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Abstract:

The diversity of the spectrum-related information yields a necessity for mechanisms that foster appropriate management and, subsequently, optimal usage of this information. In addition, the increased popularity of the wireless systems in general raised the questions of spectrum scarcity and the (under)utilization of the available spectrum further emphasizing the need for advanced spectrum management techniques. This document analyses the problem of efficient spectrum information management, particularly in the direction towards its usage for enabling environmentally aware and self-optimizing wireless systems. All relevant aspects such as spectrum information representation, spectrum information analysis and spectrum information usage in practical systems are carefully scrutinized in order to provide a comprehensive overview of the topic.

Keywords: Spectrum information, Spectrum information management, IEEE 1900.4, IEEE 1900.6, Radio Environmental Map (REM).

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Executive Summary

This document focuses on the mechanisms, technologies and architectural viewpoints of the problem of spectrum information management for future wireless systems. It discusses the versatility of the spectrum information and pinpoints relevant standardization efforts towards reliable and unambiguous representation of this information. The document also elaborates the most important aspects of the management of the spectrum information having in mind the limitations in practical deployments (e.g. centralized/distributed underlying technology, cooperative/non-cooperative underlying technology etc.). Finally, the document presents standardization and recent research efforts in the area of constructing practically deployable architectures for increased usage of the spectrum information leading to and facilitating various optimization procedures.

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1. Introduction

The increasing popularity of wireless devices, networks and applications leads to an increased interest in spectrum management solutions. The ideas of Dynamic Spectrum Access (DSA) and Cognitive Radio (CR) further accentuate the necessity of integrated frameworks for reliable and wide-ranging management of spectrum-related information. There needs to be a distinguishable mechanism for collecting, storing and interpreting spectrum information for various subsequent purposes.

The spectrum information is manifold because of the spatio-temporal variations of the spectrum usage as well as because of the variety of spectrum stakeholders and potential application scenarios and use-cases. The approach to efficient spectrum information management must inevitably address these aspects in the design phase of the management solution as they may significantly and substantially influence the feasibility of the entire solution.

There are several key components that must be carefully analysed when dealing with spectrum information management. First and foremost, a focal point of every successful information management system is the *information representation*. It is crucial that there exists an unambiguous and all-inclusive syntax able to capture all specific nuances of the information to be represented. This will foster easy understanding among all involved stakeholders. Referring to the spectrum case, the spectrum information is essentially rich in details such as duty cycles, activity patterns, transmitters' and receivers' locations, propagation models, terrain models etc. Therefore, an appropriate representation is a must for the subsequent *information management* allowing easy information exchange, fast information retrieval and reliable decision-making. Furthermore, the spectrum information management solution must encompass the limitations of the underlying technology in terms of network organization, nodes' capabilities, supported functional procedures etc. Last, but not least, the spectrum information management must be viable within the *architectural confines* of wireless communications systems.

This document addresses all previously raised questions regarding the management of spectrum information. Section 2 elaborates on the spectrum information representation problem showcasing standardization efforts in the field as well as latest research results and directions. Section 3 discusses the management issues from a technology applicable point-of-view such as centralized/distributed approach, cooperative/non-cooperative approach etc. Section 4 elaborates architectural aspects when designing a spectrum information management framework and showcases a practically feasible solution for various DSA and CR scenarios. Finally, section 5 draws the most important conclusions from the document.

2. Spectrum information representation

This section defines the relevant spectrum information types, e.g. Primary User (PU) presence/absence, PU location, Secondary User (SU) presence/absence, SU location, duty cycle, propagation models etc., and elaborates on their utilization in the process of dynamic spectrum access and allocation.

2.1 Information from Mobile Terminals (MTs) related to spectrum management process

In the emerging radio landscape, intelligent Mobile Terminals (MTs), characterized by cognitive capability, will demand high-speed services, often while on the move. They will strive to find the most suitable radio resources to use in order to satisfy their needs in the best possible way. Simultaneously, network operators will struggle to find the appropriate configuration of their radio access networks, in terms of operating radio access technologies and frequencies, in order to tackle the limited available spectrum as well as the unstable traffic load (measurements have shown underutilization of frequency zones at specific geographical areas). In this context, the spectrum management procedures (e.g. transfer of spectrum usage rights and dynamic change of specific frequencies) need information acquisition from networks and MTs for accurate and reliable picture of the radio environment and the network conditions. The information from MTs related to spectrum management processes will include *context information*, which illustrates the radio conditions in MT's vicinity, and *status information*. Context information can also be utilized by other MTs in opportunistic networks in order to select optimal radio access and/or to utilize available unused frequencies for secondary usage.

The information sent from MTs has to be sufficient to enable relevant operations, but not excessively large because this would burden considerably the MT's computational and power resources. Additionally, significant augmentation of the information, such as detailed information about MT's hardware and software characteristics (e.g. power consumption and power saving schemes, supported coding schemes), may lead to optimization of spectrum allocation, but, simultaneously, will considerably complicate the procedures and the computational processes.

The MT's context information may comprise:

- A set of sensed Radio Access Networks (RANs) in its vicinity along with the geographical position (geographic coordinates), the velocity and the direction of the MT at the time of sending the relevant information.
- Signal strength for the sensed RANs, i.e. the Signal-to-Interference-plus-Noise Ratio (SINR) measurements for the RANs.

The MT's status information may comprise [1]:

- The reconfiguration capability of the MT and its possible different configurations. This information is needed for estimating the number of MTs that can apply the reconfiguration decisions resulting from spectrum management procedures. This is important as MTs of different kinds and generations will coexist, especially for the first period of next generation networks deployment.

- The current MT's configuration in terms of radio access technology and operating frequency. In case of MTs with multihoming capabilities (i.e. MTs that can maintain simultaneous different links via different radio access technologies and/or frequencies), the MT's configuration information consists of the configuration of each active interface.
- The measured QoS level of each operative service, which comprises a set of specific QoS metrics. QoS metrics illustrate the conditions in several communication layers, e.g. in physical layer by means of the physical rate or Bit Error Rate (BER), in MAC sublayer by means of the access delay, in network layer by means of throughput or blocking probability etc.

2.2 IEEE 1900.6 based spectrum information representation

IEEE 1900.6 specifies interfaces and data structures for spectrum sensing information exchange serving cognitive radio and other "advanced" radio systems [2]. Therefore, it has a significant wealth of information that is relevant to this document.

The key elements that IEEE 1900.6 defines are the Sensor (S), the decision making entity known as the Cognitive Engine (CE), which is the sink of information from the S, and the Data Archive (DA), which acts as a form of repository for spectrum sensing information. The S might also be a client of information, in scenarios such as collaborative sensing since it is very important to distinguish between collaborative sensing as opposed to cooperative sensing.

The IEEE 1900.6 standard is essentially divided into 4 key parts [3]. A first key part is the *System Model*, which specifies that the information is based on the duration of the primary spectrum usage model. This comprises both short-term spectrum usage, such as ad-hoc licenses, and long-term spectrum usage, such as emergency services spectrum. Additionally, this section of the standard also specifies the communication scenarios and elements involved, including CE-S communication, S-S communication and CE/DA-S communication. The standard then describes the reference model including the various Service Access Points (SAPs) defined within and their placing based on the three communications scenarios highlighted above. Also, this section of the standard defines the primitives used to request/specify, obtain and exchange spectrum sensing information. The next key part of the standard defines the information itself. The information comprises control information for sensing, sensing information and data types defined and used in the standard. The final key part is the state diagram and the corresponding generic procedures for spectrum sensing information obtain and exchange, followed by "informative" content in Annexes, including an extremely wide range of use cases for the standard and their classification.

The information representation in IEEE 1900.6, as already stated, is subdivided into *control information* required in, e.g. requesting readings from sensors and an exchange of information on such readings, as well as the *sensing (or sensor) information* itself. Regarding the control information, IEEE 1900.6 specifies command class, function, version and (optionally) parameter fields. The control information from clients to sources (i.e. sensors) can either require an action (e.g. return a measurement) or set a parameter (e.g. change the duration or type of sensing). More complex derivatives of these cases are discussed in the associated primitives in the standard. Also, the standard describes two types of commands, i.e. standards commands and proprietary commands already provided by the manufacturers of sensors and utilised to configure or obtain information from the sensor. It also specifies information pertains to requirements derived from regulation.

Before discussing information types, it is necessary to introduce the units and data types that the standard assumes as a basis. The *base units* are: Second, Meter, Hertz, Radian, Watt, Degree of arc and Power ratio. The *primitive simple data types* that the standard assumes are: Boolean, Integer, Unsigned Integer, Float, String, Vector and Array. The *complex and derived data types* are: Enumeration, Fixed point, Unsigned fixed point and Structured. The reader is invited to refer to [3], pp. 73-75, for more information if required.

The standard describes a range of spectrum sensing-related parameters, each of which are fully specified using the abovementioned data types and units, and each of which is tagged as applying to either sensing information, sensing control information, sensor capabilities, regulatory requirements or any combination thereof. The described parameters and uses are given in Table 2-1.

ID	ParameterName	Sensing	SensingControl	Sensor	Regulatory
1	Frequency	•	•	•	•
2	Second	•	•	•	•
3	TimeReference	•	•	•	•
4	Microsecond	•	•	•	•
5	Angle	•	•	•	•
6	ReferenceGeolocation	•	•	•	•
7	Power	•	•	•	•
8	TimeStamp	•	•	•	•
9	TimeDuration	•	•	•	•
10	ChannelList	•	•	•	•
101	Bandwidth	•	•		•
102	TotalMeasurementDuration	•	•		
103	ChannelOrder	•	•		
104	ReportingRate	•	•		
105	ReportingMode	•	•		
106	PerformanceMetric	•	•		
107	Route		•		
108	ClientPriorityFlag		•		
109	SensorPriority		•	•	
110	SecurityLevel			•	
111	DataKey	•	•		
112	ClientLogID		•		
201	TimeSynchronization		•		
202	Scan		•		
301	AbsoluteSensorLocation	•		•	
302	RelativeSensorLocation	•		•	
303	MeasurementRange	•	•	•	
304	SensingMode	•	•	•	
305	SensorID		•	•	
306	SensorLogicalID		•	•	
307	BatteryStatus	•		•	
308	DataSheet			•	
309	ConfidenceLevel	•			
401	MeasurementBandwidth	•			
402	NoisePower	•			
403	SignalLevel	•			
404	ModulationType	•			
405	TrafficPattern	•			
406	TrafficInformation	•			
407	SignalType	•			
408	SignalDesc	•			
409	RATID	•			

Table 2-1: IEEE 1900.6 sensing parameters and their uses

The use and structure of these parameters is explained in detail in the IEEE 1900.6 standard [3], pp. 75-88.

2.3 The role of localization information as spectrum information

Characterizing an information source can prove very useful in order to enrich Radio Environmental Awareness (REA) in a wireless communication system. Furthermore, it can be used as an intermediate step for the estimation of the power spectral density in space and time. Source characterization mainly refers to identifying the presence, number, location and power spectral density of transmitting sources, although other characteristics such as signal bandwidth can also be used.

The localization of a source based on partial or full knowledge of the transmit (*Tx*) signal is a widely investigated field in the literature as well as in practice. Various ranging techniques are engaged for spatially localizing the radio sources (emitters). These techniques provide sensor-local estimates in terms of distance or orientation related to the neighbors of a cognitive radio device. This sensor-local information (estimation) is then usually gathered from multiple CRs and further combined appropriately in order to provide the location estimates. The most usual types of information used for ranging techniques are:

- ***Time*.** This is used in the Time of Arrival (TOA) of a known or unknown (i.e. blindly processed) Rx signal. Known signals are usually named “pilot signals”, which are pre-designed for a specific communication system. The Time Difference of Arrival (TDOA) can be treated as a special case of TOA when the sensors are not clock-synchronized with the transmitter (as is true in most cases in cognitive radio scenarios).
- ***Angle*.** This is used in the Angle of Arrival (AOA) of a known or unknown (blindly processed) Rx signal. The same assumptions hold as in TOA estimation.
- ***Power or Receive Signal Strength (RSS)*.** This is the total power that is received from a known or unknown signal. The measurement bandwidth can be narrow (in order to sense a small number of transmitters) or wide (for sensing a potentially large number of transmitters). The time horizon of the measurements is also a very critical parameter.

All this information is useful only in combination with a radio propagation model that can be used to characterize the interference field of an area of interest. This is a challenging task ever since the very beginning of wireless communication systems involving understanding the underlying physical laws of electro-magnetic wave propagation and the adoption of proper mathematical models to describe it. Having such a model is a very tedious task, often leading to the adoption of various approximations. Propagation models for the large-scale effects calculate the mean signal reception strength for an arbitrary transmitter-receiver (Tx-Rx) separation distance and are useful in estimating the radio coverage (or interference) area of a transmitter. They characterize the signal strength over large Tx-Rx separation distances (several hundreds or thousands of meters). There exist a large number of prediction models that differ on the complexity requirements and their applicability over different terrain and environmental conditions. What is certain is that no one model stands out as being ideally suited to all environments, so careful choice is required based on the characteristics of the target scenario for building a successful REA.

Based on all of the above described measurements and models, the role of passive localization techniques is to provide estimates for the emitter positions as well as its transmit power. The positions can either be represented by specific geographical regions (or grid points from a pre-specified list) or as points in space. All three forms of representation can be of statistical nature. The transmit power, usually measured in dBm and for a reference location away from an emitter, can be a simple scalar value or can have a statistical nature. The statistical description of the estimated data is straightforward (at least in principle) as they can be derived based on the estimation method used. General Cramer-Rao bounds for the estimation accuracy of position localization based on various estimated parameters, such as Tx-power, TDOA, AOA, can be found in [4]. These bounds can be used as proxies to assess the accuracy of the estimated values.

2.4 From spectrum information towards Radio Environment Maps (REMs)

Previous subsections discussed the combination of spectrum information along with location data as key enablers for dynamic spectrum access as well as more general types of cognitive wireless networks. Both concepts can be developed further and combined with additional sources and types of information to yield *Radio Environment Maps (REMs)*, i.e. geospatial knowledge bases on transmitters, receivers, propagation models, coverage areas and other similar quantities. This subsection provides a brief overview of REMs and discusses the connections in REM formation in relation to other topics discussed below.

One of the key concepts in REM formation is fusing spectrum sensing and measurement information from geolocalized sources to form estimates on locations of transmitters and receivers and on coverage regions of different transmitters. The challenges in extracting location information from spectrum measurements have already been discussed above. As discussed in [5], some of these difficulties can be overcome by focusing on *statistical modelling* of, especially, receiver locations, as opposed to trying to localize individual nodes. Accurate statistical models enable many of the similar computations to be carried out as actual collections of receiver locations, such as estimates of the interference probabilities related to a particular transmission decision, but in a manner that is robust to quantifiable localization errors at individual receiver locations.

The reasoning about transmitters, especially regarding interference patterns and coverage regions, can be based on various approaches. One possibility discussed in [5] and also in [6] is to eschew usage of estimated transmitter locations and propagation models separately altogether and focus instead on fusing of individual geolocalized measurements towards estimates of coverage regions without intermediate localization step. Example techniques from spatial statistics and geostatistics that can be used to form such estimates are discussed in detail in [6], where empirical evaluation of such spatial interpolation methods is also carried out for the indoor environment. Such techniques result in estimates of *random fields*, i.e. spatial stochastic processes defining random variables at each location of the region of interest for received power or field strength in a given range of frequencies. REMs can also be used in the temporal domain forming a logically centralized database of spectrum information based on which estimates of individual transmitter activity patterns can be made [5].

Finally, REMs are potentially applicable significantly beyond classical dynamic spectrum access based systems. For example, [7] discusses applications of REMs into cellular networks. The authors note that spectrum information obtained through routine drive tests or based on measurements carried out routinely by mobile terminals can be used as information to build REMs on cellular network coverage and, thus, as key enablers of various self-organizing network functions of future cellular systems. This is an important example on usage of cognitive wireless networking principles outside DSA based systems.

2.5 Summary

The process of accurate and unambiguous representation of spectrum information is a must for efficient and practically deployable DSA. The spectrum information itself is very diverse ranging from duty cycles of certain stakeholders to spatio-temporal variations of the spectrum usage and positions of various PU- and/or SU-based transmitters. Therefore, the problem of spectrum information representation becomes complex and highly dependent on the actual application scenario of interest.

This section elaborated on the currently most prominent solutions (from a standardization and research point of view) for spectrum information representation. The following section will provide insight into the management details of the represented spectrum information.

3. Management of spectrum information

After the previously introduced information representation, this section elaborates the most relevant concepts for management of spectrum information in CR networks today. It specifically distinguishes the nuances between centralized and de-centralized concepts, both based on single-node sensing, cooperative sensing (hard and soft combining) or database provided spectrum information.

The management of spectrum information can be perceived as a set of processes and tasks performed by a spectrum management entity which is responsible for handling the spectrum information. These processes vary from: collecting sensing information from various actuators (sensor nodes), combining and storing the information in repositories like REM servers, databases, fusion centres, etc., processing of the gathered spectrum information (e.g. Radio Interference Field Estimation (RIFE), transmitter localization, spectrum band occupancy calculation, fusion of sensing information, etc.) etc. The processes can be managed by a centralized management entity (e.g. REM Manager), but also by a local management entity (e.g. collaborative spectrum sensing fusion centre).

3.1 Centralized concepts

This subsection elaborates the existing generic management concepts, their architectures and information flows in terms of a centralized dynamic spectrum access and allocation approach.

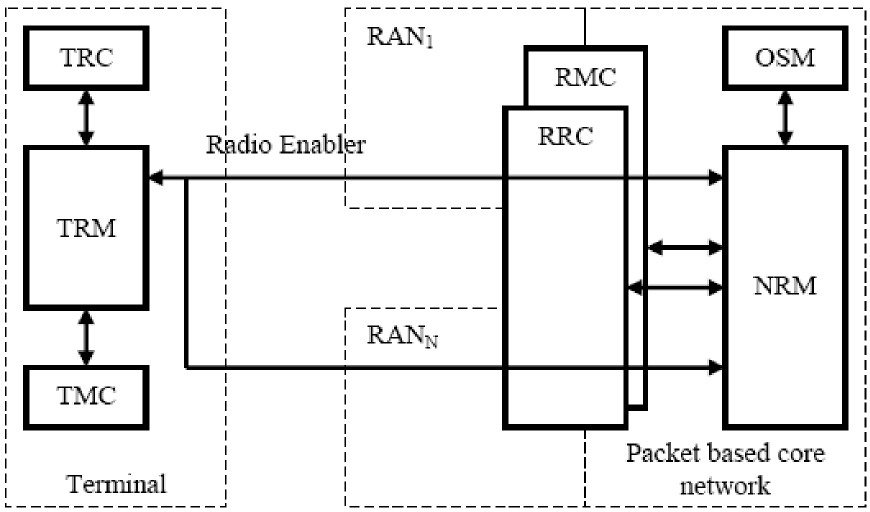
3.1.1 IEEE 1900.4

The IEEE 1900.4-2009-IEEE Standard for Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks was published in February 2009. It is an outcome of efforts of the IEEE 1900.4 Working Group [8], which works on radio resource management and reconfiguration management in composite wireless networks. Composite wireless networks comprise RANs of diverse legacy and future radio access technologies.

The IEEE 1900.4 standard defines three general use cases: (i) “Dynamic Spectrum Assignment”, (ii) “Dynamic Spectrum Sharing” and (iii) “Distributed Radio Resource Usage Optimization”. The “Dynamic Spectrum Assignment” concerns processes and mechanisms that dynamically assign frequency bands to RANs of the composite wireless network, in the framework of the relevant official regulations, in order to optimize spectrum usage. The “Dynamic Spectrum Sharing” concerns processes and mechanisms that enable efficient opportunistic spectrum usage, when RANs and terminals dynamically access the same frequency bands. Finally, the “Distributed Radio Resource Usage Optimization” refers to processes and mechanisms that govern the optimization of radio resource usage by the composite wireless network and terminals in a distributed way. Based on these use cases, system and functional requirements, system and functional architecture, information model and generic procedures were defined.

The functional architecture of IEEE 1900.4 standard consists of seven functional entities, i.e. OSM, NRM, TRM, RRC, RMC, TRC and TMC, explained and illustrated in Figure 3-1 [8]. The role of the NRM is to manage both the composite wireless network and the terminals. The TRM has the responsibility to manage the terminal according to its own strategy, but at the same time being in compliance with the policies provided by the NRM. The policies refer to radio resource selection rules/constraints that aim at optimization of the radio resource usage. The logical communication channel between the NRM and the TRM entities is called Radio Enabler (RE) and may be mapped onto one or several RANs used for data transmission (in-band channel) and/or onto one or several dedicated RANs (out-of-band channel).

More analytically, the NRM collects context information from its managed RANs and sends them reconfiguration commands in terms of operating RAT and frequency. In general, RAN context may contain information for the radio and transport capabilities of the RAN, RAN measurements etc. Policies, as well as context information for the managed RANs, are sent to the TRM from the NRM, whereas terminal related context information is sent in the opposite direction. Similarly with RAN context information, terminal context information may include information such as terminal capabilities and measurements, user preferences, required QoS levels etc.



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 3-1: IEEE Standard 1900.4-2009 functional architecture

The abovementioned tasks of measurement collection are performed by the RMC, in the network side, and the TMC, in the terminal side. The RRC executes the suitable reconfiguration of RANs requested from the NRM and the TRC executes the suitable reconfiguration action of the terminal requested from the TRM. Furthermore, there is a central entity OSM that “enables the operator to control the dynamic spectrum assignment decisions of the NRM” [8].

Concerning the information model in IEEE 1900.4, there are a number of requirements given in the specification. These are (broadly, paraphrasing):

- It must be extensible,
- It must use an object-oriented approach,
- It must support sufficient simple relationships between different classes,

- It must allow for inclusion of both uniform and non-uniform data structures,
- It must allow for definition of new abstract data types to describe the information model items,
- It must allow the provision of information items specification of precision and accuracy,
- It must include exclusivity or consistency relationships between objects to determine conflicts,
- It must provide means for unique identification of managed objects,
- It must utilize platform-independent unambiguous information/data type definitions,
- It must allow for the inclusion of information about information objects,
- It must be open to incorporate:
    - Corresponding information elements developing a shared knowledge framework,
    - A notifications list, such as configuration changes, threshold crossings etc.,
    - Information elements to ensure alternative information retrieval in support of an efficient retrieval mechanism to obtain performance, quality-of-service and related information and measurements data,
    - Information elements that can provide value (instantiate) through mechanisms such as statistical operations to reduce data transfers,
    - Managed objects in order to coordinate the measurements scheduling.

In addition to the requirements specified above, IEEE 1900.4 specifies a number of more general requirements of the information model in the associated Section 5 (“Requirements”) of the standard [8]. These are:

- The information model must provide a specified representation of information within the scope of this standard,
- It must support two sets of managed objects, i.e. Cognitive Wireless Networks (CWNs) and Terminals,
- CWN-related classes must abstract the operator, RAN, BS and cell concepts within the scope of this standard,
- Terminal-related classes must abstract the user, application, terminal, frequency channel, and active connection concepts within the scope of this standard,
- The information model must abstract the policy concept within the scope of this standard, including spectrum assignment policy and radio resource selection policy,
- The information model might include time and duration references related to the validity of the provided information. For instance, the time at which measurements were made or the valid period in which they are to be taken,
- The information model should provide geo-location related information items.

These requirements are clearly related to the overall architecture and purpose of the standard and implicitly define the scope within which the information model operates.

Taking into account these requirements, it is clear that IEEE 1900.4 is highly generic in its information management and aims to consider both future network capabilities as well as a range of present and future management scenarios that are pertinent to the standard. Moreover, it takes into account aspects such as uncertainty in the available information, conflicts in provided information, platform independency, scheduling of measurements etc. The key elements regarding the collection of information and measurements from terminals and RANs are respectively the Terminal Measurement Collector (TMC) and the RAN Measurement Collector (RMC), as illustrated in Figure 3-1.

IEEE 1900.4 defines three types of classes. These include *base classes* such as value characteristics, which are applicable to all types of devices, *terminal related classes*, and *CWN related classes*. It assumes that the underlying network management policies are Event-Condition-Action (ECA), i.e. they are event driven, subject to certain conditions, and, given the event and conditions being satisfied, will implement an action. Terminal and CWN classes are further sub-divided on the terminal side into User classes, Application classes, Device classes, and RRS Policy classes and on the CWN side into Operator and RAN classes.

IEEE 1900.4 defines the basic elements of the information model classes along with a description of them and UML class models in the core of the standard (Section 7). It also elaborates more detailed specifics (named precise class definitions) in a normative annex, which is a form of annex that is to be considered as a required part of the standard, and also specifies data types in another normative annex giving a usage example in a further informative annex. Without delving into the details of the precise class structures, some insight into the application of the information model in IEEE 1900.4 can be obtained by investigation of the provided usage example. In the particular context of the information model, this example is presented for distributed radio resource usage optimisation, whereby frequency bands and configurations of RANs are fixed, but terminals can be dynamically reconfigured in order to access the different RANs. It describes how a radio resource selection policy might be generated by the network side (NRM) and this information be transferred to the TRM on the terminal side. Based on this, the terminal, through the TRM, performs two actions: (i) periodically selects new RANs to access and (ii) periodically collects measurement reports from the TMC and sends this information back to the NRM. Using the base class objects to define actions that are involved, the usage example illustrates the following steps:

A. Creation of a ValueCharacteristic object to take measurements for each link and store the data,
B. Creation of a MeasurementReporter to collect statistics and report the information to the NRM,
C. Creation of a Scheduler object to trigger the periodic executions of the radio resource selection policy on the terminal side,
D. Creation of a Policy object to define radio resource selection policies,
E. Creation of an ECA policy rule to determine selection of policies

A key related insight into information management in IEEE 1900.4 is obtained by looking at the MeasurementReporter object. This specifies the name of the MeasurementReporter object, a target for the report, a related scheduler that will trigger the report, the contained/requested values and the time that has elapsed since the last report. The associated annex specifies this to be contained in the classes BaseStationMeasurements, CellMeasurements, ApplicationMeasurements, DeviceConfiguration, and DevicesMeasurements (indicating the types of elements that can make such measurements and report them). The MeasurementReporter class supports the MeasurementReport object, which simply specifies that the report contains an array of values.

3.1.2 IEEE 1900.6

The IEEE 1900.6 working group ("Spectrum Sensing Interfaces and Data Structures…") is not heavily focused on information management. Rather than that, it concentrates particularly on the interfaces for spectrum sensing information and how it is structured. The currently published IEEE 1900.6 is solely concerned with aspects such as the structuring of information and the specification of primitives and services access points for the exchange of sensing information and the control of how the information is obtained. However, IEEE 1900.6 does specify the presence of the DA, an element that would archive spectrum sensing information. This is the most relevant aspect of the standard to management of information, although it does not specify exactly how that information is stored and managed in the DA.

At the time of writing, IEEE 1900.6 is working on an amendment, one aspect of which will be the enhanced interfaces with the DA [9]. This could be slightly more pertinent to specifying how such information is managed.

Until the mentioned amendment is published, it is however possible to present an information management scheme compatible with the standard that follows a centralized approach. Figure 3-2 depicts the system architecture: a single DA is available in the whole architecture and acts as a central collecting point.

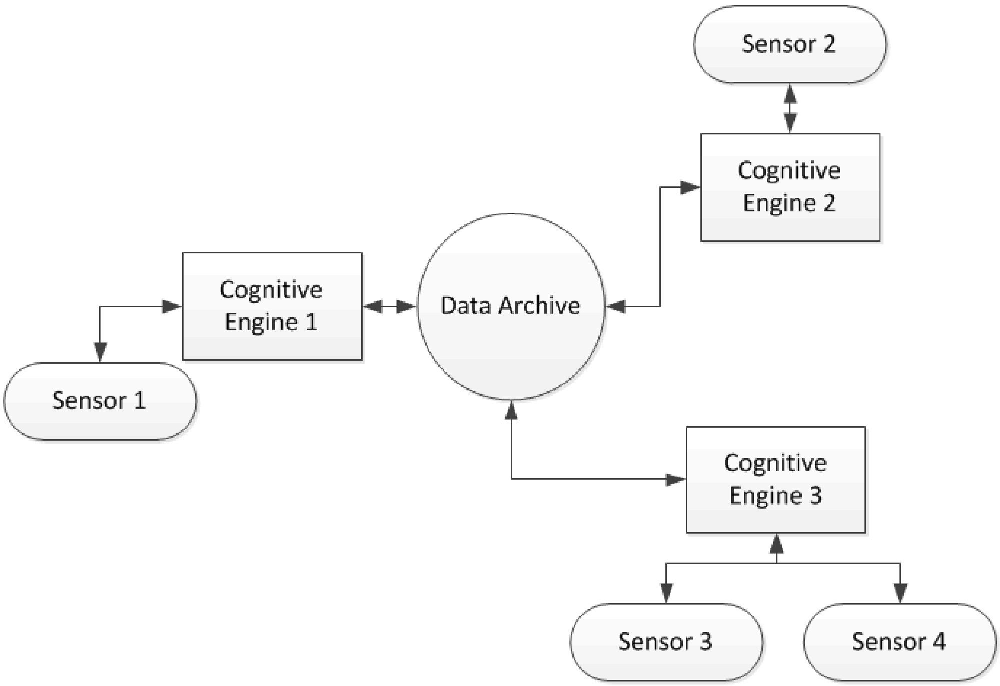


Figure 3-2: Information management architecture with a centralised data archive

Sensing output measurements (either raw data or hard decision depending on the available bandwidth on the common control channel) are sent to the central DA by the CEs. Sensing information may be saved together with a timestamp reporting the time they were generated, as well as sensor location, sensor ID and, optionally, the reporting CE.

Data can be made publicly accessible to any entity belonging to the system or restricted to a subset of authorised CEs. They can be exploited to perform cooperative sensing algorithms: in this case an additional benefit consisting on an increased level of consistency during the data processing phase comes from a slightly different architecture as depicted in Figure 3-3. In fact, the cooperative algorithms are executed in the central CE; hence it is guaranteed that sensing measurements are handled univocally within the system as opposed to the case illustrated in Figure 3-2, where any CE may execute its own algorithms.

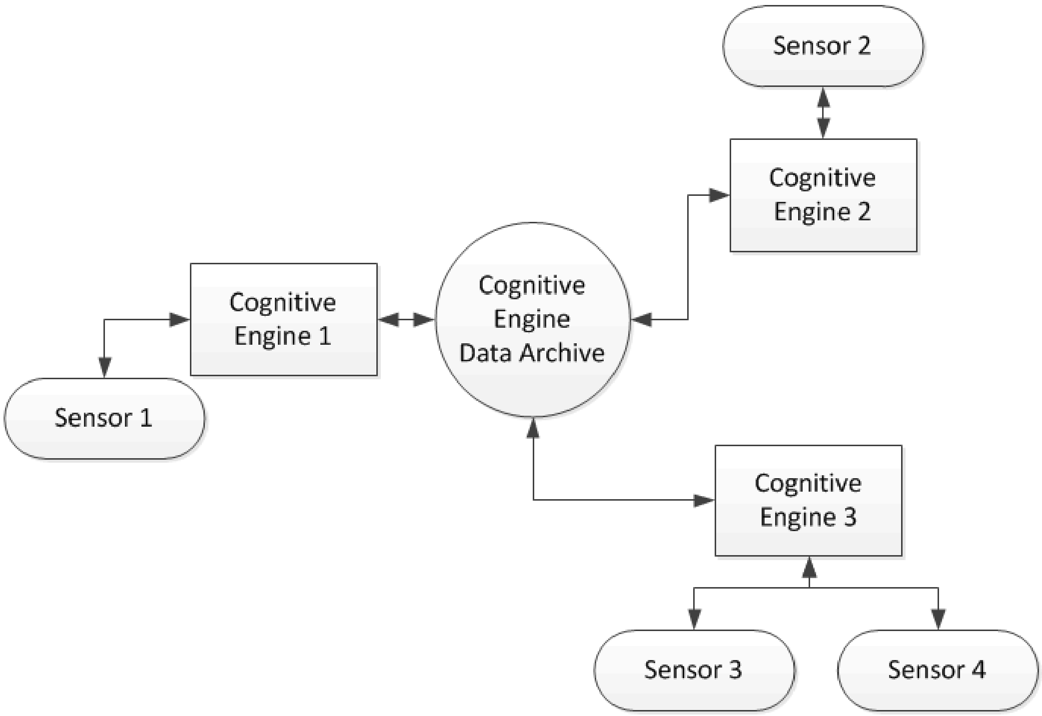


Figure 3-3: Information management architecture with a centralized data archive and cognitive engine

3.1.3 End-to-End Efficiency (E3) project

The End-to-End Efficiency (E3) project [10] was an FP7 EC Large Scale Integrating Project (IP), which aimed at integrating cognitive wireless systems in the Beyond 3G (B3G) world and evolving current heterogeneous wireless system infrastructures into an integrated, scalable and efficiently managed B3G cognitive system framework. This was accomplished by using cognition, autonomicity and reconfigurability, in order to build a novel architecture that confronts the requirements of future networks.

The design of the architecture was based on a large number of use cases that led to identification of functionalities, which in turn led to the design of the Functional Architecture (FA) of E3 (Figure 3-4 [11]). The FA consists of the Dynamic Spectrum Management (DSM), the Dynamic, Self-Organising Network Planning and Management (DSNPM), the Joint Radio Resource Management (JRRM), the Self-x for Radio Access Networks (Self-x for RAN) and the Reconfiguration Control Module (RCM), which cater for different operational needs and goals. It is noted that the FA encompasses network elements and MTs and the term RAT comprises the set of network elements operating at specific radio access technology. The architectural blocks are explained in details in the following text.

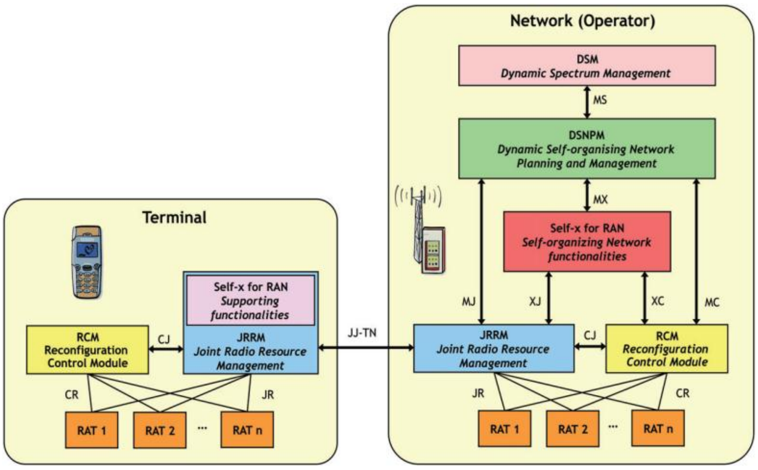


Figure 3-4: Functional architecture of E3

Dynamic Spectrum Management (DSM)

The Dynamic Spectrum Management (DSM) provides the medium-term and long-term management of the spectrum for different managed radio systems, as well as knowledge on the policies for spectrum assignment. The policies must include the constraints that are imposed by the relevant official organizations (e.g. the spectrum usage rights for the licensed operating frequencies). The spectrum assignment and the related knowledge are forwarded to the DSNPM.

DSM's operation is based on spectrum information management. This information is retrieved from the network/base station configuration information and/or from spectrum measurements and sensing by the cognition enablers, which are presented in the sequel, with the assistance of DSNPM. Furthermore, DSNPM provides information to DSM on the load status in the used frequency bands.

Dynamic, Self-Organising Network Planning and Management (DSNPM)

The Dynamic, Self-Organising Network Planning and Management (DSNPM) entity provides medium-term and long-term decisions on the reconfiguration actions of a network segment, which are forwarded to the Reconfiguration Control Module (RCM). These reconfiguration decisions are result of cognitive operation carried out by an optimization function enhanced with learning capabilities. The learning capabilities are based on certain input information including context information, policies, knowledge and profiles [12]. The learning capabilities also include the appropriate processes that enable the acquisition and accumulation of knowledge, which is extracted from the processing of all the available information combined with the decisions/actions that have been taken/realized based on this information. Context information includes spectrum usage measurements, information related to the status of the managed network elements and the network conditions of the close environment. Policies are the rules that constitute the framework of the operation of DSNPM illustrating the network operator's strategy and regulatory constraints. In this context, policies include rules such as spectrum usage policies, allocation of services to radio access technologies and permissible configurations of the managed network elements. Profiles comprise information such as capabilities, operating characteristics and possible alternative configurations of the managed entities, as well as statistical data derived from their behavior and user's preferences (e.g. preferable operating radio access technology per service).

Joint Radio Resource Management (JRRM)
The Joint Radio Resource Management (JRRM) performs the joint management of radio resources that might belong to heterogeneous RATs. Specifically, JRRM selects the best radio access for a given user, based on the requested QoS for the demanded service, the existent radio conditions (e.g. signal strength), the access network conditions (e.g. current cell load), user preferences and network policies. Furthermore, JRRM also provides neighbourhood information to the mobile terminals for efficient discovery of the available radio access networks.

Self-x for Radio Access Networks (Self-x for RAN)
The Self-x for Radio Access Networks (Self-x for RAN) focuses on radio access technology specific operator use cases, implementing the relevant self-organising functionalities. In this framework, Self-x for RAN cooperates with the DSNPM (regarding the acquisition of performance information and relevant policies), with the JRRM (regarding the execution of Self-x for RAN decisions and provision of measurements) and with the RCM (regarding the various reconfiguration control functions). Self-x for RAN on the terminal side supports the self-x operations of the network components (e.g. collects statistical information). The communication between Self-x for RAN on the terminal side and Self-x for RAN on the network side is realized through JRRM.

Reconfiguration Control Module (RCM)
The Reconfiguration Control Module (RCM) is responsible for the execution of the reconfiguration of terminals and network elements, based on the directives of DSNPM, Self-x for RAN and JRRM.

Cognition enablers
The operation of the presented blocks is enabled by three identified "cognition enablers", the Cognitive Pilot Channel (CPC), the Cognitive Control Radio (CCR) and the Spectrum Sensing (SS). The CPC is a logical or physical channel that provides necessary information for discovery of available radio accesses and optimal radio access selection from the mobile terminals, such as the available radio access technologies in a geographical area, the frequencies that these technologies are using and spectrum-usage policies. The CCR is an out-band peer-to-peer communication radio between heterogeneous network nodes (e.g. between terminals or between an access network and associated terminals) for the exchange of cognition related information, which operates on a known frequency of the unlicensed bands. The SS targets at gaining knowledge related to the available radio systems by sensing the radio conditions and the radio link quality. In cooperation with the CCR or the CPC, SS information can be distributed between different nodes.

The necessary information flow is accomplished via several interfaces:

- **JJ-TN interface** (between the JRRM on the terminal and on the network side) used for sending information from the network to the terminal about its close environment and access selection policies and decisions, as well as for exchanging measurement information.
- **MS interface** (between the DSNPM and the DSM) used for provision of spectrum information, from the DSM to the DSNPM, such as the available frequency bands for

different RATs, spectrum usage metrics, unoccupied spectrum bands for secondary spectrum usage, spectrum usage policies etc.

- **MJ interface** (between the DSNPM and the JRRM) mainly used for informing the DSNPM about the current context in the network.
- **MX interface** (between the DSNPM and the Self-x for RAN) mainly used for provision of information from the DSNPM to the Self-x for RAN on KPIs and policies, as well as from the Self-x for RAN to the DSNPM about context updates after reconfigurations initiated by Self-x for RAN.
- **MC interface** (between the DSNPM and the RCM) used for the exchange of configuration information between the RCM and the DSNPM. The configuration information of the managed network elements may include information such as their operating radio access technology and frequencies, the possible different operating radio access technologies and a variety of operating parameters e.g. the allocated bandwidth to uplink and downlink.
- **XJ interface** (between the Self-x for RAN and the JRRM on network side) used for sending context information from JRRM to Self-x for RAN according to the specific operation of the Self-x for RAN (e.g. load balancing).
- **XC interface** (between the Self-x for RAN on the network side and the RCM on the network side) used for exchange of configuration information depending on the implemented use case and for transferring reconfiguration request to the RCM on the network side.
- **CJ interface** (between the RCM and the JRRM on the terminal side) used for exchange of information for synchronization of a set of actions e.g. reconfiguration execution.
- **JR interface** (between the JRRM and the RAT, on the network and the terminal side) used for reporting information such as resource usage measurements on network side and link performance on terminal side.
- **CR interface** (between the RCM and the RAT, on the network and the terminal side) is used for reconfiguration execution of the underlying RATs, based on DSNPM's decisions on the network side or terminal decisions, as well as exchange information such as the current configuration of the radio applications of a base station on the network side.

The architecture is slightly differentiated in case of a multi-operator environment and incorporates three new interfaces (Figure 3-5) [12]:

- **SS interface** between the DSM instances of the different network operators used for information exchange of spectrum usage and spectrum policies and negotiation for spectrum usage between operators. For example, it may transfer the demand of an operator for usage of a frequency band in a specific geographical area and for determined time period and the response to this demand (rejection of the demand or acceptance and indication of the respective frequency band).
- **MM interface** between the DSNPM instances used for the exchange of information on the network configuration in order to avoid or reduce interference between the

networks. For example, a network operator may inform the co-operating network operators about modification of the network context as a result of the new configuration (regarding RAT or operating frequency) of a number of network elements or about available frequencies for secondary spectrum usage.

- **JJ-NN interface** between JRRM instances on the network side used to support the handover of terminals between networks of different operators. For example, it is used for transferring the user context before performing a handover to a cell of a co-operating network. The dashed line between the terminal and the JRRM instance of network operator 2 illustrates the case in which the terminal is also connected with two (or more operator networks) at the same time, receiving, for example, different services from different networks. During a handover procedure between the networks, the terminal may also use both JJ-TN interfaces to both operator networks.

The information flow between corresponding instances of functional blocks operating in networks of different network operators (namely, the number of interworking interfaces) depends on the co-operation level.

Furthermore, ad-hoc and multi-hop scenarios are also supported by the functional architecture of E3 (Figure 3-6). Instead of a JRRM building block, this scenario contains the Autonomic Entity Management (AEM) building block, which selects the best radio access based on context information (e.g. spectrum sensing results and measurements) communicating directly with other devices via the AA interface between the AEM instances.

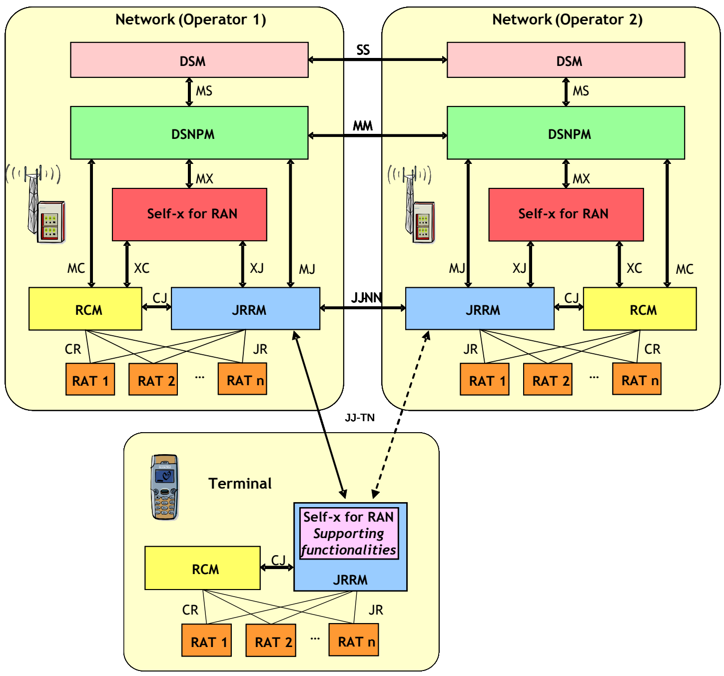


Figure 3-5: Functional Architecture of E3 for multi-operator case

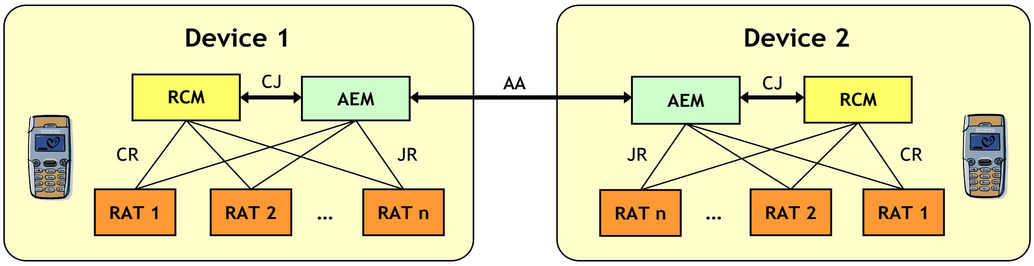


Figure 3-6: Functional Architecture of E3 for ad hoc/multi-hop scenario

3.2 Decentralized concepts

This subsection elaborates on the existing generic management concepts, their architectures and information flows in terms of a decentralized dynamic spectrum access and allocation approach.

3.2.1 IEEE 1900.6

Spectrum sensing information can generally be managed according to a distributed scheme where no central entity is in charge of maintaining a globally consistent and updated version of the data content. A similar architecture can be developed in compliance with the IEEE 1900.6 as illustrated in Figure 3-7. In this case, every CE stores the information retrieved by the serving sensors in a local data archive. It is however still possible to collaborate among peer CEs exchanging their measurements. The received information might also be stored locally for a delayed use, although it shall not be forwarded to third-parties as the originating CE should represent the only trusted source of the correspondent data.

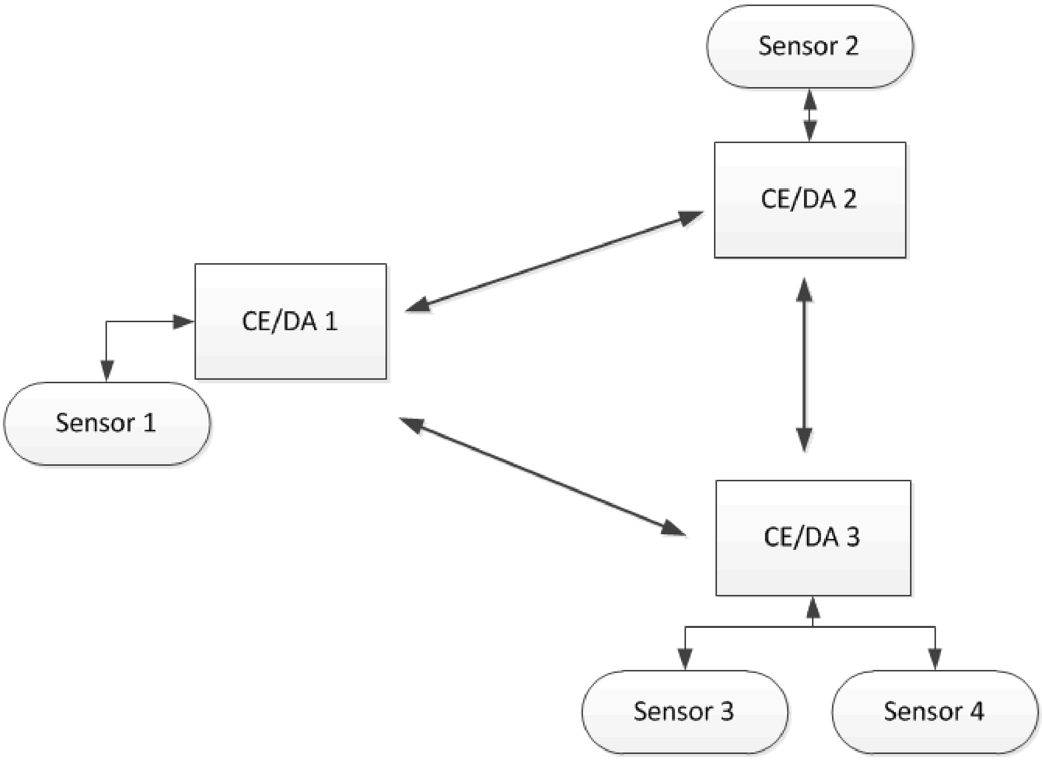


Figure 3-7: Information management architecture with a distributed scheme

3.2.2 Resource Awareness Channel (RAC)

Decentralized sharing of information may be achieved through the common control channel concept. The channel can provide various devices and networks with information such as available devices in an area or spectrum resource already being used by the same devices (and available by inference). Decentralized cases are, however, complicated by the fact that there is generally no centralized point of control or known repository of the information. Therefore, the information must be sent by all devices or collections of elements/devices (e.g. a network) on the common channel in order for all other devices in the area to be able access it. One example of this vision is the Resource Awareness Channel (RAC) concept [13], originally conceived as means of proactively sharing information on resource usages by devices in radio range (so that other resources can be opportunistically used), while also assisting channel quality awareness through reciprocity. The RAC concept can be easily extended to other situations such as the sharing of information for connectivity awareness purposes.

A key realisation in the management of spectrum information by the RAC concept is that Information on resource usages can often be treated in a hierarchical manner. For instance, a spectrum band that a RAT is using might be specified, followed by an identifier for a certain hopping pattern in that band at the next level etc. Another important realisation refers to the case when the devices that use the RAC for transmission do not know about each other. Hence, there is a need for a mechanism such as carrier sense in order to avoid the interference. The information in this case will be periodic and (generally) have to be updated in each period. Devices and networks that are going to access the channel will know with a high degree of predictability when transmissions are going to occur and will be (based on that) able to cooperatively converge on appropriate time slots, also adjusting time slot usages such that they are contiguous.

3.2.3 Network coding for decentralized management of spectrum information

As pointed out above, the RAC offers a promising concept to implement decentralised management and distribution of spectrum information. Undoubtedly, the concept is feasible as long as small data sets have to be distributed through the RAC and the available bandwidth supports this. However, more sophisticated cognitive radio concepts that potentially employ large databases may require more bandwidth for sharing their knowledge. In such scenarios, network coding may be a means to increase the bandwidth usage efficiency of the RAC.

The problem described above, distributing a large amount of data through a heterogeneous network, is very similar to the problem formulation that motivated the invention of the so-called fountain code [14]. Fountain coding (or rate-less coding) is a coding technique that encodes a large data file into a large number of small data packets. Perfect reconstruction of the original data is possible based on any combination of small packets as soon as a critical number of small packets have been received (“collected”). Decoding becomes possible for ideal fountain codes as soon as the amount of collected data equals the size of the original data file.

To illustrate how fountain codes can be applied to manage distributed spectrum information, consider the following example. Assume that a set of nodes in a network is keeping identical copies of the same database and a (distributed) fountain code is used across the nodes to encode the database. A new node enters the network and wishes to download a copy of the spectrum information database. However, due to the mobility of the nodes and bandwidth constraints, the database cannot be downloaded in one session. Instead, whenever the new node comes into communication range of another node in the network, it downloads as many packets as possible. Once a sufficiently large number of packets have been collected, the new node can decode the database and use it. It is not surprising to see that similar concepts based on network coding ideas have been proposed for distributed storage. A survey on this topic is given in [15].

The previous example considered the case where a new node in the network had to download a complete database. It may however be more realistic that a node has an out-dated copy of the database available which it wishes to update. Assuming that the database evolves slowly over time, one can expect that the old copy of the database is still correlated with the current version. In such a situation, employing distributed source-coding techniques like Slepian-Wolf coding can decrease the data rate. Considering that Slepian-Wolf coding can be efficiently implemented using a so-called syndrome-coding approach, which essentially describes the key concept underlying fountain codes, one can expect that fountain codes will be applicable in this scenario as well.

3.3 Summary

The versatility of the spectrum information poses serious challenges in front of the spectrum management solutions. Moreover, the dynamism and the unpredictability of the wireless environment and the corresponding stakeholders further complicate the spectrum information management. This section tried to classify existing spectrum information management solutions and pinpoint their advantages, disadvantages and applicability in certain scenarios. The analysis is a significant aid for fostering the design of an architecture for spectrum information management, which is discussed in details in the subsequent section.

4. System architecture for management of spectrum information

This section focuses on a system architecture for management of spectrum information. It elaborates on the possible architectural blocks, interfaces and data structures, as well as their requirements, in order to provide efficient management and sharing of the spectrum information.

4.1 Requirements on architectural blocks

Efficient management and sharing of spectrum information requires a system architecture that has to:

- Assign the available frequencies to the different RATs/Networks per region and time scale based on:
  - Knowledge of current spectrum assignment,
  - Constraints imposed by relevant official organizations (e.g. the spectrum usage rights for the licensed operating frequencies),
  - Spectrum utilization metrics,
  - Spectrum assignment policies, which are predefined rules that have been designated by the network operator according to techno-economical criteria and constraints.
- Detect long-term available frequency bands for sharing or trading between different networks in the framework of a consortium of network operators or free cooperation, respectively.
- Derive spectrum policies for secondary usage.
- Derive economical parameters for spectrum trading.
- Bargain in spectrum sharing/trading with other network operators.

The spectrum utilization metrics correspond to the grade of usage of the operating frequencies in a specific time frame for certain managed sections of the whole managed area. They result from the information sent by the operating RANs and MTs (e.g. measurements of signal strength for each operating frequency combined with data about the load of the RANs operating on the corresponding frequencies). The exact definition of spectrum utilization metrics may be defined differently for each network based on the operators' strategy.

In order to accomplish these goals/requirements, the system architecture needs a set of building blocks (Figure 4-1), i.e.:

- **Information Processing** building block, which processes spectrum related information from operating RANs and MTs and calculates the spectrum utilization metrics.
- **Spectrum Assignment** building block, which determines the allocation of available frequencies to RATs/Networks per region and time scale based on the aforementioned information and rules and detects the available spectrum for sharing/trading (Spectrum Pool) with the corresponding spectrum usage rights.

- **Spectrum Derivation Policies** building block, which derives spectrum policies for secondary usage and for usage of unlicensed frequencies.
- **Spectrum Negotiation** building block, which is responsible for bargain in spectrum sharing and trading with other network operators and for the determination of the acquisition costs, in case of trading, of the available frequencies of the spectrum pool for a definite time period. It is noted that the cost of different frequencies bands is determined based on conjunction of technological and economical factors and may be variant for different time periods.

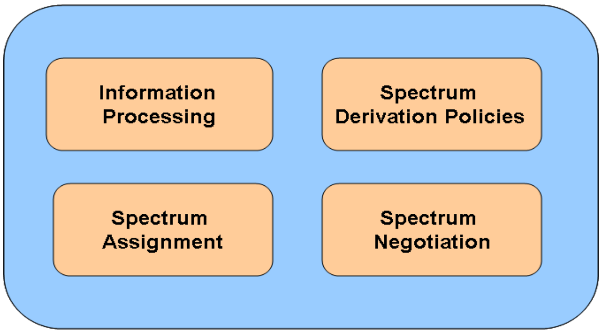


Figure 4-1: Building blocks of architecture for management of spectrum information

Figure 4-2 depicts the respective information for the architecture's operation.

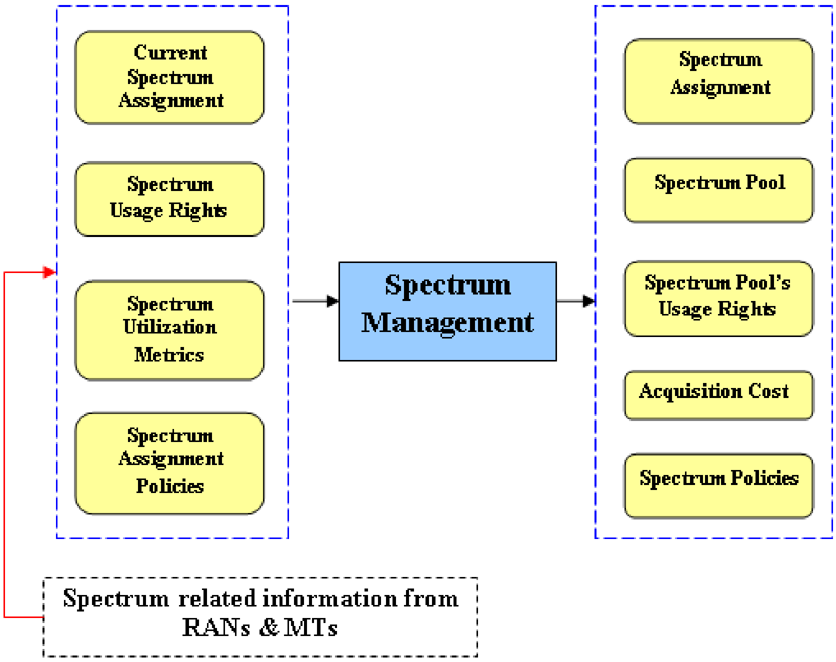


Figure 4-2: Information pertaining to operation of building blocks of system architecture for management of spectrum information

4.1.1 IEEE 1900.4

The previously elaborated requirements are met in the context of IEEE 1900.4-2009 standard by the defined functions of the NRM, specifically by the information extraction, collection and storage function, the RAN selection function, the network reconfiguration decision and control function, the spectrum assignment evaluation function, the policy derivation function and the policy efficiency evaluation function:

- The information extraction, collection, and storage function receives context information from RANs and terminals (namely, from the RMC and the TMC entities), processes it and stores the processed information. Furthermore, the information extraction, collection and storage function provides required information to other functions of the NRM, forwards RAN context information to the TRM and may, as well, forward to the TRM, terminal context information related to other terminals.
- The RAN selection function selects the proper RANs for exchange of policies and context information between the NRM and the TRM.
- The network reconfiguration decision and control function, taking into consideration the spectrum assignment policies of the OSM, decides on the RANs reconfiguration. In case of a reconfiguration decision, the relevant command is sent to the corresponding RRC. Moreover, the reconfiguration decisions are also sent to the OSM.
- The spectrum assignment evaluation function evaluates the efficiency of the spectrum usage of the assigned frequency bands and the evaluation results are utilized from the network reconfiguration decision and control function for its decisions.
- The policy derivation function, based on the context information from the information extraction, collection and storage function, derives policies that constitute the framework of the TRM's reconfiguration decisions.
- The policy efficiency evaluation function evaluates the efficiency of the derived policies. The evaluation results are utilized from the policy derivation function in the derivation process.

The IEEE 1900.4 Working Group, in April 2009, started working on the project P1900.4.1 entitled "Standard for interfaces and protocols enabling distributed decision making for optimized radio resource usage in heterogeneous wireless networks" [16], whose scope is to "provide detailed description of the interfaces and service access points defined in the IEEE 1900.4 standard, enabling distributed decision making in heterogeneous wireless networks and obtaining context information for this decision making". Some input was also provided by [17].

4.1.2 IEEE 1900.6

The elements involved in IEEE 1900.6 (as explained in section 2 of this document) are the CE, the S and the DA. The IEEE 1900.6 service, as defined in the standard, must interface with the control/application through the Application-Service Access Point (A-SAP) in the CE or CE/DA and in a S in the case of collaborative sensing, the Measurements-Service Access Point (M-SAP) in a S and the Communication-Service Access Point (C-SAP) in all such elements as the sensed information has to be communicated or received through communication. IEEE 1900.6 must therefore specify control and configuration of sensors and the sensing system through the CE and CE/DA, the sensing capabilities in the S and the communication capabilities in all cases.

Further information on the supporting architecture can be obtained through reference to sections 4 and 5 as well as the use case annexes of the published IEEE 1900.6 [3]. One key factor affecting the utilised structure of the system architecture is the precise form of sensing being deployed. To this end, Annex A defines four classes of sensing:

- Peer-to-peer sensing,
- Cooperative sensing,
- Collaborative sensing and
- Selective sensing.

In the peer-to-peer case, sensing is performed by peers in a communication link or looking to form a communication link, in which case one or both of the associated devices (e.g. peer-to-peer communicating terminals) will have both the CE and S capabilities as well as CE-S related interfaces.

In the cooperative sensing case, sensing information is reported individually by Ss to a CE, whereby the CE might make a decision based on the collection of information as reported individually. Hence, sensors will have purely S capabilities and the CE will have CE capability, whereby again the CE-S interface (or perhaps the CE/DA-S interface) is being used.

In the collaborative sensing case, sensors may exchange sensing-related information and process it locally to some extent before forwarding the information to the CE. In this case, some sensors that receive information from other sensors must also act as clients requiring the use of the S-S interface as well as the CE-S and perhaps the CE/DA-S.

The selective sensing case is largely similar to the collaborative sensing case with the exception that in this case the client sensor might choose which information to forward to the CE or CE/DA as opposed to forwarding all of it or a processed version thereof.

4.2 Requirements on interfaces

The previously introduced architectural blocks and their requirements also yield interconnecting interfaces for transparent and reliable communication. This subsection provides standardization efforts in the area.

4.2.1 IEEE 1900.4

The IEEE 1900.4 standard specifies the necessity of interfaces between:

- NRM and TRM,
- TRM and TRC,
- TRM and TMC,
- NRM and RRC,
- NRM and RMC and

- NRM and OSM.

A number of specific requirements are outlined for each of these interfaces particularly on the information they must transmit, subdivided into the NRM and the TRM. They are specified both in the context of interfaces among actual elements and interfaces between the vast range of functions incorporated within. The detail of these information exchange requirements is reasonably intuitive given the detail outlined in sections 3.1.1 and 4.1.1 of this document. However, the reader may refer to [8], pp. 15—23, if more detail is required.

4.2.2 IEEE 1900.6

Although IEEE 1900.6 does not explicitly state the requirements on its interfaces, such information is easily inferred by studying the primitives defined for the SAPs specified in Section 5 of the standard [3], as well as some of the early information description given in Section 6. Referring to this, the M-SAP provides the IEEE 1900.6 logical entities the following services, particularly related to interactions with sensors:

Measurement capabilities discovery services

Provide a set of primitives or methods via which the IEEE 1900.6 user can obtain information related to the measurement capabilities of the associated measurement module (e.g. a sensor).

Measurement configuration discovery services

Provide a set of primitives or methods via which the IEEE 1900.6 user can obtain information related to the measurement configuration of the spectrum measurement module (e.g. a sensor).

Measurement configuration services

Provide a set of primitives or methods via which the IEEE 1900.6 user can configure the spectrum measurement module (e.g. a sensor).

Information services

Provide a set of primitives or methods via which the IEEE 1900.6 user can collect information related to the measurement configuration of the spectrum measurement module.

The associated primitives are summarized in Table 4-1.

Primitive	*Description*
Get_Supported_Spectrum_Measurement_Description	Used to obtain a supported measurement of the measurement module
Get_Sensor_PHY _Description	Used to obtain information related to the physical layer configuration of the spectrum measurement module
Get_Sensor_Antenna _Description	Used to obtain information related to the antenna configuration of the spectrum measurement module
Get_Sensor_Location _Description	Used to obtain information related

	to the location of the spectrum measurement module. This location corresponds to the location of the measurement
Set_Sensor_Measurement_Obj	Used to set the measurement objective of the spectrum measurement module
Set_Sensor_Measurement_Profile	Used to set the measurement profile of the spectrum measurement module
Set_Sensor_Measurement_Performance	Used to set the objective performance of the spectrum measurement module
Get_Sensor_Manufacturer_Profile	Used to collect information on the manufacturer of the spectrum measurement module
Get_Sensor_Power_Profile	Used to collect information on the power consumption of the spectrum measurement module
Get_Measurement_Profile	Used to obtain information on the spectrum measurement that has been carried out
Get_Measurement_Location_Information	Used to collect information on the location of the spectrum measurement
Get_Signal_Measurement_Value	Used to collect the measured value related to a signal
Get_Channel_Measurement_Value	Used to collect the measured value related to a channel
Get_RAT_ID_Value	Used to collect the measured value related to a detected RAT
Notify	Used by the measurement module for status reporting to IEEE 1900.6 user

Table 4-1: M-SAP related primitives in the IEEE 1900.6 framework

The C-SAP provides the IEEE 1900.6 logical entities the following services, particularly related to communication between entities:

Sensing-related information send service

Provides a set of primitives or methods for sending sensing-related information via the C-SAP.

Sensing-related information receive service

Provides a set of primitives or methods for receiving sensing-related information via the C-SAP.

Information services

Provide a set of primitives or methods to obtain information such as IDs and capabilities of the communication subsystem via the C-SAP.

The associated primitives are summarized in Table 4-2.

Primitive	*Description*
Sensing_Related_Information_Send	Used to send sensing-related information from one IEEE 1900.6 SAP user to another
Sensing_Related_Information_Receive	Used to receive sensing-related information
Get_CommSubsys_Profile	Used to obtain information related to the communication subsystem
Notify	Used to notify the IEEE 1900.6 SAP user of a status change

Table 4-2: C-SAP related primitives in the IEEE 1900.6 framework

The A-SAP provides the IEEE 1900.6 logical entities the following services, particularly related to the control/application:

Sensor discovery service

Provides a set of primitives or methods for discovering available spectrum measurement modules via the A-SAP.

Sensing-related information access service

Provides a set of primitives or methods to access or issue sensing-related information via the A-SAP.

Management and configuration service

Provides a set of primitives or methods to manage IEEE 1900.6 logical entities and configure communication among IEEE 1900.6 logical entities via the A-SAP.

Information services

Provides a set of primitives or methods to obtain information such as IDs and capabilities of IEEE 1900.6 clients via the A-SAP.

The associated primitives are summarized in Table 4-3.

Primitive	*Description*
Get_ Sensor_Logical_ID	Used to obtain the list of sensors identified by their logical IDs
Get_CommSubsys_ID	Used to obtain the list of communication subsystems identified by their IDs
Read_Sensing_Related_Info	Used to read sensing-related information
Write_Sensing_Related_Info	Used to write sensing-related information
Lock	Used to lock IEEE 1900.6 logical entities and communication subsystems preventing access to those resources
Unlock	Used to unlock IEEE 1900.6 logical entities

	and communication subsystems enabling access to those resources
BreakLock	Used to break the lock to enable access to IEEE 1900.6 resources
Trigger	Used to trigger an action
Comm_Manage	Used to manage communications
Get_Client_Profile	Used to obtain information related to IEEE 1900.6 clients
Notify	Used to notify a status change

Table 4-3: A-SAP related primitives in the IEEE 1900.6 framework

In most cases, intuition correctly reveals at least the key purposes of these primitives. However, the reader can refer to the IEEE 1900.6 standard [3], pp. 15-70, if more detail is required.

4.3 Requirements on data structures

The management of the spectrum information within enabling communications architecture requires appropriate data model and corresponding data structures. These are quintessential elements for practical deployments and for delivering worldwide interoperability among different future wireless systems.

4.3.1 IEEE 1900.4 and 1900.6

Regarding both IEEE 1900.4 and IEEE 1900.6, the data structures therein are purposefully designed to be compatible with Abstract Syntax Notation One (ASN.1) [18]. For IEEE 1900.4, the associated requirements were previously covered in this document.

The requirements for IEEE 1900.6 are not explicitly stated, although section 6 of IEEE 1900.6 on its *Information Description* does infer the underlying requirements that have led to that information structuring. Many requirements on data structures are therefore already inherent in the information model details that have been conveyed earlier in this document. Further to this, it is noted that all parameters specified in IEEE 1900.6 broadly follow the data structure given in Table 4-4, i.e. “Name” is the name of the parameter (as specified earlier in Table 2-1), “Phys. Unit” is the type of, e.g., SI unit that would apply, “Extends” indicates whether the parameter extends another parameter (an example is the “Time reference” in IEEE 1900.6, which extends the concept of “second” to be specified in Unix time), “ID” is a unique numerical identifier for the parameter as given in IEEE 1900.6, “Size” is the number of elements in the parameter (e.g., “Tree” will have “Branches” and “Leaves” as elements being size 2 for this example), “Type” is the type of data for the parameter as specified by the IEEE 1900.6 data types, “Desc” is a textural description of the parameter, and the “.X”’s are the elements involved and the types of those elements. This particular example, demonstrating a structured parameter, is useful indicating how data structures are handled in IEEE 1900.6.

Name:	NameIdentifier	Phys. Unit:	e.g., s	Extends:	--
ID:	TBD	Size:	3 (no. of elements)	Type:	Structured

Desc:	This parameter is served X given purpose to achieve Y.		
.0	NameIdentifier.Element1	Type:	E.g., Seconds (1900.6 type)
.1	NameIdentifier.Element2	Type:	Unsigned integer
.2	NameIdentifier.Element3	Type:	Vector(Float)

Table 4-4: IEEE 1900.6 sensing parameters and their uses

4.4 Practical example of a REM-based spectrum management solution

This subsection will elaborate in details a recently developed REM architecture [6]. The architecture closely follows the previously introduced methodology on requirements and showcases the practical feasibility of the REM approach for future, environmentally aware and self-organizing capable wireless systems.

REMs are seen as a fundamental facilitating technology for practical CR networks and DSA solutions, as well as for the optimization of current legacy wireless systems. They represent technology enablers envisioned to be utilized by various network management and optimization entities in order to improve the operation of the underlying technologies. Traditionally denoted as two-dimensional representation of the spatial interference fields, they are now envisioned as rich knowledge bases storing, managing and on-the-fly updating and extending the radio environment knowledge. Specifically, besides the spatial radio information fields, the REMs can comprise information on the location and the configuration of transmitters, receivers and possible dedicated spectrum sensors, the propagation characteristics information etc. Since the radio environment is dynamic in nature, the continuous tracking of the radio network events, such as the radio/obstacles appearance or changes in the propagation conditions, is essential for the proper network operation and optimal resource allocation.

A general and broad REM data model should consider at least the following three types of information, tightly correlated between each other:

- *Information on the present transmitters and the receivers in the area of interest*. This can include information on their locations, capabilities, as well as their current configurations in terms of used frequency, power, bandwidth, employed technology etc. This information can be either pre-known, obtained from the regulator bodies or the operators, or can be dynamically estimated from the spectrum measurements coming from terminals or dedicated spectrum sensors. This information is important since it can assist the decision making process and facilitate a more optimal resource allocation.
- *Information on the underlying propagation environment*. This type of information can refer to statistical propagation models, terrain information, building plans, walls, obstacles etc. Similarly, this type of information can be pre-known or inferred from the spectrum measurements. It is vital for the proper operation in the radio environments, since it relates to the propagation characteristics in regions of interest.

- *Radio Interference Fields (RIFs)* are also an important component of the REM data model. The spatial distribution of the RSS, the SNR, the summary interference and other metrics can help in identifying coverage areas, evaluating the optimality of the conveyed strategies etc. The RIF data can be either empirically derived, using the results of the practical spectrum measurements or statistically modelled using the information regarding the previous two points.

With respect to the required REM data model, a general REM architecture should be able to execute spectrum measurements and perform spectrum data acquisition, spectrum data processing for REM construction and, finally, use the constructed REM data for various spectrum management purposes. Figure 4-3 depicts a generic REM architecture providing these functionalities [6]. Four composite elements are crucial in the REM architecture, i.e. the *Measurement Capable Devices*, the *REM data Storage and Acquisition unit*, the *REM Manager* and the *REM User*.

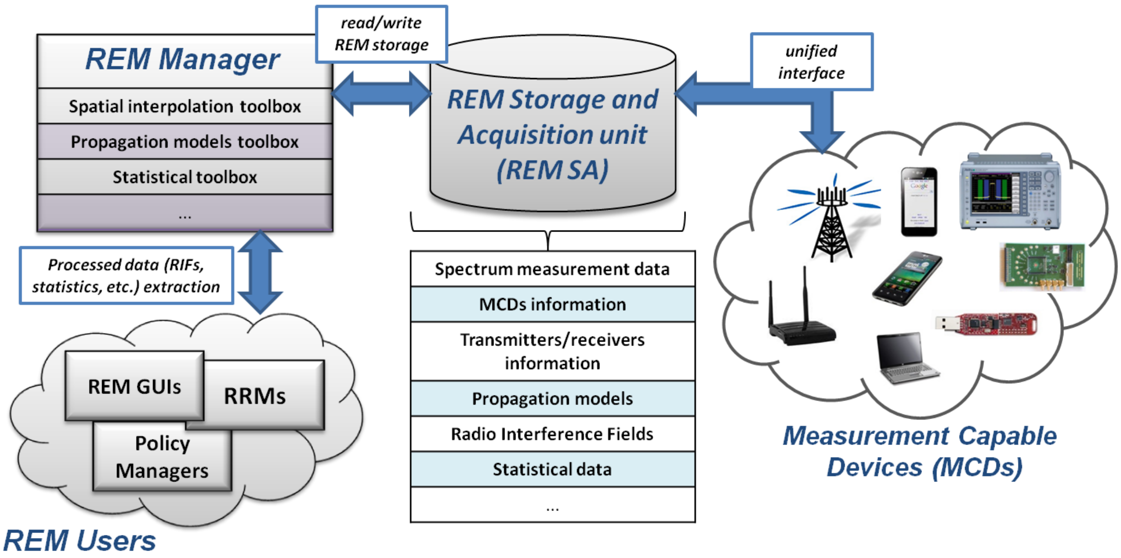


Figure 4-3: A general REM architecture [6]

4.4.1 Measurement capable devices

Any device able to perform spectrum measurements can act as an MCD, i.e. devices such as base stations, terminals or even dedicated spectrum sensors. Therefore, the REM architecture envisions and allows for the usage of the measurement capabilities of different types of legacy or non-legacy measurement devices, i.e. heterogeneous MCDs, which are seamlessly integrated into the REM architecture. The REM architecture takes into account their respective limitations and takes advantage of the MCDs diversity. The MCDs report their measurements to the central REM storage (REM SA) and provide options for remote reconfiguration (and calibration) and measurements querying through a unified interface. Besides the spectrum measurements, the MCDs can also perform signal detection/classification/recognition etc. The MCDs should be equipped with geo-location capabilities, since they should be able to associate the measurements with the location and time of execution.

4.4.2 REM Storage and Acquisition

The REM SA is the storage point of the REM architecture storing all types of REM information explained above. Namely, besides the spectrum measurement data coming from the different types of MCDs, the REM SA should keep REM-relevant information, such as information about the positions and configuration on radio transmitters and receivers, environment characteristics, as well as REM processed data. The REM storage is persistently updated with current radio environment state information to make way for the optimal radio resource management and the optimal operation of wireless networks. The type of REM information, i.e. the REM data model structure, is elaborated in subsection 4.6.

4.4.3 REM Manager

The REM Manager is the functional entity performing the main processing tasks for REM data creation and evaluation. It should be modular comprising various toolboxes, i.e.:

- *RIF toolbox* for the estimation of RIFs in a specific area of interest. The RIFs can be represented as pixel images or using a radial basis function representation. The RIF generation can be performed using various spatial interpolation techniques taking into account the computational complexity and reliability of estimated data.
- *Location estimation toolbox* for the estimation of position and basic configuration (radiated power, operating frequency etc.) of transmitters in the areas of interest. The location estimation can be performed directly using direct estimation methods (least squares, maximum likelihood, Bayesian methods etc.) or indirectly from the RIF estimates.
- *Propagation model toolbox* for the estimation of path loss characteristics in a given area of interest directly (using fitting methods on the spatial measurements) or indirectly from the RIF estimations. The toolbox should be able to incorporate terrain information, building plans etc., into the calculation of the path loss.
- *Service area toolbox* to calculate the service areas of specific transmitters. Based on the RIF estimates, the location information and the propagation model information, the service areas of particular transmitters can be calculated. Similar to the RIFs, the service areas can be represented as pixel images or using a radial basis function representation.
- *Spectrum usage toolbox* to estimate duty cycles, traffic patterns, ON/OFF channel model parameters etc., from the spectrum measurement data. These types of information are essentially important in cognitive radio network scenarios.
- *Radio resource management toolbox* providing basic RRM functionalities. It allocates the frequency/power/bandwidth to the registered communication devices in the REM SA.

4.4.4 REM Users

The REM User is the end user of the REM data. It can perform the frequency/power allocation, manage the spectrum access and usage as well as convey various cognitive network optimizations. There are different possible realizations of a REM User, i.e. a REM Graphical User Interface (GUI) can visualize the REM data, a Radio Resource Manager (RRM) entity can use the REM data to perform network and radio resource optimizations and a

Policy Manager (PM) can derive different types of spectrum access/usage policies based on statistical REM data.

4.4.5 Requirements on interfaces

This subsection discusses the requirements derived from the interfaces within the previously elaborated REM architecture.

4.4.5.1 MCD – REM SA Interface

The MCD – REM SA Interface handles the communication between the heterogeneous MCDs and the central REM SA component. The interface defines several pairs of messages serving for the registration and deregistration of MCDs, measurement/reconfiguration and location querying and feedback.

- `RegisterReq` and `RegisterRsp` messages are used to register a new MCD in the REM SA. The registration message carries the MCD location, network addresses and capabilities in terms of the supported frequency range, bandwidth, measurement modes and detection types. The response message returns the assigned ID to the MCD.
- The `MeasurementReq` and `MeasurementRsp` messages are used to query/return specific measurements from an active MCD. The `MeasurementRsp` message reporting to the REM SA can be either triggered or periodic.
- The `ReconfigureReq` message is used to enforce a reconfiguration of a specified MCD by the REM SA (REM Manager). The `ReconfigureRsp` message returns the status of the reconfiguration (success or failure).
- `LocationReq` and `LocationRsp` are messages used to query/return the location of a registered MCD device in the REM SA.
- The `StopMeasurement` message is used to trigger an active MCD to stop performing spectrum measurements.
- The `DeRegisterReq` message is used by the MCD to de-register from the REM SA.

4.4.5.2 REM SA – REM Manager Interface

The REM SA – REM Manager Interface connects the REM Manager and the REM SA components. It enables the extraction of the raw sensed data required by the REM Manager to perform the processing and calculation of the REM-related parameters. The interface can be realized with standard database read/write operations with respect to the particular REM SA database realization.

4.4.5.3 REM Manager – REM User Interface

The REM Manager – REM User Interface handles the communication between the REM Manager and the different types of REM Users. This interface defines several messages/message pairs divided into two classes: generic REM User messages and Communication Device (CD) messages. The generic REM User messages are used for the interactions related to the extraction of generic REM data, while the CD messages are focused on the interactions related to the REM facilitated RRM functionalities.

Generic REM User messages

- The `ActiveMcdsReq` and `ActiveMcdsRsp` messages are used by the REM User and the REM Manager to query/return the information about the active MCDs and their settings.
- The `RemReq` and `RemRsp` messages are used to query/return the RIF field estimation by the REM Manager. The spatial RIF field for a specific frequency band can be returned as a matrix representing the interpolated values at the grid points in the region of interest.
- `TransmitterReq` and `TransmitterRsp` are messages used to query/return the information about the active transmitters in the inspected area. `TransmitterRsp` returns the estimated transmitters locations coupled with other transmitters' information (e.g. power and frequency band of operation).
- `DutyCycleReq` and `DutyCycleRsp` are the messages used to query/return duty cycle results of the spectrum activity from a specific MCD, on a specified frequency band and time period using a specified threshold.
- The `AvgPowerReq` and `AvgPowerRsp` messages are used to query/return the average received power per MCD in a specified frequency band.
- The `OldRemReq` and `OldRemRsp` messages have the same meaning as `RemReq` and `RemRsp` messages, but they used to query/return an estimated historical RIF field in a specified time period.
- `AddStatReq` and `AddStatRsp` are messages used to query/return additional statistics such as empirical PDF or CDF of the received power for specific MCD in specified frequency band and time periods.
- `PropagationModelReq` and `PropagationModelRsp` are messages used to query/return estimated propagation model parameters from the REM Manager.
- The `FSDreq` and `FSDrsp` are messages used to query/return a measurement sweep from a specified observation point in a specified frequency band.
- The `TriggerReq`, `TriggerRsp`, `TriggerEvent` and `TriggerStop` are messages used to register, fire and stop the triggering of a specific event. An event can correspond to specific metric (RSS, SINR) surpassing a specified threshold at a given location.

Communication Device related messages

- The `CommDeviceRegReq` and `CommDeviceRegRsp` messages are used to register a new communication device in the REM Manager (REM SA). The registration message carries the device location, network address, and capabilities in terms of the supported transmit power, frequency range and bandwidth. The response message returns the assigned ID to the new/updated communication device.
- The `CommDeviceConfRsp` is the message used to enforce a specific configuration (transmit power, frequency, bandwidth of operation) to an active communication device.
- The `CommDeviceLocReq` and `CommDeviceLocRsp` messages are used to query/return the location of an active communication device.
- The `CommDeviceDeRegReq` message is used by the communication device to deregister from the REM Manager (REM SA).

- The `ActiveCommDevicesReq` and `ActiveCommDevicesRsp` are the messages used to query/return the active communication devices registered in the REM SA. The device operating parameters and current status are returned in a structured format.
- The `CommunicationReq` message is used to trigger the communication establishment between two registered devices. This message prompts the REM Manager to perform the RRM functions to allocate frequency, power and bandwidth to the querying pair.
- `CommunicationStopReq` is a message used to break an ongoing communication between two active communication devices.
- The `CommDeviceStatusRep` message is used by the communication device to report the current status (idle, transmitting, receiving) and operating parameters to the REM Manager (REM SA).

4.4.6 Requirements on data structures

The REM data model consists of several categories of REM information. The different categories are mapped to different database tables and structures, which are stored and updated in the REM SA unit. The REM SA currently supports:

- *Transmitter information*: relates to the information of the registered/estimated transmitters. The transmitter information can comprise the transmitter type, location and configuration in terms of transmit power, operating frequency and bandwidth etc. The transmitters can be associated with their service (coverage) area (in terms of RSS, SINR distribution).
- *RIF information*: refers to the radio interference fields data. The RIFs can be represented using a pixel image or radial basis function representation, while the metric of interest can be the RSS, the SNR, SINR or even the available bitrate. The RIFs are associated with the location, the frequency and the time of estimation.
- *MCD information*: refers to the information of the registered MCD devices in the REM SA. The MCD information can comprise the MCD capabilities in terms of supported detection types and methods, the supported frequency and time resolutions for spectrum measurements. The REM SA constantly keeps track on the current MCD configuration and location.
- *Spectrum data information*: refers to the raw spectrum measurement data collected from the different MCDs in the network. The spectrum measurements are associated with the MCD, the time, frequency and location of the measurement execution.
- *Propagation information*: relates to the information on the path loss characteristics of the radio environment. Can be represented using different propagation model function types. The estimated model parameters are associated with the model type, the location, frequency and time of estimation.
- *Spectrum usage information*: refers to the information of the spectrum activity. It can be represented with duty cycles of the spectrum activity, received signal distribution from different transmitters at a given point of interest, ON/OFF activity patterns etc. The spectrum usage data is associated with the respective time, frequency and location of gathering/estimation.

4.5 Summary

The practical deployment of spectrum information management architecture requires several key issues to be addressed. This section focused on the requirements and the actual design of the architectural blocks, interfaces and data structures. Additionally, the section introduced a recently developed REM architecture capable of satisfying all introduced requirements on all architectural entities. The design of the architecture itself should allow all stakeholders to efficiently co-exist and benefit in a practical DSA or CR scenario.

5. Conclusions

The management of spectrum information is becoming increasingly important topic from a regulatory, industry and academia point of view. It stems from the ubiquitous popularity of wireless devices and systems leading to a need for more optimized usage of the available spectrum resources.

The latest developments in wireless communications point in the direction of environmentally aware and self-optimizing based wireless technologies that will inevitably need reliable management systems. Additionally, as the problem of spectrum scarcity becomes more evident, these management systems must encompass all aspects related to reliable and flexible spectrum management. In terms of DSA and CR, this effectively means that the spectrum management of future wireless systems must be able to unequivocally protect the PUs, while at the same time be able to exhibit scalability and high QoS for the SUs.

Several key areas accompany the design of an appropriate spectrum information management system. First, there is a need for unambiguous spectrum information representation syntax as this would guarantee clear and distinct radio environment information for all players. Moreover, the level of details in the spectrum information representation directly influences the fidelity of the spectrum management solution in general. Then, the design should also consider the confines of the underlying technology and be able to transparently and smoothly integrate within regardless of the imposed limitations. This means that the spectrum management should operate in various environments (e.g. centralized and decentralized, cooperative and non-cooperative etc.). Lastly, the spectrum management solution must be technically feasible and, in this sense, practically deployable. The latest advances in the area pinpoint the REM concept as a powerful enabler and facilitator of a viable spectrum management for increased radio environmental awareness.

This document addressed the previously mentioned key areas of the design of an appropriate spectrum information management system. It focused both on standardization efforts as well as latest research achievements in order to provide a comprehensive overview of the tackled problem.

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Glossary and Definitions

Acronym	Meaning
A-SAP	Application-Service Access Point
AEM	Autonomic Entity Management
AOA	Angle Of Arrival
B3G	Beyond 3G
BER	Bit Error Rate
BS	Base Station
C-SAP	Communication- Service Access Point
CCR	Cognitive Control Radio
CD	Communication Device
CE	Cognitive Engine
CPC	Cognitive Pilot Channel
CR	Cognitive Radio
CWN	Cognitive Wireless Network
DA	Data Archive
DSA	Dynamic Spectrum Access
DSM	Dynamic Spectrum Management
DSNPM	Dynamic, Self-organising Network Planning and Management
E3	End-to-End Efficiency
ECA	Event-Condition-Action
FA	Functional Architecture
GUI	Graphical User Interface
ID	IDentifier
IEEE	Institute of Electrical and Electronics Engineers
JRRM	Joint Radio Resource Management
M-SAP	Measurement- Service Access Point
MAC	Medium Access Control
MCD	Measurement Capable Device
MT	Mobile Terminal
NRM	Network Reconfiguration Manager
OSM	Operator Spectrum Manager
PM	Policy Manager
PU	Primary User
QoS	Quality-of-Service
RAC	Resource Awareness Channel

RAN	Radio Access Network
RAT	Radio Access Technology
RCM	Reconfiguration Control Module
RE	Radio Enabler
REA	Radio Environmental Awareness
REM	Radio Environmental Map
REM SA	REM Storage and Acquisition
RIF	Radio Interference Field
RMC	RAN Measurement Controller
RRC	RAN Reconfiguration Controller
RRM	Radio Resource Manager
RSS	Received Signal Strength
S	Sensor
SAP	Service Access Point
Self-x for RAN	Self-x for Radio Access Network
SI	Système International d'unités
SINR	Signal-to-Interference-plus-Noise Ratio
SNR	Signal-to-Noise Ratio
SS	Spectrum Sensing
SU	Secondary User
TDOA	Time Difference Of Arrival
TMC	Terminal Measurement Controller
TOA	Time Of Arrival
TRC	Terminal Reconfiguration Controller
TRM	Terminal Reconfiguration Manager
UML	Unified Markup Language