Flexible Architecture for Spectrum and Resource Management in the Whitespace

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Abstract— **Spectrum resources unused in the spatio-temporal domain, so-called whitespace, can be utilised by opportunistic devices during the absence of their incumbent users. The possibility to opportunistically use whitespace implies the knowledge of diverse constraints: knowledge about whitespace utilisation, which can be obtained by spectrum sensing or from a data repository and constraints internal to the opportunistic system, such as quality of service (QoS) levels and mobility targets. The use of whitespace requires therefore a multi-faced management of the above constraints. In this paper, an architecture for use of whitespaces under QoS and mobility constraints is proposed. The proposed architecture flexibly adapts to different operating scenarios also described in this paper. Examples show how different realisations of the same architecture are derived. The interactions of constituent blocks are illustrated also with the help of charts, showing the management of context information and its use.**

Keywords- Cognitive radio system, Flexible design, Heterogeneous networks, Incumbent user protection, Mobility, Opportunistic spectrum use, Quality of service, Radio resource management, Radio spectrum coexistence, Reference model, Spectrum management, System architecture, Topologies, Whitespace.

I. INTRODUCTION

Radio spectrum resources statically assigned for exclusive use have not always and everywhere been actually exploited by the assignee. Those spectrum resources unused in the spatio-temporal domain, so-called whitespace, can be utilised by opportunistic devices during the absence of their incumbent users. This opportunity must not harm the operations of the incumbent user, when it is present.

Therefore, the possibility to opportunistically use whitespace implies the awareness of diverse constraints: knowledge about whitespace utilisation, which can be obtained by spectrum sensing or from a data repository; and constraints internal to the opportunistic system, such as QoS levels and mobility targets. It is now clear that the use of whitespace requires a multi-faced management of the above constraints.

Among a number of challenges faced in opportunistic use of whitespace, one of the most demanding is the management of spectrum resources, considering upcoming technologies able to provide efficient dynamic access to (fragmented) shared, licensed and licence-exempt frequency spectrum, and changes of regulatory paradigms responding to the potentials of this new technology. Hence, spectrum resource management must consider both the traditional radio resource management in a highly sophisticated technological environment as well as the (potential) real-time management of spectrum usage rights in a regulatory and business environment.

The proposed reference model (described in Sect. II and put into its framework in terms of domains in Sect. III) addresses this by splitting responsibilities between a resource manager and a spectrum manager entity, both employing cognitive methods to optimise spectrum resource utilisation within their specific objective. The proposed model is also able to adapt this concept to different operating scenarios (Sect. II), as illustrated by the mapping to example topologies (Sect. IV).

II. REFERENCE MODEL

A fundamental design goal for the proposed system architecture is to be flexible enough to be adaptable to a wide range of application scenarios. It is worth clarifying that the system as the set of functional blocks is targeted to be flexible, while a specific realisation of such a system will obviously have a more limited scope.

A set of application scenarios were defined in [1] [2]. *Rural broadband*: wireless connectivity to rural locations through a base station. *Dynamic backhaul* (including emergency): wireless backhaul connections from access networks and remote terminals to a core network. Backhaul is possibly made of several point-to-point links. *Cellular extension in whitespace*: mobile networks utilising whitespace in addition to their own licensed spectrum. *Cognitive ad hoc network* (including emergency): network possibly having one or more nodes with access to the Internet via other networks. *Direct terminal-to-terminal in cellular*: communication in an infrastructure-based network with mobile terminals communicating directly without traffic going through the base stations. *Cognitive femtocell*: femtocells (always connected to an infrastructure) can be small base stations connected to a cellular core network via a fixed infrastructure or Wi-Fi type access points, providing both indoor and outdoor coverage, e.g., in urban/suburban streets.

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As outlined in the introduction, the opportunistic use of whitespace sets challenges from different perspectives. Moreover, the target is a flexible functional architecture able to cover diverse scenarios. To comply with such multi-faced requirements [3], several functional blocks have been defined and their relations captured in a reference model. The proposed reference model consists of the main functional blocks depicted in Figure 1.

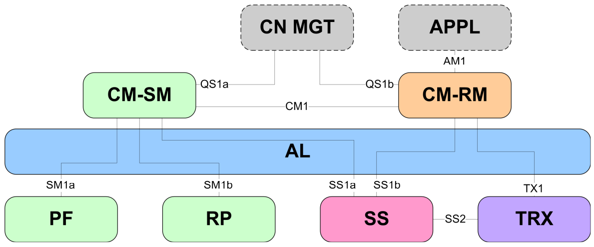

Figure 1. The proposed reference model.

The cognitive manager for spectrum management (CM-SM) is responsible for the management of the information concerning the use of the whitespaces and represented by the spectrum portfolio, discussed in more detail in Sect. V. In particular, the spectrum portfolio includes the constraints set by the regulator and other possible policies. This block manages the information supported by the common portfolio repository (PF) and the regulations and policies repositories (RP) and provides it to the cognitive manager for resource management (CM-RM) block described here below. For the reasons that will be explained in Sects. III and IV, the CM-SM functionalities are split into a portion dedicated to access the repositories (CM-SM REP), the localised version of the relevant context (CM-SM LOC) and the macro-block in charge of selection or spectrum portions and related functionalities (CM-SM SEL).

The CM-RM is responsible for the resource control and its usage and is also correspondingly split into CM-RM RC and CM-RM RU macro-blocks [4]. The CM-RM decides on the operating parameters of network devices, based on QoS and mobility constraints and according to the spectral environment defined by the spectrum portfolio. The CM-RM also ensures the protection of incumbent users by controlling the spectrum sensing to be done in the operating channels [5] in order to be able to timely vacate the operating channel upon an incumbent appearance. The CM-RM therefore identifies reserve or back-up channels needed to maintain QoS of the opportunistic users. Finally, the CM-RM provides the CM-SM with usage and performance reports. CM-SM and its interaction with CM-RM will be further discussed in Sect. V.

The spectrum sensing (SS) block has the responsibility of controlling the spectrum sensing process. The sensing can be done either locally at a node or in a distributed way. The selection of the the most appropriate sensing technique and of the sensing parameters (sensing time, order of the channels to be sensed, etc.) is done with the objective to comply with detection requirements and to minimise the load on the system. The SS can be split into a macro-block in charge of controlling the spectrum sensor (CTL) and another in charge of the management of the sensing process, including the related decisions on spectrum occupation (MGT).

The frequency agile transceiver (TRX) block includes the baseband processing for data transmission and the modules used to perform the sensing tasks requested by the SS.

The adaptation layer (AL) is responsible for abstracting the heterogeneity of radio access technologies (RATs) and to facilitate the communication between remote entities. The AL will be discussed in more detail in Sect. VI.

Figure 1 shows the interfaces to external entities namely the user application (APPL), which expresses its QoS requirements to the CM-RM and whose transmissions are managed by the CM-RM, and the core network management (CN MGT), present only in scenarios in which a core network (CN) exists, allows integrating the proposed system into an operator's CN.

Key procedures for a system opportunistically operating in whitespaces under QoS and mobility constraints include spectrum portfolio management, resource management, transceiver measurement reporting and spectrum sensing as well as incumbent user protection, base station and terminal reconfiguration. Some of these procedures, showing the interaction between the functional blocks constituting the reference model, are presented in the following sections.

III. THE COGNITIVE AND TOPOLOGICAL DOMAINS

One of the peculiarities of the proposed architecture is the distinction of cognitive functions under two cognitive domains, the resource management (RM) and the spectrum management (SM) domains. Moreover, four topological domains are identified in correspondence with the relevant network entities. The *terminal domain* covers entities at the wireless border, therefore user equipment (UE) and base station (BS) (in a centralised, e.g., cellular case), or mobile terminal (MT), with gateway (GW) (in distributed, e.g., ad hoc network case). The *networking domain* corresponds to the control of devices belonging to a network, i.e., the cell or network, respectively. The *coordination domain* is the place where the coordination of neighbouring and related networks takes place and. It corresponds to the CN in a centralised example. More generally, it is present in hierarchical networks, but in a flat, distributed network its role may be limited. The *coexistence domain* includes the entities responsible for larger-scale coexistence. Specifically, this concerns the common portfolio and the regulatory and policies repositories. Issues concerning the coexistence domain will be discussed in Sect. VII.

The proposed reference model described in this paper shares some similarities with the architectures of some current and upcoming standards, the most relevant being the ones originating from the Reconfigurable Radio Systems technical committee of the European Telecommunications Standards Institute (ETSI RRS) [6] [7] and the IEEE P1900.4 architecture specified under the Standards Coordinating Committee 41 (SCC41) [9] [10]. Also related is IEEE 802.19.1 proposal within IEEE 802 wireless coexistence working group.

Figure 2 illustrates a comparison of the scopes of the functional blocks of the proposed model with the aforementioned proposals. There is no exact correspondence of CM-RM and CM-SM scopes, although roughly CM-RM corresponds to configuration control module (CCM) plus joint radio resource management (JRRM) of ETSI RRS and correspondingly to terminal reconfiguration manager, reconfiguration controller and measurement collector (TRM, TRC and TMC) and its network and radio access network (RAN) counterparts (NRM, RRC and RMC) of IEEE P1900.4, or coexistence enabler (CE) of IEEE802.19.1. Also, services and functionalities provided by the CM-SM approximately map dynamic spectrum management (DSM) plus dynamic self-organising network planning and management (DSONPM) of ETSI RRS, and operator spectrum manager (OSM) of IEEE P1900.4, or coexistence discovery and information server (CDIS) of IEEE802.19.1, with coexistence manager (CM) across both CM-RM and CM-SM. The IEEE P1900.4a for whitespace operation [10] includes a cognitive base station RM, CBSRM (with CBSRC and CBSMC) and a whitespace manager (WSM), equivalent to NRM and OSM, respectively, of IEEE P1900.4, but tailored for whitespace operation. Figure 2 reports also the corresponding topological domains. The topology mapping for ETSI RRS is for 3GPP LTE [6].

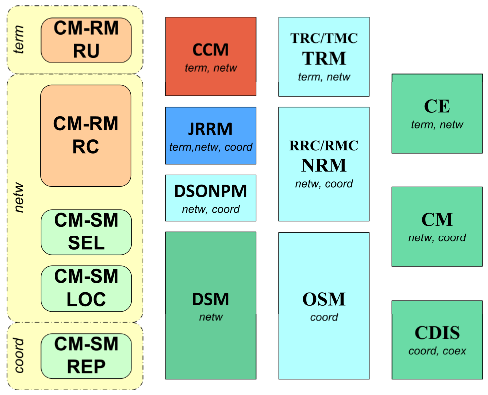

Figure 2. Comparison of scopes of functional blocks of proposed architecture with, from left to right, ETSI RRS, IEEE P1900.4, and 802.19.1.

ETSI RRS and IEEE P1900.4 architectures have been specified with in mind primarily specific applications. The former mainly targeted to centrally controlled systems [6] [7] [8] (although within its scope fall also emergency and defence systems [7] [8]), whereas the latter envisages partial distributed control [9]. This is reflected by the fact that the blocks of those architectures either act at both terminal and network side (as with JRRM and CCM of ETSI RRS [6] [8]), or although assigned to a specific network device, the associated functionalities actually belong to more topological domains (e.g., the TRM of IEEE P1900.4 covering both terminal and networking [9] domain as defined here).

One target of the proposed functional architecture, achieved through its organisation over the previously defined topological domains, is to allow a clean mapping of the same architecture onto different topologies. This is illustrated in the following Sect. IV for two example, but relevant, topologies.

IV. Topology Mapping

The proposed reference model is intended to address the needs of a wide range of scenarios (see Sect. II). Depending on the scenario, the functionalities of a block are properly assigned to the different network nodes (mobile terminal, base station, gateway, etc.), possibly limiting its scope to match the scenario. For the sake of simplicity, the possible scenarios listed in Sect. II are abstracted in this section including only the most relevant characteristics. In particular, they will have either a centralised or a distributed resource control.

To illustrate how all the entities of the proposed reference model map to different topologies, two examples, depicted in Figures 3 and 4, are considered: a) centralised resource control with centralised collaborative or cooperative spectrum sensing (which could represent a cellular scenario); b) distributed resource control with local spectrum sensing (possibly corresponding to an ad hoc network).

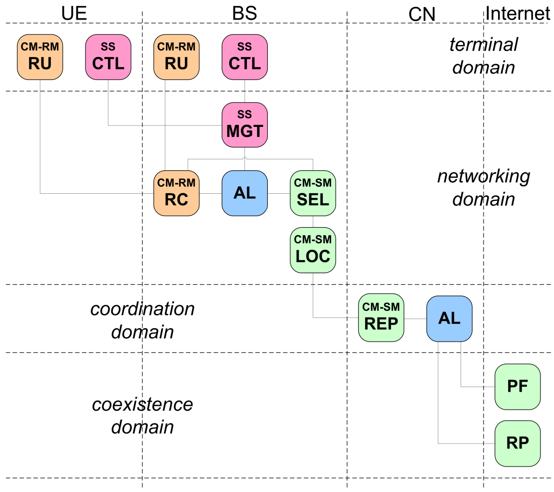

Figure 3. Centralised resource control with centralised sensing.

In the first example case represented in Figure 3, the resource allocation is centrally controlled. Therefore, the resource control block (RC) is located at the BS. The CM-RM at the BS needs to interface the CM-SM (for example to get the spectrum portfolio). The inputs to build the portfolio, such as regulations, policies, etc., are gathered at the CN, for example from the Internet, through an AL at coordination domain that enables technology-agnostic access to those structures (see Sect. VII). In Figure 3, the spectrum sensing is centralised and uses inputs coming from scattered sensors, for example the UEs. The spectrum sensors (in the terminal domain) provide their measurements to the SS management block (SS MGT in the network domain), which also performs data fusion and generates the sensing decision at the BS. The sensing decision is then delivered to all the involved CM-RM entities. These operating spectrum sensing results may be exploited also for portfolio updates. Therefore, the AL at networking domain may dispatch those results also to the CM-SM (see Sect. VII).

In the second example case, depicted in Figure 4, the resource control is distributed and is done at all the peer devices, all having a CM-RM RC block at networking domain. This implies that they all need to interface the core CM-SM, through the entities at the network domain. However, not necessarily all peers have access to the information needed to manage the portfolio, which is located also in this example in the Internet. Indeed, it may be not efficient to have all peers acting as gateway, but some controlled duplication may be beneficial for robustness. Therefore, one or more network devices are elected as the gateway for the CM-SM information, supported by the LOC and REP entities. Those GW devices have therefore also the core CM-SM (portfolio deployment, see Sect. V), residing again in the coordination domain.

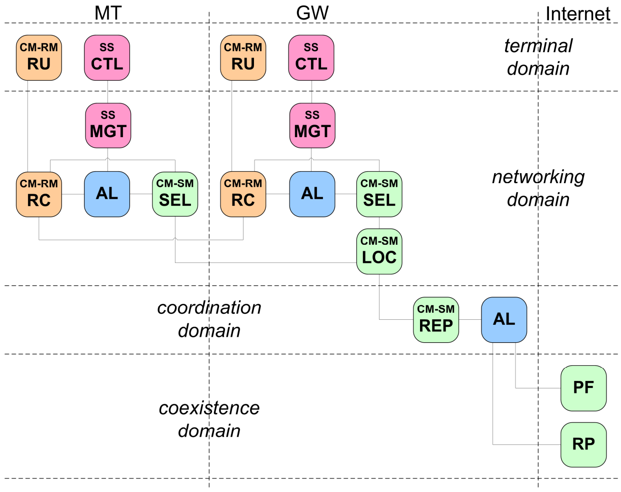

Figure 4. Distributed resource control with local sensing.

V. INTERACTION BETWEEN COGNITIVE DOMAINS

The interaction between the CM-RM and the CM-SM is described by the exchange of spectrum portfolios, with the CM-RM requesting a portfolio to satisfy service demands and the CM-SM responding by providing a portfolio satisfying also other constraints such as regulatory, or due to location. A spectrum portfolio is considered a descriptive data structure, a set of frequency spectrum blocks and, if applicable, additional information, such as usage policies, key quality indicators, etc. The basic information flow is shown in Figure 5.

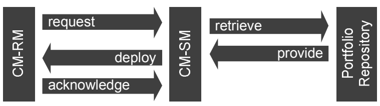

Figure 5. CM-RM requesting a spectrum portfolio.

In order to deploy (create/modify and distribute) a spectrum portfolio, the CM-SM is assisted by the portfolio repository, keeping track on spectrum already deployed or still available. The most straightforward realisation of a spectrum repository is in a database, but may also interface with geolocation databases or distributed spectrum sensing infrastructures. Clearly, the initial set of spectrum portfolios in this process must have been handed to the CM-SM in an allotment, auction or (potentially real-time) spectrum trading or sharing process. Here, it can be safely assumed that frequency spectrum blocks and related policies are provided by a regulatory authority.

The CM-SM is considered as a distributed entity where instances can be associated with stakeholders such as regulatory authority, spectrum provider (or otherwise the temporary owner of spectrum usage rights), operator (or otherwise the distributor and user of spectrum usage rights) for example. All changes to a deployed portfolio requested by a CM-RM may need to propagate through the various stakeholders' domains until, for example, a CM-RM's request for an increased amount of spectrum can be satisfied. Figure 6 outlines this example summarising the information flow as initiated by the sensor indicating detection of an incumbent (see also [4]). After instructing the transceiver to evade from frequency bands affected by the incumbent, the CM-RM requests a new or extended portfolio, potentially causing the CM-SM in the operator's domain to request in turn an extension to its portfolios in use from a spectrum provider, if it is not in a position to satisfy the CM-RM's request. After receiving new spectrum from the CM-SM in the spectrum provider's domain, the operator's CM-SM deploys a new or updated portfolio and revokes the earlier deployed portfolio.

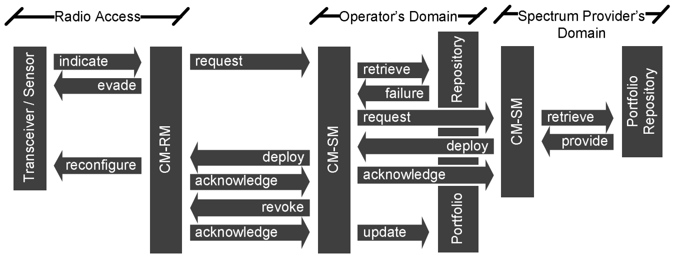

Figure 6. CM-RM requesting a change of the spectrum portfolio deployed in reaction of incumbent detection.

In extension to the information flow depicted by Figure 6, the operator's CM-SM may decide to forward information upon incumbent activity, along with measurement reports, across stakeholders' domains, potentially up to the regulatory authority, enabling the optimisation of spectrum utilisation through future spectrum assignment procedures.

In an ad hoc network scenario, the above domains collapses and the node serving as CM-SM (see Figure 4) may be for example selected as those having the most recent information about spectrum portfolios obtained from other stakeholders.

VI. TRANSCEIVER RECONFIGURATION

A cognitive radio system operating in whitespace requires the ability to dynamically react, e.g., due to incumbent user detection (see Sect. V). As a consequence, an opportunistic device may have to configure its transceiver subsystem to meet the spectral needs and constraints. For an example cellular scenario, the message sequence chart presented in Figure 7 depicts the message flow between entities involved in the reconfiguration of a base station.

Different external and internal causes can trigger the reconfiguration process. An external trigger can be a policy enforcement (spectrum portfolio update) initiated by the CM-SM at CN side. An internal trigger can be an indication message from the own transceiver with new link measurements, or spectrum sensing measurements. The controlling CM-RM analyses the measurements and is able to make a decision about reconfiguration. An important step, before reconfiguration is to inform all affected terminals MTs about the upcoming action.

Contextually with the reconfiguration, the CM-RM informs relevant entities (e.g., a CN-MGT) about the new configuration and also indicates to the CM-SM the new used spectrum, which marks the spectrum as currently used and distributes this information, if necessary, to other network entities (Sect. V).

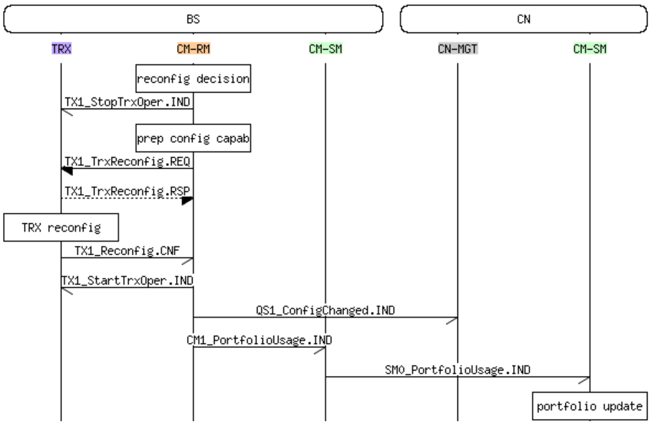

Figure 7. Base station reconfiguration.

VII. COGNITIVE INFORMATION DELIVERY

As seen (Sect. V), the spectrum portfolio is built up with inputs coming from regulations and other policies together with the information about the actual use of the relevant spectrum portions. This information, belonging to the coexistence domain (see Sects. III and IV), should be made available to any possible opportunistic player using the same whitespace. For example, this might be the case of interoperation between a cellular operator and an ad hoc network. More generally, the heterogeneity of the different communication technologies involved in the exchange of whitespace information poses a challenge related to the data management and representation that requires a level of abstraction and an agnostic way of communication between all the involved network entities.

An enabler of the aforementioned capabilities is the AL, defined to ease the exchange of information and commands between functional entities involved in the opportunistic spectrum management process. The AL is used both locally in a node, converting RAT-specific parameters and measurements, and for the communication between remote entities, abstracting the heterogeneity of RATs when necessary. This is needed especially in case of coexistence of different RATs, as seen above about the spectrum portfolio. The AL provides an agnostic interface to the cognitive management entities CM-RM/CM-SM, in a similar way as the one introduced by IEEE 802.21 standard [12]. In addition, the AL enables the collection of RAT-specific information (e.g. load levels, signal to noise ratio (SNR) limits, received signal strength indications, (RSSI), etc.) through medium specific interfaces, its conversion and analysis.

Besides the abstraction capabilities, the AL presents other functionalities that are needed both in multi-RAT and single-RAT scenarios, such as data dispatcher capabilities and event subscriptions support. The AL receives and manages information from different functional blocks, dispatching primitives, both at local and at remote level, to their final destination and helping to avoid duplicity of paths. An example at local level is the management of sensing measurements from the SS, possibly dispatched to CM-RM, CM-SM or both of them, depending on the case addressed (see Sect. IV), but the AL is also involved as a dispatcher in communications at remote level of sensing measurements QoS reports, etc.

All the features previously presented and associated with the AL are supported by the definition of a common data model that describes clearly the information exchanged between the different blocks of the QoSMOS system.

VIII. SUMMARY

This paper proposed a functional architecture for a system using opportunistically in the spatio-temporal domain the spectrum resources left unused by their incumbent users, i.e., the whitespace. The functional blocks have been divided into two cognitive domains and mapped onto four topological domains, corresponding to the roles of communication network entities, also showing the flexibility of the architecture to adapt to diverse target scenarios. The interaction of the aforementioned cognitive domains has been illustrated and the consequent reconfiguration needed in network devices has been presented. The exchange of cognitive information, also among coexisting opportunistic players, has been presented.

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