.

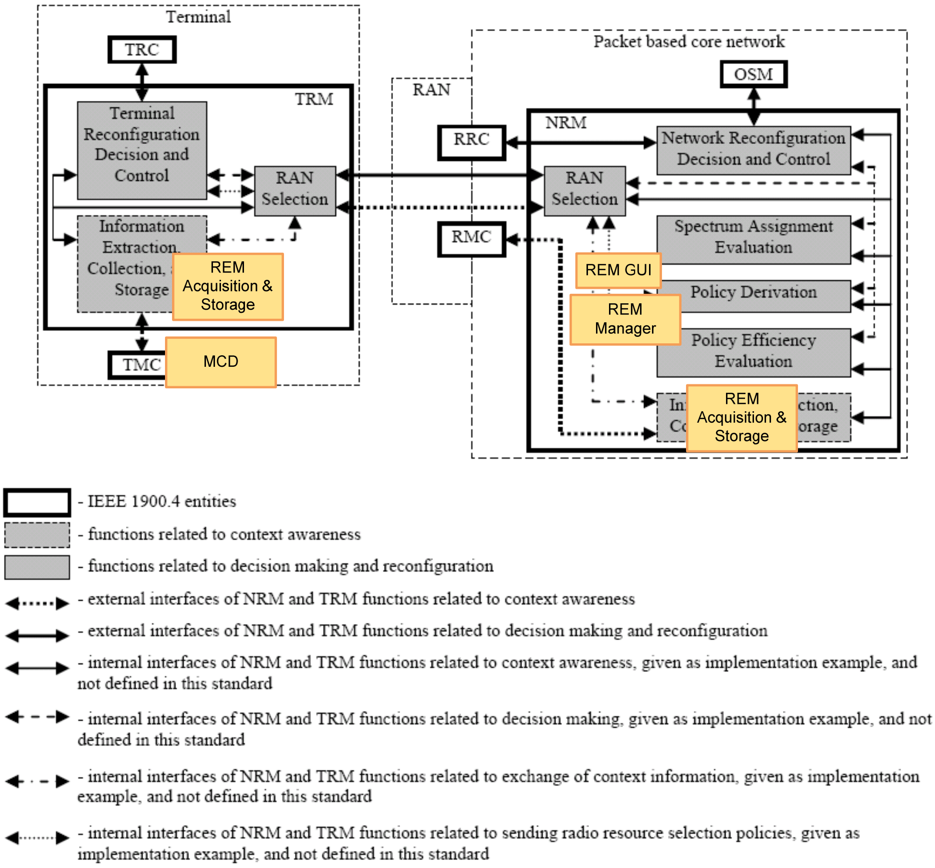


Figure 26: Mapping FARAMIR functional entities to IEEE 1900.4 functional architecture.

The interesting characteristic of this non-coordination spectrum access scenario is that, there exists multiple radio access networks and REM functioning as coordinator between networks. The 1900.4-2009 standards considered this multiple operator scenario. Figure 27 illustrate the coordination between the different NRM entities. Figure 28 illustrate the scenario where single NRM coordinate between multiple CWNs.

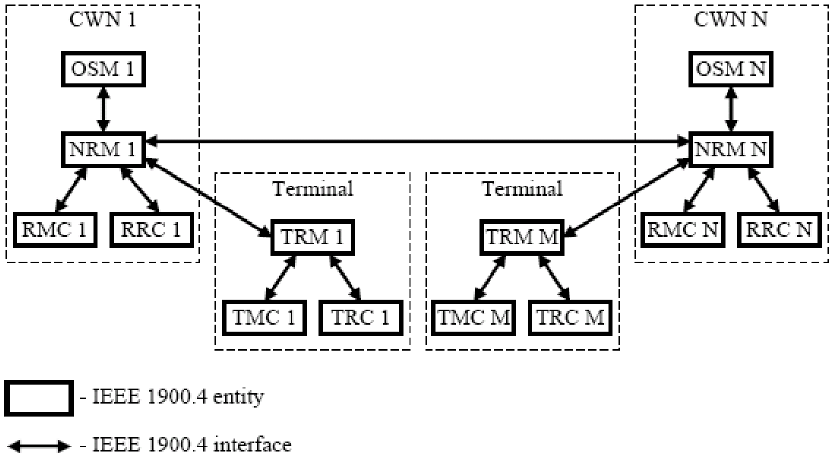


Figure 27: Multiple Operator - Scenario 1 (NRM inside).

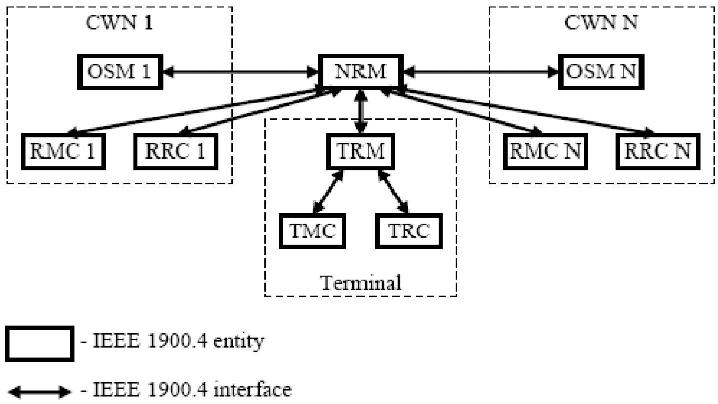


Figure 28: Multiple Operator -Scenario 2 - NRM outside.

3.4.8.2 Coordinating White Space Resource Management

An overview of the IEEE 1900.4a-2011 standard and its relevance to the FARAMIR architecture and network mapping is presented. For a detailed explanation of the terms and abbreviations used in this sub-section, the reader is referred to the *Glossary and Definitions* section at the end of this document.

The IEEE 1900.4a architecture specifically provides white space resource management where it was purposefully build for coexistence of different secondary system. White space resource management includes classification of white space resources, and exchange of classification results between the base stations (Cognitive Base Station Reconfiguration Managers, or CBSRMs in short), and coordination of white space resource usage between base stations (CBSRMs).

P1900.4a defines additional entities and interfaces to enable efficient operation of white space wireless systems. P1900.4a uses IEEE standard 1900.4-2009 as a baseline. It concentrates on dynamic spectrum sharing use case of IEEE standard 1900.4-2009. P1900.4a defines additional entities and interfaces to enable efficient operation of white space wireless systems. The collaboration between IEEE 1900.4 and IEEE 1900.4a systems is illustrated in Figure 29.

Within the dynamic spectrum sharing use case, P1900.4a use cases identify two stages of operation: white space wireless system start-up and white space wireless system operation. These stages occur during the three scenarios: sharing spectrum with non-1900.4 system, sharing spectrum with 1900.4 system, and sharing spectrum with other P1900.4a system.

Alternative mappings are also possible when a White Space Manager (WSM) entity is introduced (i.e. using the IEEE 1900.4a amendment) and illustrated in Figure 30. The WSM interrogates the white spaces database of the appropriate regulator. The REM Manager function is mapped to CBSRM and it is the responsibility of the CBSRM to determine the appropriate frequency assignment based on the measurements retrieved from MCDs in the terminals (TMC) and also the network (CBSMC).

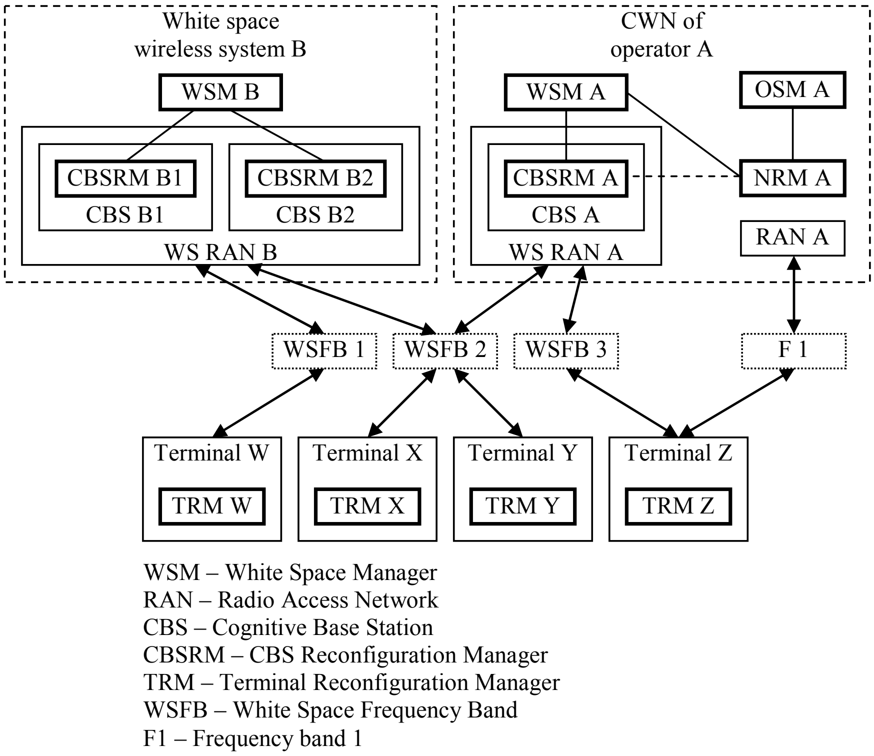


Figure 29: 1900.4a overview: collaboration with IEEE 1900.4 system.

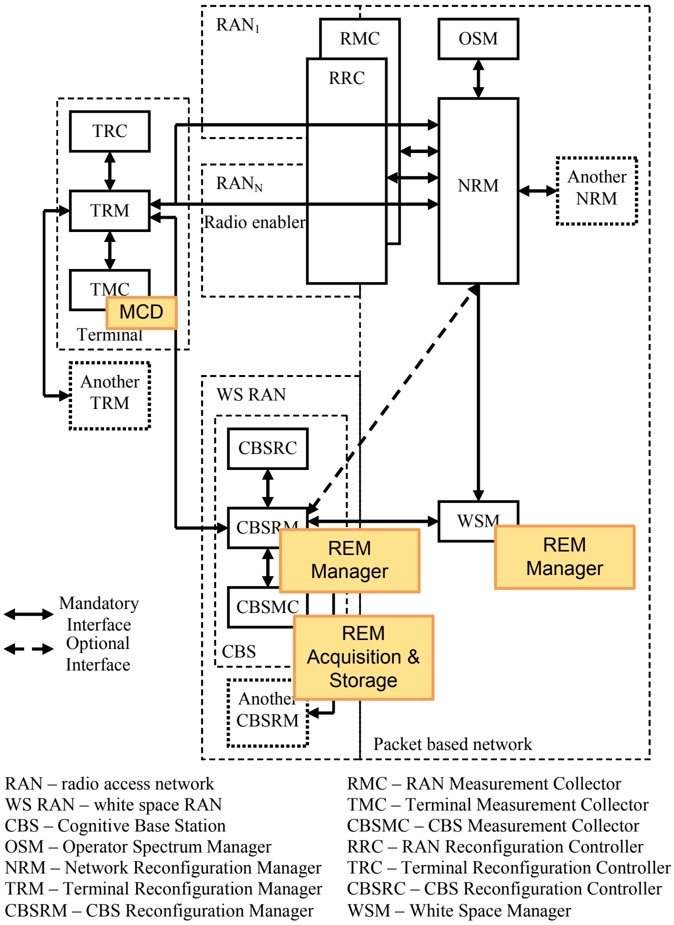


Figure 30: Mapping of FARAMIR functional entities to 1900.4a System Architecture:

3.4.8.3 1900.6 Interfaces:

In this section, an overview of the IEEE 1900.6-2011 standard and its relevance to the FARAMIR architecture is presented. The IEEE 1900.6-2011 standard defines the interfaces and data structures required to exchange sensing-related information for increasing interoperability between sensors and their clients developed by different manufacturers. In FARAMIR architecture the variety of MCDs are required to exchange sensing-related information to the REM-SA. The new project IEEE 1900.6a aims to specify procedures, protocols and message formats for the exchange of sensing related data, control data and configuration data between spectrum sensors and data archive/cognitive engine.

In 1900.6 standard, the logical interface and supporting data structures are defined abstractly without constraining the sensing technology, client design, or data link between sensor and client. It further elaborates on the service access points and service primitives. Generic procedures used to realize this information exchange are defined by this standard.

The new technologies that access multiple spectrum bands require reliable, dependable, and trusted spectrum sensing capabilities in order to make accurate assessments of spectrum availability in the surrounding operational area. Such capabilities will assist devices and associated radio equipment in identifying locally/temporally available spectrum that can be accessed without causing harmful interference to the incumbent users of that spectrum.

Recently proposed advanced radio systems based on sensing technology (e.g., those being worked on within IEEE P802.22) combine sensing and the protocols and Cognitive Engines (CEs) that use the sensing results into proprietary architectures. This model of development reduces innovation and limits the opportunities for integrating new component technologies for better system performance. Furthermore, the results of sensing extend beyond the activities of a single system and are ideally integrated into the larger spectrum management process including the development of spectrum use monitoring and enforcement activities.

Many different sensing techniques have been defined and implemented, yet there has been no effort to provide interoperability between sensors and clients developed by different manufacturers. In 1900.6 standards the clients can be cognitive engines as in the focus of this standard or can be any other type of algorithms or devices (e.g., adaptive radio) that use sensing-related information. Being aware of evolving technologies, interfaces are developed to accommodate future extensions, new service primitives, and parameters.

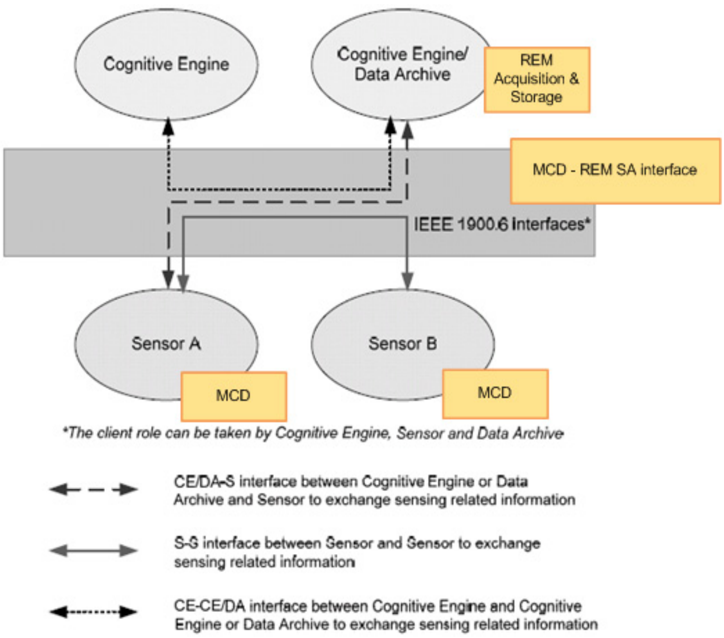


Figure 31: Mapping MCD-REM SA interface to IEEE 1900.6 Interface.

Three types of interfaces are defined in 1900.6 standards. The interface between the Sensor and CE/Data-Archive (DA) is the one that is specifically relevant to our context. (The other interface definitions between sensors may not be relevant to FARAMIR architecture context).

The CE/DA–S interface is used for exchanging sensing-related information between a CE or DA and a Sensor. As an example, the CE/DA–S interface is used in scenarios where a given CE or DA obtains sensing-related information from one or several Sensors or a given Sensor provides sensing-related information to one or several CEs or DAs. In Figure 31 the MCD-REM SA interface is mapped to IEEE 1900.6 interface.

The newly approved project P1900.6a is an amendment that adds procedures, protocols and message format specifications for the exchange of sensing related data, control data and configuration data between spectrum sensors and their clients. In addition, it adds specifications for the exchange of sensing related and other relevant data and specifies related interfaces between the data archive and other data sources.

The messaging sequence between wide variety of MCDs and the REM-SA that are being considered in FARAMIR architecture is exactly the scope of this new project. We have identified this as an exciting opportunity to work with this standard and as an ideal dissemination route to standardize the interfaces.

3.4.8.4 Protocols and message sequence charts

The first use-case supported by the IEEE 1900.4 standard is the single operator scenario with an OSM dynamically assigning spectrum to networks within a CWN. The mapping from FARAMIR functional blocks to IEEE1900.4 entities is illustrated in Figure 32. In this mapping, the policy is received within NRM (from OSM) to permit the NRM to determine the appropriate frequencies and RATs to allocate to the CWN. In the first instance the NRM requests measurements (i.e. collects context information), which is based on link and observed channel related information within the IEEE 1900.4 approach. Therefore, either specific channels or links can be monitored and the measurements reported back at specified intervals or in response to certain changes. The NRM (which can utilise the REM Manager function) can then decide on which RAT and frequencies to utilise within the limitation of the OSM policy. The NRM then configures the CWN and issues policies to the TRMs to perform resource selection.

In this first scenario the NRM (using the REM Manager) is performing the coordination between CWN networks and hence there is no distinction between PU and SU as they are all CWN RANs using a shared frequency resource that is allocated by the OSM/NRM. However, the same deployment and mapping can be used in a second scenario in which the RATs are able to share the same resource without coordination from OSM. This permits OSM to assign the same frequencies to different RATs within the same geographic area. In this case the NRM (or REM Manager) can still perform the RAT frequency assignments, but this time utilising just the measurements coming from MCDs within TMC and RMC. Therefore, the same sequence is utilised as in the first scenario. In this scenario there is even more importance on the timeliness of the measurements in order to react quickly to the presence of changes in the environment (i.e. PU network).

Further extensions are possible for multi-operator scenarios, which assumes that multiple NRM (and hence REM Managers) will exist in the same geographic area and require interaction. Within the IEEE 1900.4 standard this is not fully defined and hence is implementation specific.

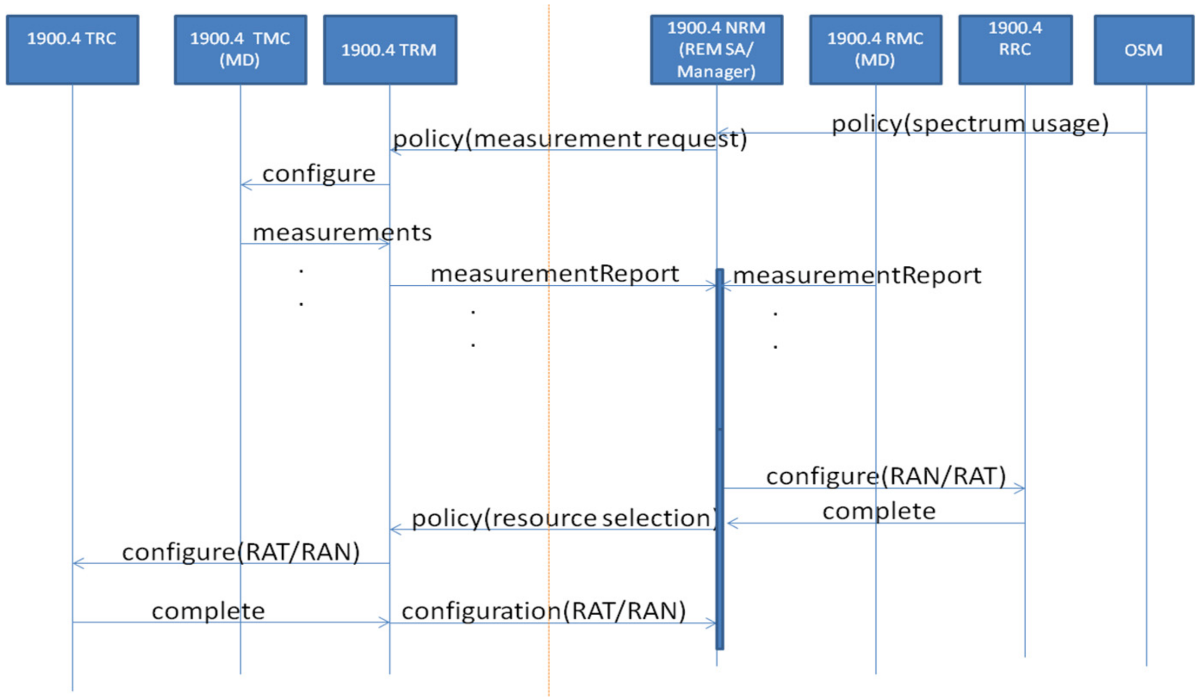


Figure 32: IEEE 1900.4 MSC for Single Operator Use-Case.

Alternative mappings are also possible when a White Space Manager (WSM) entity is introduced (i.e. using the IEEE 1900.4a amendment) and illustrated in Figure 33. The WSM is responsible for coordinating the use of white space spectrum for cognitive base stations that opportunistically utilise white space spectrum. Hence, rather than OSM providing the policies for spectrum usage, the WSM interrogates the white spaces database of the appropriate regulator. Typically this requires geographic location information (i.e. using GPS or similar methods). It is then the responsibility of the CBSRM (which can contain the REM Manager function) to determine the appropriate frequency assignment based on the measurements retrieved from MCDs in the terminals (TMC) and also the network (CBSMC). Therefore, the main difference between this deployment scenario compared with the IEEE 1900.4 scenarios is that instead of OSM providing spectrum policy, it is obtained from the regulator-provided database and that the frequency assignment decision making is performed within the base station entity (where the REM Manager function can reside). In addition (i.e. to support hierarchical REM model) the WSM can also contain a REM Manager function. In this alternative deployment the WSM REM will derive the policies based on a "global" REM knowledge whereas the CBSRM level REMs only consider the "local" cell context.

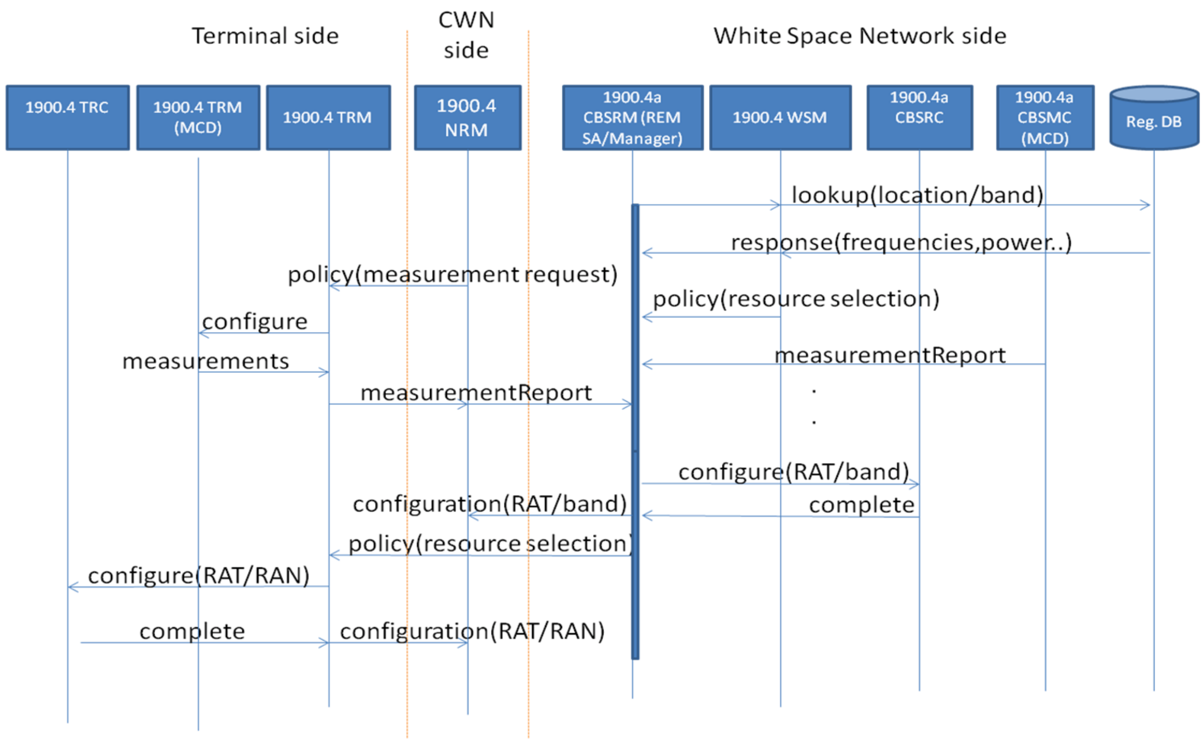


Figure 33: IEEE 1900.4a MSC for White Space DSA.

3.4.8.5 Gap Analysis

The IEEE 1900.4 and 1900.4a examples above have shown two main ways of mapping FARAMIR REM functionality to existing standards. The key points to identify from these mappings are the interfaces that are missing from those standards. For instance, the OSM-NRM interface is not defined in IEEE 1900.4 and also the CBSRM/WSM interface to the regulatory database is also not fully defined, so other standards (or regulatory guidelines), such as those defined in ITU-R 5A and ITU-R 5D, need to be considered. The IEEE 1900.4 standard provides an extensible set of techniques to determine the type of measurements to be performed. Therefore, missing measurements can be added to the data model with relative ease, but with the consequence that legacy devices conforming to the original data model may not be able to perform these new measurements. For instance, the channel profile for which the measurements are conducted are currently defined as follows:

```
observedChannelId: NameType

observedChannelFrequencyRange: FrequencyRange

associatedCellId: OptionalObjectName

radioInterface: RadioInterface
```

The above profile definition may not be sufficient, for instance, if a channel is defined by more than just a frequency range. For instance, as REM adds a spatial dimension to representing the information, there will be a need to also represent the coverage area of the channel (i.e. the spatial dimension). Also, if MCDs are capable of resolving direction of arrival, the channel representation will need to take this into account and so a directional term (such as angle range) will also be required.

3.5 Ad-hoc networks

3.5.1 The description of the scenario and the optimization problem

Most peculiar characteristics of ad hoc networks are the absence of infrastructure and the capability of nodes to cover different functions. Nodes are able to discover their neighbours and to self-organize the network topology. In D2.2 several scenarios of interest involving ad-hoc networks are introduced and the impact that REM concept could have on them is suggested. The most interesting challenge concerning the proposed scenarios consists in guaranteeing the coexistence of several ad hoc networks in the same area. Basically, it is necessary to select in each network the appropriate channel to use and be ready to dynamically adapt the choice. The adaptation should take into account variations in the environment, appearance of sources of interference and evolutions of the nodes of the networks themselves (both in terms of movements and communication activities).

The scenario on which the attention will be focused considers several mobile ad-hoc networks coexisting in the same area. Each network is composed by users that, at the beginning, elect one of them as Network Head (NH). The NH is in charge of the resource allocation in the network to satisfy needs of users in terms of communications.

From this perspective, several interferers (other ad-hoc networks, but also external source of interference) are present. The NH is connected to an external REM; moreover users of the network have sensing capabilities that NH can exploit to enrich its environmental knowledge.

From an optimization point of view, the problem consists in guaranteeing to each network involved the satisfaction of its communication needs, minimizing the interference generated on neighbour networks and reducing the time necessary to adapt the resource allocation choices.

3.5.2 Functional and operational (system) requirements

The specific declination of REM-based architecture for ad-hoc networks requires a two level REM:

- At each network level (L-REM), a local REM SA pilots sensing and collects data from MCDs of the network. Besides, it transmits collected information to the Global-REM (G-REM). A local REM Manager analyzes data stored in the local REM Storage module and provides information required by the network RRM Manager. If necessary, local REM Manager can provide more information to the G-REM.

- At a global level (G-REM) where there are a global REM Storage module, that collects the data received from the different L-REMs, and a REM Manager that elaborates these data. Notice that at G-REM level also a REM Acquisition module could be present if external MCDs are implied (i.e. MCDs that are not members of one of the ad-hoc networks). On the other side, the configuration and piloting of MCDs in each ad-hoc network is assured by the local REM Acquisition module, so at G-REM level, even if these sensing data are received, there is no direct control on acquisition operations.

3.5.3 Mapping of the functional REM architecture blocks on the physical network entities

All nodes of mobile ad-hoc networks considered have similar characteristics and can cover different functionalities according to the needs of the network in a specific moment.

In the beginning, users elect a Network Head (NH) among them. NH will then specialize in coordination of sensing activities and in radio resource management operations. From the REM point of view, the NH acts as the L-REM of the network, implementing REM SA functionalities to pilot sensing in the network and to collect measurement data from active MCDs, as well as REM Management functionality in order to analyze information retrieved both from L-REM SA and G-REM. Again from the REM point of view, the other nodes of the network are seen as MCDs. The NH will be the only node of the network that communicates with the G-REM in order to report local measurements and network information and to obtain useful data to pilot radio resource allocation in the network.

From single network point of view, NH covers also the functionality of Radio Resource Management (RRM) attributing the channels and the authorized power to use to users of the network that need to communicate. All nodes (including NH) can have user data to transmit, hence they can send allocation requests to the NH and communicate using the resources that NH will attribute them.

The previously described NH corresponds to the *master* of the network if we use the terminology of the master-slave mode for ad hoc networks described in ECMA-392 standard [25]. In this standard, in addition to the general structure of the network, are specified physical and MAC layers for ad hoc networks operating in TV white space. In the future document D6.2, it will be explained how the standard has been followed on physical and MAC layers and in which parts modifications have been necessary to implement REM-based architecture.

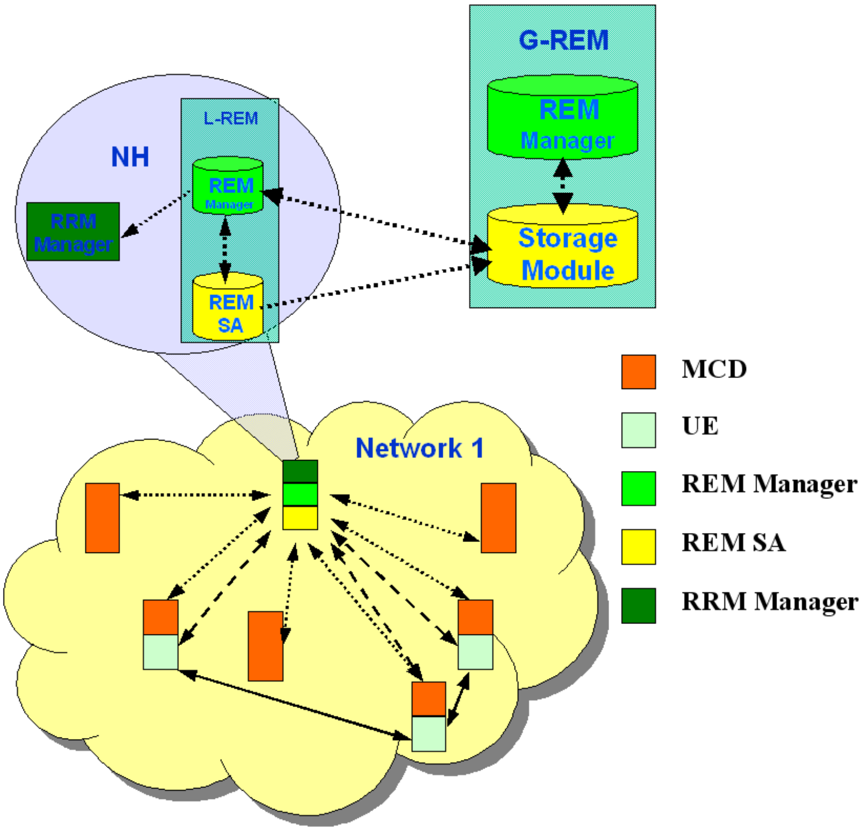


Figure 34: Mapping of REM blocks in physical entities.

3.5.4 Interfaces

With respect to the general REM architecture, some more interfaces should be defined in order to take into account the presence of two levels of REM. In particular two interfaces are added to connect the G-REM Storage module with the L-REM Manager and the L-REM SA of each network.

According to the mapping of functional blocks on physical architecture, interfaces inside each network will be the following:

L-REM SA–MCDs: This interface is used to communicate the instructions to pilot the sensing and to report measurement data inside each ad-hoc network.

L-REM Manager–L-REM SA (internal interface): Interface internal at the NH through which observations of MCDs of the network (acquired by the L-REM SA) can be retrieved in order to be analyzed by L-REM Manager.

L-REM SA–G-REM Storage module: Mono-directional interface used by L-REM SA to report observation data to G-REM.

L-REM Manager–G-REM Storage module: Interface that allows the L-REM Manager of a network to obtain observations of MCDs of other networks and global data elaborated by the G-REM.

G-REM Manager–G-REM Storage module: Interface that allows the G-REM Manager to analyze data obtained from L-REMs of the various ad-hoc networks.

L-REM Manager–RRM Manager (internal interface): Interface internal at the NH through which RRM Manager can obtain REM information to take decisions about resource management.

RRM Manager–UE: Through this interface users of a network can ask for resources to satisfy their communication needs and the RRM Manager can communicate decisions about resource allocation.

Owing to the fact that the RRM Manager and the L-REM SA are implemented in the same node, the physical channel that guarantees the interface between MCD and L-REM SA will be the same that guarantees the exchange of information between the RRM Manager and the UEs.

3.5.5 Protocols and Message Sequence Charts (MSCs)

3.5.5.1 L-REM–G-REM protocol

The protocol that permits the interactions between G-REM and L-REM uses two interfaces: the one, mono-directional, that links the L-REM SA with the G-REM Storage module and the one, bidirectional, between L-REM Manager and G-REM Storage module.

Basically the L-REM Manager communicates with the G-REM to inform it of the presence of the network and to register the L-REM in the global database. Periodically, it will also report meaningful information about the network to the G-REM such as the channel in use or the position of the network. Moreover the L-REM Manager can contact the G-REM to ask for data about radio environment and presence of other networks in the area. The L-REM SA, instead, communicates with G-REM only to report measurements and characteristics of MCDs of the network.

The exchanged messages between L-REM and G-REM are:

- From L-REM Manager to G-REM Storage:
    - **L-REM registration**: when a network enters in the area of a G-REM, the L-REM Manager sends to the G-REM a *L-REM registration* message in which it specifies the position of the network, the measurement capabilities of its MCDs and the channel in use within the network.
    - **Network characteristics update**: message sent to the G-REM each time that a significant evolution happens in the network. Information can include change of channel in use, change of position of the network, changes in measurement capabilities and so on.
    - **Data request**: to prepare the answer to an *available channels query* message, the L-REM Manager firstly retrieves information from the L-REM SA. If the data obtained are considered not sufficient, it sends a *data request* message to G-REM to obtain a more global knowledge of the radio environmental situation.

- From G-REM Storage to L-REM Manager:
    - **L-REM registration ACK/NACK**: The G-REM sends this message in response to the L-REM registration message of a L-REM entering in its area. In the message are also included some information to help the registered network to proceed to RRM operations. This includes available channels, presence of primary systems in the area, their positions and activities, presence of other secondary systems and their typology (i.e. other ad-hoc networks, secondary systems registered in the G-REM, completely independent secondary systems etc.).
    - **Data response**: this message carries radio environmental information required by the RRM Manager with the *data request* message. This information is the combination of data received from all registered L-REMs that are active in the area.

- From L-REM SA to G-REM Storage:
    - **L-REM data update**: Message periodically sent to the G-REM containing measurement results. These measurement results are extracted from the reports received by the L-REM SA from the different MCDs of the network.

3.5.5.2 Users–NH protocol

The messages exchanged between users and NH permits to build the network at the beginning, to keep compliance information of the network, to pilot and report measurements and to proceed to resource allocation.

Basically two protocols are implemented on the same physical channel between users and NH: MCDs – L-REM SA interface protocol and UEs – RRM Manager interface protocol

3.5.5.2.1 MCDs–L-REM SA interface protocol

Through this protocol, measurement operations in a network are controlled, leading to the construction and alimentation of the L-REM. The messages from the L-REM to the MCDs are broadcasted in the network in order to reach all the available MCDs. In the opposite direction each MCD sends its messages directly to the node implementing the REM functionality.

The exchanged messages are:

- From L-REM SA to MCDs:
    - **L-REM identification**: the node that will cover the REM functionalities in the network (i.e. the NH) broadcasts this message to members of the network to identify itself as the L-REM.
    - ***config.measurements* message**: according to the characteristics of the network and the information on the radio environment received from the G-REM, the L-REM identifies the channels on which to perform measurements. Through the *config.measurements* message the L-REM informs, then, the MCDs of the characteristics and ID of the identified channels.

  - **Measurement order**: this is a command sent by the L-REM to the MCDs to start measurements. This message is sent periodically and specifies for each MCD in which time slots and on which channels it should perform measurements. Moreover, it is detailed in the message what kind of measurements are required: only interference power or also angle of arrival, identification of interference type etc.

- From MCD to L-REM SA:
  - **MCD registration**: this message is sent in response to the *L-REM identification* message and it has a double purpose. On one side, it acknowledges the received message by informing the user (which had sent the *L-REM identification* message) that the MCD recognizes it as its reference L-REM. On the other side, the MCD uses this message to register itself in the L-REM database and to communicate its position and its measurement capabilities.
  - **Measurement results**: this message is sent periodically by each MCD concerned by the *measurement order* sent by L-REM SA. It contains the results of the measurements performed in the previous time period.

3.5.5.2.2 MCD–REM Manager interface protocol

The protocol regarding the RRM Manager – UEs interface concerns the process of resource allocation both in terms of frequency channel used by the network and in terms of specific resources attributed to each user that wants to communicate.

Exchanged messages are:

- From UE to RRM Manager:
  - **Communication request**: when a UE wants to communicate with another UE in the network, it has to ask the RRM Manager for radio resources to transmit. UE sends, then, a *communication request* to the NH (that is the node that implements RRM functionality) specifying the UE destination of the transmission, the size of data to send and their priority.

- From RRM Manager to UEs:
  - **Resources allocation**: periodically, RRM manager broadcasts to all users a *resources allocation* message in which it specifies which resources are attributed to each active link in the following period.
  - **New channel update**: when the channel in use in the network is not anymore available, the RRM Manager selects a new channel and broadcasts a *new channel update* message informing all users of the network of the forthcoming channel change.

3.5.5.3 NH internal protocol (interfaces between L-REM Manager, L-REM SA and RRM Manager)

The messages exchanged among the three REM modules implemented in the NH permit the exploitation of L-REM data for resource allocation purposes.

Exchanged messages are:

- From L-REM Manager to L-REM SA:
  - **G-REM registration ACK**: The information received from the G-REM in the *G-REM registration ACK/NACK* message is saved in the L-REM SA through this message. In particular, the available channels and the characteristics of possible sources of interference are saved in the L-REM SA. Through these data, L-REM SA can better manage measurement operations of the MCDs active in the network.
  - **Acquisition configuration**: after the reception of the information about the channel in use from the RRM Manager and about the available channels in the area from the G-REM, L-REM Manager sends *acquisition configuration* message to L-REM SA in order to precise parameters for measurement operations.
  - **Current channel measurements request**: Once the acquisition is configured, L-REM Manager sends a *current channel measurements request* message in order to monitor the interference situation of the channel in use in the network.
  - **All channels measurements request**: when L-REM Manager receives an *available channels query* message from the RRM Manager, it sends an *all channels measurements request* message to the L-REM SA in order to obtain information on all channels measured by MCDs of the network.

- From L-REM SA to L-REM Manager:
  - **Acquisition configuration ACK**: message used to confirm the right configuration of the measurement operations in the network.
  - **Current channel measurements response**: message sent periodically to report the measurements on the channel in use performed by the MCDs. The reception of a *current channel measurements request* message starts the periodic transmission of this message.
  - **All channels measurements response**: Response to the *all channels measurements request* message. It contains interference conditions and identified characteristics of all channels on which recent measurement data are available.

- From RRM Manager to L-REM Manager:
  - **Interference levels request**: When receiving one or more *communication request* messages from UEs of the network, RRM Manager asks L-REM Manager about the interference and propagation conditions in the different sub-bands of the channel in use. Using this information, RRM Manager can optimize the allocation of resources among the different UEs.

  - **Current channel update**: RRM Manager informs L-REM Manager about the channel selected by the network through *current channel update* message. This message is sent to the L-REM Manager each time that the channel in use changes.
  - **Available channels query**: in the process that leads the RRM Manager to select a new channel for the network, the first step consists in sending an *available channels query* message to the L-REM in order to know channels availabilities.

- From L-REM Manager to RRM Manager:
  - **Data on interferences**: message sent in response to an *interference levels request* message and containing data on interferences and propagation characteristics of the sub-frequencies of the channel in use. Information contained in this message allows the RRM Manager to optimize the allocation of resources among the communicating UEs of the network.
  - **Channel in use busy**: if, when analyzing one of the periodically received *current channel measurements response* messages, the L-REM Manager detects a too strong interference on the channel in use, it sends a *channel in use busy* message to the RRM Manager in order to start a *new channel selection* process.
  - **Available channels characteristics**: sent in response to an *available channels query* message, this message can contain both local (retrieved in the L-REM SA) and global (obtained from G-REM) information on the characteristics of available channels.

Figure 35 depicts the Message Sequence Chart that allows the population of both L-REM and G-REM. This activity concerns the interface between MCDs and L-REM SA, the interface between L-REM SA and L-REM Manager, the interface between L-REM SA and G-REM Storage and the one between L-REM Manager and G-REM Storage. Notice that also the interface between G-REM Storage and G-REM Manager is indirectly concerned doing to the fact that the G-REM Manager can analyze data saved in G-REM Storage module in order to add more advanced contents.

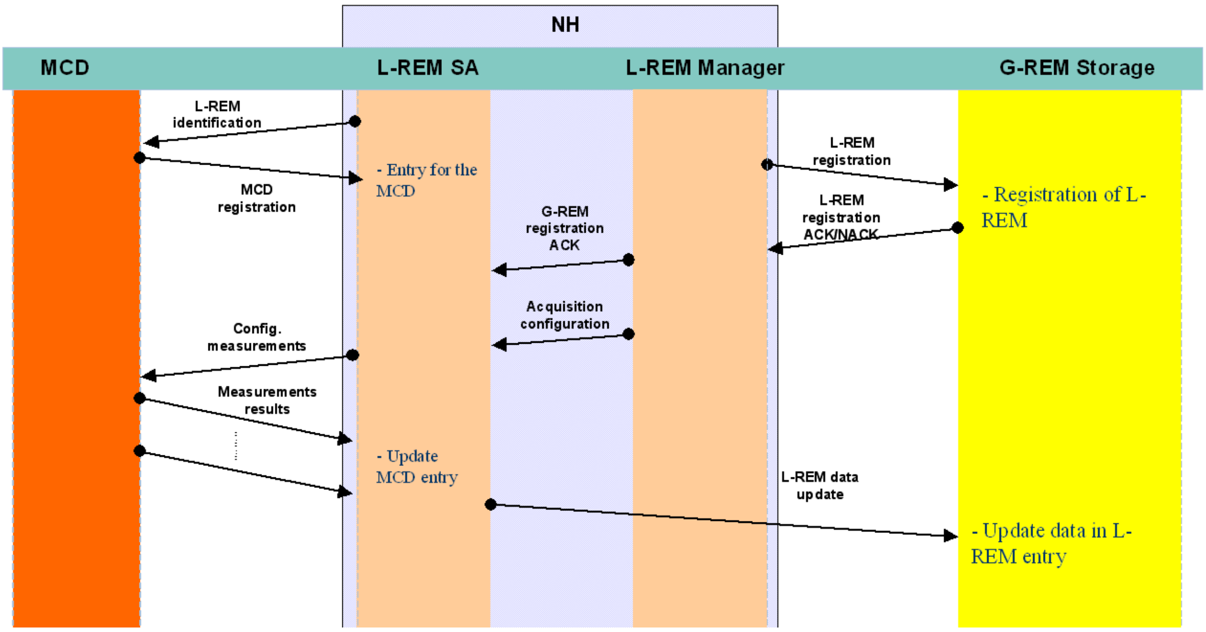


Figure 35: Messages to populate the local and global REMs.

Figure 36 presents the messages exchanged among UEs, RRM Manager, L-REM and G-REM, through the different interfaces involved, to determine resource allocation in the ad-hoc network and to react to interference detection on channel in use. In other words, Figure 36 shows the exchanged messages to use REM information for radio resource allocation.

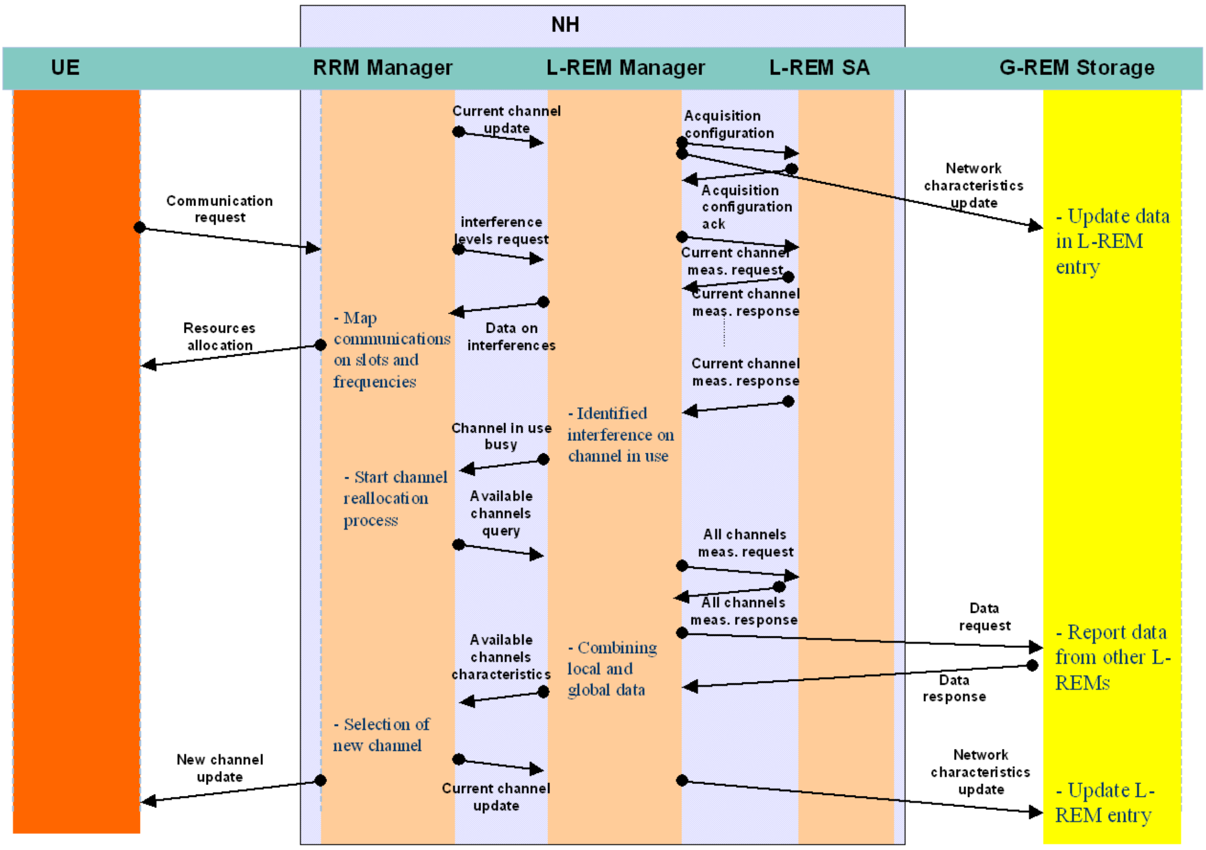


Figure 36: Messages to manage resource allocation.

3.5.6 Information/data models

From measurement point of view some specific information have to be exchanged to populate both L-REM and G-REM. Considering the L-REM–MCDs interface, measurement messages should contain the following fields:

1. **MCD ID**: identifier of the MCD.
2. **MCD position**: longitude-latitude coordinates identifying the position of the MCD performing the measurements.

Moreover for each channel measured:

3. **Channel measured ID**: identifier of the channel on which the measurement was performed
4. **Measurement time**: reference to the time in which the measurement began.
5. **Measurement duration**: duration of the time period in which the measurements have been performed on the channel.
6. **Average interference**: average power level received during measurement period.
7. **Peak interference**: max power level received during measurement period

In addition some other information could be included according to capabilities of each MCD:

8. **Interferer number**: number of sources of interferences detected.
9. **Direction**: angle of arrival of each detected interferer.
10. **Interference nature**: distinction among interferences coming from networks of the same kind of the network of the MCD and other kind of interferences.

Received information is analyzed by the REM Manager and stored in L-REM SA. The REM Manager puts together the measurements of different MCDs trying to have a clear picture of the spectrum environment in the area occupied by the network. In particular, the objective of REM Manager is to identify the possible presence of interferers both on the channel in use in the network and in the other channels on which measurements have been performed. The detection and the characterization of the sources of interference are of primary importance for the network in order to correctly allocate resources to UEs, obtaining the required quality of services and avoiding harmful interferences. Beside the presence and the power level of the interferences, it is useful to distinguish the components of the interference identifying the number of sources of interference and their probable position in space. Furthermore the identification of interferers of the same kind (i. e. other ad-hoc networks) with respect to other external interferences, such as primary systems, can strongly improve RRM performance. Hence, when reporting measurements to the G-REM Storage module, after analysis of REM Manager, L-REM SA provides a meaningful synthesis of the information received from the MCDs.

In addition to the measurements obtained from the MCDs that the L-REM SA reports to the G-REM Storage module, some more information is exchanged on the same physical channel between G-REM and L-REM. This information is sent by the L-REM Manager through *network characteristics update* messages and contains data about the network that can improve the radio environment awareness of the G-REM. Fields included in the *network characteristics update* messages are:

1. **Network ID**: identifier of the network.
2. **Network position**: localization of the network in the area.
3. **Network direction**: in case of network in movement this field specifies the direction in which the network is moving.
4. **Network speed**: speed of network movement.
5. **Channel ID**: identifier of the channel used by the network.
6. **Active transmissions**: table containing all the links of the network on which data messages are transmitted. In the table for each active link the position of transmitters, the position of receiver and the power employed for the transmission is reported.

4 Data integrity, reliability and security

Elements of the REM data model are used by planning and RRM techniques in order to reconstruct a partial view of the radio environment with a specific time and space granularities that is required for the good performance of the network. Depending on their characteristics, the data can be distributed over different network elements in the same layer or different layers in the hierarchical architecture. Therefore, the design of the REM architecture should fulfill three main requirements: data integrity, reliability and security.

The requirement on data integrity, reliability and security comes from the following facts:

- Data are generated by measurements performed by different MCDs that have different data representation and precision. Depending on the hardware type, the sampling time can range from μs to seconds, the power sensitivity can have a range of few 10^{th} of dBs, the measured bandwidth can be of few Hz or MHz, position precision can be few centimetres or meters, etc. In addition some sensors can be provided with the capability of decoding the received signals, which can allow a better channel or signal power estimation than others sensors. This leads to the presence of data with different precisions in the REM Manager. For instance, a macro base station would have more capabilities than a home base station and much more than a mobile terminal. Moreover, mobile terminal capabilities and reliability will depend on the class of the used mobile and can have a wide range. The heterogeneous data collected from the different MCDs should be then processed by the REM Manager before storing it in the REM SA.

- The measured data will be communicated to different elements in the network. This will generate signalling overhead that should be minimized. One way to minimize the overhead is to generate statistical representation of the raw data. This representation will, of course, lead to a loss in data precision. Depending on the used statistical metric and the approach used to generate it, the precision of the generated information and thus the way it can be used will change. In addition, the precision of the statistical representation depends on both the precision of each sensor and the number of these sensors.

- During the data transfer, errors can be added due to interference and noise. These errors can be normally detected and corrected by different techniques. However, in some cases data retransmission can be needed. The decision of using data retransmission depends on the dynamics of the measured data and the precision.

- Radio information can change in very short scale as in the case, for instance, of fast fading, interference in OFDMA-based femtocells and data traffic. Therefore, each collected information item can be only valid for a specific time after which this information should be discarded.

- Some MCDs can be providing erroneous data due to malfunction or misbehaviour. This type of errors should be differentiated from the errors generated by the hardware limitation or transmission since they need different mechanisms to handle them.

Processing the heterogeneous data in the REM Manager can either be by saving the raw data together with a precision metric or generating a homogeneous representation. In the first case, a new metric called *precision metric* is introduced. The precision metric can be either a hardcoded value such as the sensitivity value or dynamically evaluated by the MCD such as the sensing time that can be set by the RRM or network elements. In the latter case, the decision entity should be aware of the minimum capability of the sensor. Therefore another metric should be associated to each MCD for each data type. Each MCD should provide the REM Manager with the precision metric values on registration time or when the precision metric is changed. This information can be used to define a more optimized data model. For instance we can group the MCDs in clusters that share the same characteristics and then we use only one entry for the precision metrics. When generating homogenous representation from heterogeneous data, the REM Manager should not only store the generated statistics in the REM SA but also information about the input data, such as the type of used MDTs, their number, their spatial distribution and the used method (e.g. kernel density function with Gaussian kernel). This type of information is denoted by *statistical inventory*. The statistical inventory will be computed by the REM Manager and stored in the REM SA together with the statistical information.

The error generated by the transmission can be corrected by retransmission if the retransmission time is lower than the expiration time of the data. For instance, it is better to discard the information in case of fast fading whereas the retransmission can be repeated until the data is correctly received by the end point in case of the location of a fixed network element. The number of retransmissions is determined by the REM Manager based on the expiration date, update frequency and the precision metric.

In general, statistical representations are more reliable than raw data especially because their expiration date is longer. In addition, they are less sensitive to errors generated by individual samples. However, not all RRM techniques can use statistical information. For instance fast power control in WCDMA-based networks requires real time SINR values. Furthermore, when defining a statistical representation the designer should take into account the trade-off, not only between reliability and signalling overhead but also the trade-off between the former and the computation complexity. For instance, the median is a more robust metric that can be used for data following any skewed distribution whereas the mean can be used only for data following a Normal distribution. This is due to the fact that the mean gets unduly impacted by values in the sample that are too small or too large. However the median requires more difficult mathematical operation to be computed while there are simple formulas to compute the average in an iterative way. Moreover, the reliability of the higher level statistics such as standard deviation and skewness are more sensitive to errors than the mean and the median.

In Figure 37, we show the absolute error in the estimation of the propagation exponent for an Okumura-Hata model with lognormal shadow fading when using either the average (top figures) or the median (bottom figures). The exponent is estimated by first estimating either the average or the median of N_d MCDs at a given distance in the logarithmic scale in order to eliminate the shadow fading that have zero mean. Therefore the average or the median should represent the distant-dependent path loss without neither spatial nor temporal variation. We evaluated these movements at different distances from 100 m to 1km separated by 50 m. The MCDs that are at the same distance from the transmitter are separated by distance *d*. Then, we apply a linear regression with first order on the average or the median using the following equation: $Y = k + \alpha.X$, where Y represents the estimated average or median, $X = \log_{10}(d)$, and k and α are the propagation constants. We also assume that there are 2% of malfunctioning MCDs with an error $e \sim \mathcal{N}(a,10)$. The figure shows clearly that for the same percentage of malfunctioning MCDs, the error in the estimation of the exponent is much higher when using the average. In addition, this error is increasing very fast when the average error introduced by the MCD increases from 50 to 100 dB when the average is used whereas it is kept at the same level when the median is used. This shows that using the median is more robust for estimating the path loss exponent to mal functioning MCDs. However, as it can be seen from the figure, the error in the exponent is about 0.5, which is relatively high to the real value of the exponent, which is 3.5. Therefore, even more robust techniques should be used and can be based on the raw data instead of the average or the median although this might increase the signalization overhead.

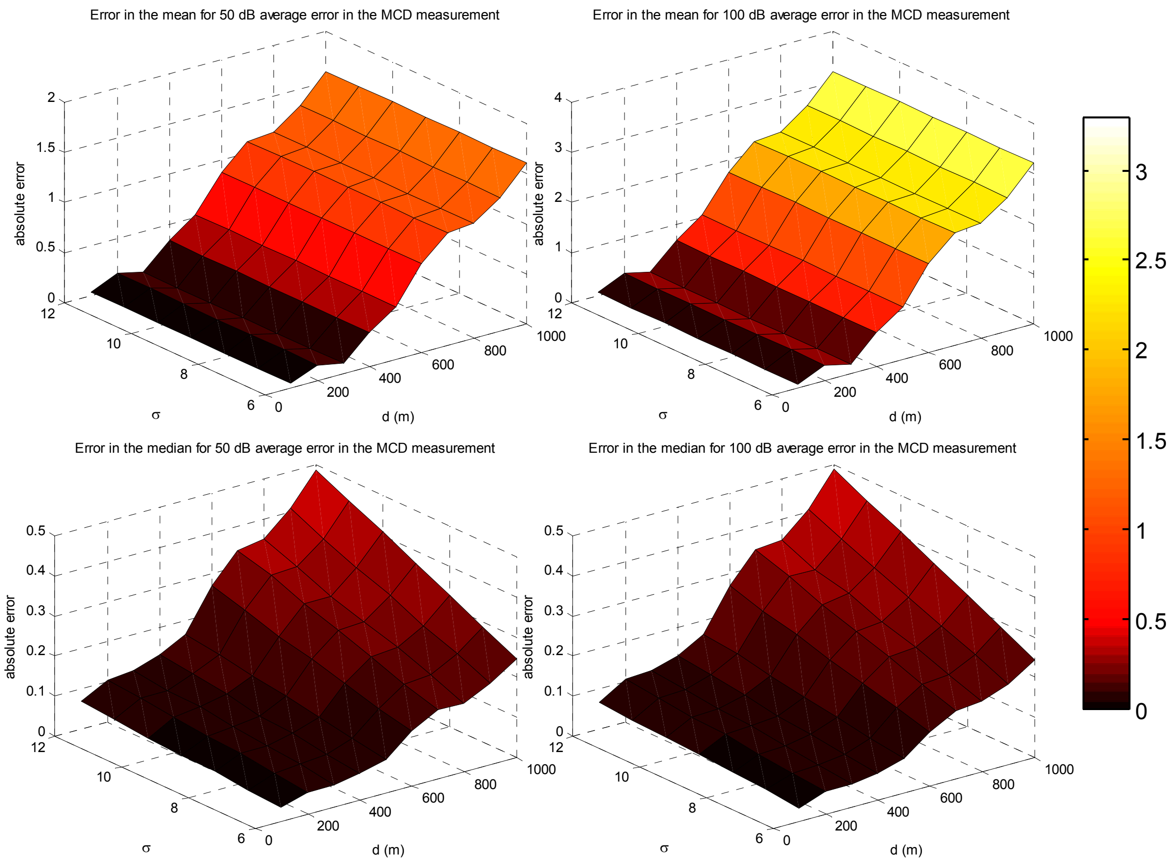


Figure 37. Impact of malfunctioning users on the estimation of the propagation exponent.

4.1.1 Precision Metrics

It is very difficult to design a universal precision metric for all measurement data. Therefore, each type of data should be assigned to a type of precision metric. This metric can be defined by the designer of the data measurement, the RRM designer or the operator. When defining a precision metric, the designer should take into account hardware capabilities and interface definition. This means that the designer should know what type of hardware information can be exposed to the operating system in the MCD. In addition the definition of generic interfaces that allow on-demand information collection such as Universal Link Layer API (ULLA) and Generic Network Interface (GENI) [26].

The simplest example of precision metrics is localization precision where some MCDs have a GPS and others have localization based on the signal received from the WiFi access nodes. The REM SA should be configured in a way that it contains a table containing the information needed for the computation of localization errors. For the GPS case, an example of Sources of User Equivalent Range Errors (UERE) is given. From these values and the positions of the satellites and the receiver, the standard deviation of the error in receiver position can be computed [28]. For the WiFi case, triangulation methods are used. In order to estimate the precision, information about the environment, the level of signals and the positions of the WiFi access points are needed. In addition, the MCD should take into account a threshold for the received signal either from the GPS or from the WiFi access nodes in order to determine how to perform localization. Nowadays, the precision of the localization technique can be estimated by mobile terminals. This can be seen, in fact, as a rudimentary REM. In the hierarchical REM architecture, the REM SA will only have two columns for position information, namely the estimated position and the errors computed by the MCDs.

Table 3: Example of Sources of User Equivalent Range Errors (UERE).

Signal arrival C/A	Signal arrival P(Y)	Ionospheric effects	Ephemeris errors	Satellite clock errors	Multipath distortion	Tropospheric effects	Numerical error
±3 m	±0.3 m	±5 m	±2.5 m	±2 m	±1 m	±0.5 m	±1 m

4.1.2 Statistical inventory

Similar to the precision metric the statistical inventory cannot be defined in a generic way since each type of data representation and data type requires different types of statistical inventory. The information contained in the statistical inventory of each type of data can be defined by either the network operator or the RRM designer. In the following we give two illustrative scenarios.

In the first scenario, we consider a network that is collecting information about fast fading distribution of the fast fading between two fixed elements such as a HeNB and a eNB. In this case, the statistical inventory includes the measurement time, the sampling frequency, and the sensitivity level.

In the second scenario, we consider more complex information such as interference map where the information is collected from different MCDs that can have different precision metric values. In this case, the statistical inventory includes distribution of the MCD locations, the minimum precision value of all sensors, the sampling frequency, the sensitivity level and the used technique.

In addition, information about the goodness of the statistics such as Chi-Square and Kolmogorov-Smirnov test outputs [27] should be provided in all scenarios.

4.1.3 Expiration time

The expiration time is a very important metric for all data types. The expiration time does not only depend on the type of data but also on the type of representation and the environment. For instance the statistical distribution of the fast fading can have an expiration time in the scale of hours in the case of outdoor scenario where the properties of the environment change very slowly due to the high number of the obstacles impacting the fast fading. However, this time can become in the order of minutes in the case of indoor environment where few obstacles such as moving humans can appear and disappear frequently. Moreover the raw data of the fast fading have an expiration date in the order of ms while its statistical representation can have a longer expiration date in the order of minutes or hours.

4.1.4 Malfunctioning and misbehavior problem

In some cases, the MCDs might generate erroneous information. This can be due to a miss-behavior or a malfunction.

For the case of misbehavior we adopt the solution of cellular networks where the procedure to collect the information are hard-coded by the manufacturer and does not allow any changes by the client.

In order to solve the malfunctioning problem that can occur in any MCD, the REM Manager should apply filtering mechanisms that detects malfunctioning MCDs. We adopt a Bayesian filtering mechanism where we can detect the malfunctioning MCDs which will normally generate data that does not fit with the distribution of the collected data by all MCDs. For instance a Maximum Likelihood Estimator can be applied to the collected data to detect malfunctioning MCDs based on the residual likelihoods of the samples.

5 Conclusions

This deliverable presents the final FARAMIR architecture, which is a migration from the generic functional REM architecture proposed in D2.3 towards more concrete and ready-to-implement system architectures for four selected FARAMIR RRM optimization scenarios:

1. In-band femtocell optimization,
2. LTE in TVWS,
3. Non-coordinated spectrum access between PUs and SUs
4. Ad-Hoc networks

The developed system architectures define:

- Exact mappings of the functional REM blocks onto organic network entities
- Concrete interfaces between these entities with:
  - Detailed protocols involving the exact messaging/signalling over the interface
  - The information/data models used to realize the messaging/signalling.

Along with the proposed system architectures, we have also addressed data integrity, reliability and security issues. First, we have shown empirically the impact of erroneous data (in case of malfunctioning measurement devices) on estimation of propagation path loss, for two different statistical measures: mean and median. Secondly, we have proposed solid statistical and pragmatic measures, such as:

- A precision metric together with a statistical inventory for data integrity,
- A Bayesian filtering approach with Maximum Likelihood Estimation to identify malfunctioning devices as outliers,
- A time-of-validity metric for data reliability.

Having a purpose of sticking to real-world applications for showing their real-world value in radio resource optimization, we have adopted an approach where the proposed system architectures are based on the existing closely matching standards. In doing so, we have made use of the existing standard work as much as possible, identifying the interfaces that are already implemented and that can be used readily for our purposes. We have also mentioned the missing elements in those standards, which are not implemented and which we deem mandatory for the identified REM-related RRM optimization tasks. More precisely, we have identified the Minimization of Drive Tests (MDT) framework of 3GPP and IEEE DYSPAN-SC WG6 as prominent potential avenues to standardize the interfaces considered in FARAMIR project, the former providing a rich source of geo-located measurements coming from the mobile terminals of a cellular network to be used as an input to REMs and the latter providing interoperability between heterogeneous sensors (MCDs) and multi-vendor REMs. Both standards have been identified as being extremely relevant (and therefore as exciting standardization and dissemination opportunities) for FARAMIR architecture work since they add procedures, protocols and message format specifications for the exchange of MCD data.

This approach allows us:

- To identify and exploit possible standardization opportunities by proposing REM-related architectural elements which are missing in the existing standards, and
- To ease implementation and integration in the ongoing prototyping/demonstration task.

Regarding the first point above, it is worth to underline that a work item has been launched in ETSI Reconfigurable Radio systems (RRS) as France Telecom/Orange as the leading partner [29]. This work item aims at proposing REM-related system architectures with interfaces and protocols for operator-centric scenarios that are identified to bring added value to the operator. The system architecture work developed for in-band femtocells in this deliverable allows us to proceed actively in this standardization action in ETSI RRS.

We also note that even though the detailed system architectures have been very carefully mapped towards existing technologies, and we have on purpose been highly implementation oriented in the present work, the consortium has also been very careful so as to keep the overall functional architecture both highly extendable, as well as neutral with respect to the way it is realized an deployed. By the latter we mean the architecture is designed on the functional level to be stake-holder neutral allowing different operational possibilities and modes. In particular, we do not force through architecture the adoption of any particular business or trust models. We also allow different implementations of the realizations of the elements of the functional architecture to coexists seamlessly as long as the mapped system level interfaces are respected. Thus, although FARAMIR is developing its own REM database, it is possible to build any competing REM database realizations and connect them with other components of the FARAMIR architecture as long as the interface and data model specifications are followed.

Glossary and Definitions

Term	*Description*
3G	3rd Generation (cellular mobile standards)
3GPP	3rd Generation Partnership Project
ACK/NACK	Acknowledgement/Non-Acknowledgement
AP	Access Point
API	Application Programming Interface
Architecture	An organisational structure of a system or component, their relationships, and the principles and guidelines governing their design and evolution over time
AS	Access Stratum
ASN.1	Abstract Syntax Notation One
BS	Base Station
CBS	Cognitive Base Station
CBSRM	Cognitive Base Station Reconfiguration Manager. It is the entity that manages the CBS and terminals for network-terminal distributed optimization of spectrum usage. The key functions of the CBSRM specific to dynamic spectrum access in white space frequency bands are: management of spectrum sensing, e.g., by coordinating silent periods for measurements, classification of white space frequency bands, coordination of white space frequency bands usage with CBSRMs of the same RAN for radio resource management and with CBSRMs of other RANs for coexistence
CE	Cognitive Engine
Closed interfaces	Privately controlled system/subsystem boundary descriptions that are not disclosed to the public or are unique to a single supplier
CR	Cognitive Radio
CRN	Cognitive Radio network
CSI	Channel State Information

Term	*Description*
CWN	Composite Wireless Networks
DA	Data Archive
eNB	enhanced Node B
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
GPS	Global Positioning System
HeNB	Home eNB
HeNB MS	HeNB Management System
HNB	Home Node B
HSS	Home Subscriber Service
IE	Information Element
Interoperability	Ability of two or more systems or components to exchange data and use information
Intra-operability	Ability to interchange and use information, functions and services among components within a system
LTE	Long Term Evolution
MBS	Macrocell Base Station
MCD	Measurement Capable Devices
MDT	Minimization of Drive Tests
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
Modular	Pertaining to the design concept in which interchangeable units are employed to create a functional end product.
Module	Interchangeable item that contains components. In computer programming, a program unit that is discrete and identifiable with respect to compiling, combining with other modules, and loading is called a module.

Term	*Description*
MSC	Message Sequence Chart
MUE	Macro UE
NAS	Non-Access Stratum
NH	Network Head
NRM	Network Reconfiguration Manager
OMC	Operation and Maintenance Center
OSM	Operator Spectrum Manager
PE	Policy Engine
Physical architecture	Minimal set of rules governing the arrangement, interaction, and interdependence of the parts or elements whose purpose is to ensure that a conformant system satisfies a specified set of requirements. The physical architecture identifies the services, interfaces, standards, and their relationships. It provides the technical guidelines for implementation of systems upon which engineering specifications are based and common building blocks are built.
plug & play	term for easy integration of HW/SW
PM	Policy Manager
portability	the ease with which a system, component, data, or user can be transferred from one hardware or software environment to another
PU	Primary User
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
Reference model	A generally accepted abstract representation that allows users to focus on establishing definitions, building common understandings and identifying issues for resolution. A reference model provides a mechanism for identifying the key issues associated with applications portability, modularity, scalability and interoperability.

Term	*Description*
	Most importantly, reference models will aid in the evaluation and analysis of domain-specific architectures.
REM	Radio Environmental Map
REM GUI	REM Graphical User Interface
REM SA	REM Storage and Acquisition
RIF	Radio Interference Field
RLF	Radio Link Failure
RMC	RAN Measurement Collector
RRC	Radio Resource Control
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indication
Scalability	Capability to adapt hardware or software to accommodate changing workloads
SINR	Signal to Interference plus Noise Ratio
SU	Secondary User
System architecture	Description, including graphics, of systems and interconnections providing for or supporting management functions. The SA defines the physical connection, location, and identification of the key nodes, circuits, networks, platforms, etc., and specifies system and component performance parameters. It is constructed to satisfy Operational Architecture requirements per standards defined in the Physical Architecture. The SA shows how multiple systems within a subject area link and inter-operate, and may describe the internal construction or operations of particular systems within the architecture.
TRM	Terminal Reconfiguration Manager

Term	*Description*
TVWS	TV White Spaces
UE	User Equipment
URIP	Uplink Received Interference Power
UTNP	Uplink Thermal Noise Power
WCDMA	Wideband Code Division Multiple Access
White space	part(s) of spectrum allocated to a particular radio system (primary radio system) in particular location(s) that may be temporary unused by this primary radio system in some location(s) and thus allowed by radio regulations to be used by another radio system(s) (secondary radio system) on a temporary secondary basis without causing harmful interference to the primary radio system, where harmful interference and protection mechanisms are defined in the radio regulations
White Space Manager	the entity that enables collaboration between IEEE 1900.4a system and IEEE 1900.4 system, provides regulatory context information to CBSRM, records the statuses of the CBSs connected to it, and enables communication between CBSRM and white space database
White space resource management	management of white space resource usage performed by the CBSRM(s) and the TRM(s) for the purpose of self-coexistence inside one secondary system and for coexistence between different secondary systems. White space resource management includes classification of white space resources by the CBSRM(s) and the TRM(s), exchange of the classification results between the CBSRM(s) and the TRM(s), and coordination of white space resource usage between several CBSRM(s)
WSM	White Space Manager

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