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ETSI Reconfigurable Radio Systems – Status and Future Directions on Software Defined Radio and Cognitive Radio Standards

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Abstract— **This paper details the current work status of the ETSI Reconfigurable Radio Systems (RRS) Technical Committee (TC), positions the ETSI work with respect to other standards efforts (IEEE 802, IEEE SCC41) as well as the European Regulatory Framework and gives an outlook on the future evolution. In particular, Software Defined Radio (SDR) related study results are presented with a focus on SDR architectures for Mobile Devices (MD), such as mobile phones, etc. For MDs, a novel architecture and inherent interfaces are presented enabling the usage of SDR principles in a mass market context. Cognitive Radio (CR) principles within ETSI RRS are concentrated on two topics, a Cognitive Pilot Channel (CPC) proposal and a Functional Architecture (FA) for Management and Control of Reconfigurable Radio Systems, including Dynamic Self-Organising Planning and Management, Dynamic Spectrum Management, Joint Radio Resource Management, etc. Finally, study results are indicated which are targeting a SDR/CR security framework.**

Index Terms—**Cognitive Radio, Software Defined Radio**

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I. INTRODUCTION

Cognitive Radio (CR) has first been identified as a preferred technology for high-end applications in the military and public safety domain, since the general CR concept had emerged [1]. Then, CR research was also oriented towards the needs of civil wide area (cellular) and short-range communication systems, as for example demonstrated by early prototypes of institutions such as the Communications Research Center of Canada, the Shared Spectrum Company, etc. In Europe, a series of related collaborative research programs were set up including IST-E^{2}R I and II, ICT-E^3 [2], etc. Early civil CR research was mainly motivated by ensuring an efficient operation of license exempt equipment in the 5 GHz bands; finally, those studies opened the doors for further investigations in lower frequency bands. The involved industrial, regulatory and academic partners were attracted to CR by the prospect of a hugely increased level of spectral efficiency and an improved overall system capacity exploitation, among others, thanks to i) the dual exploitation of spectrum by applying opportunistic spectrum usage, ii) a Mobile Device (MD) being (partially/fully) aware of its (heterogeneous) context (radio context, application context, etc.) and dynamically adapting its parameters such that its operational objectives are reached in an optimum way; e.g., a MD is aware of surrounding Radio Access Technologies (RATs) and selects those which guarantee to fulfill its Quality of Service (QoS) requirements at the lowest cost (in terms of subscription cost, power consumption, etc.). Software Defined Radio (SDR), on the other hand, is considered to be an "enabling technology" introducing the required level of flexibility in order to "enable" a device to adapt to its context.

Following CR related rulemaking by the Federal Communications Commission (FCC) [3], several CR standards are currently under development, mainly within the IEEE and ETSI framework. One of the first IEEE Working Groups (WG) to consider CR technology was IEEE 802.22, created in 2004 and developing a standard for Wireless Regional Area Networks (WRAN) using White Spaces in the TV frequency spectrum. Another relevant standard is ECMA-392, published in 2009, which specifies a Medium Access Control (MAC) sub-layer and a Physical (PHY) layer for personal/portable cognitive wireless networks operating in TV bands. Most recently, a new CR boom set in and several novel groups were created end of 2009: i) IEEE 802.11af defines modifications to both the 802.11 physical layers (PHY) and the 802.11 Medium Access Control Layer (MAC), to meet the legal requirements for channel access and coexistence in the TV White Space. It is expected that this work will build on IEEE 802.11y results, where an inherent key issue was addressed and resolved in a different context: the *Dependent Station Enablement* (DSE) mechanism defines how an operator extends and retracts permission to devices to use licensed radio spectrum; ii) IEEE 802.19, on the other hand, works towards enabling the family of IEEE 802 Wireless Standards to most effectively use TV White Space by providing standard coexistence methods. Furthermore, IEEE SCC41 is developing standards related to dynamic spectrum access networks with a focus on improved spectrum usage. In this framework, the IEEE standard 1900.4-2009 defines a management system supporting network-terminal distributed optimization of radio resource usage and improvement in QoS in heterogeneous wireless networks. Further standards are currently in preparation within IEEE SCC41, including P1900.4a for enabling mobile wireless access service in white space frequency bands without any limitation on used radio interface.

The ETSI Reconfigurable Radio Systems (RRS) Technical Committee (TC), on the other hand, is performing work that is complementary to the IEEE SCC41 and IEEE 802 activities, with a focus on the following: i) SDR standards beyond the IEEE scope, ii) CR/SDR standards addressing the specific needs of the European Regulatory Framework and iii) CR/SDR TV White Space standards adapted to the digital TV signal characteristics in Europe. Further details are given in the sequel of the paper: Section II gives a general overview on ETSI RRS and comments on the European Regulatory Framework, Section III gives a general overview on the ETSI RRS concept and vision; Section IV details CR aspects focusing in particular on a Cognitive Pilot Channel (CPC) and a Functional Architecture (FA) for Management and Control of Reconfigurable Radio Systems. Section V presents the SDR related study results, currently focusing on an MD SDR architecture and related interfaces. Section VI highlights security issues addressed in the ETSI RRS framework, while Section VII gives an outlook on future topics based on current progress in academic research and a conclusion.

II. ETSI RRS – OVERVIEW AND ROLE IN THE EUROPEAN REGULATORY FRAMEWORK

At the inaugural meeting, the ETSI RRS TC created the following four Working Groups (WGs), in which the technical discussions are organized and reports are produced (see Fig. 1):

i) **WG1** focuses on "**System Aspects**" and develops proposals from a system aspects point of view for a common framework in TC RRS with the aim to guarantee coherence among the different TC RRS WGs and to avoid overlapping and gaps between related activities;

ii) **WG2** focuses on SDR technology with a particular interest in "**Radio Equipment Architecture**" and proposes common reference architectures for SDR/CR radio equipments (mobile handset devices, radio base stations, etc.), related interfaces, etc.

iii) **WG3** focuses on "**Cognitive Management and Control**"; the group collects and defines the system functionalities for Reconfigurable Radio Systems which are related to the Spectrum Management and Joint Radio Resource Management across heterogeneous access technologies. Furthermore, the group has developed a Functional Architecture for the Management and Control for Reconfigurable Radio Systems as well as a report on the Cognitive Pilot Channel as an enabler to support the management of the RRS;

iv) **WG4** focuses on "**Public Safety**" and collects and defines the related RRS requirements from relevant stakeholders in the Public Safety and Defense domain. The group defines the system aspects for the applications of RRS in Public Safety and Defense.
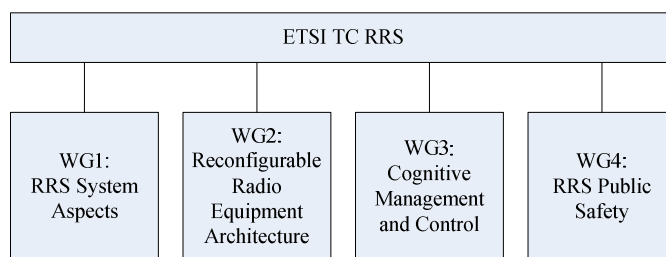

Figure 1: ETSI RRS Structure.

Building on this structure, ETSI RRS will complement ongoing effort in other bodies, such as IEEE standardization bodies, by proposing technological solutions beyond the existing scope (related to SDR interfaces, CR specific Management and Control architectures and interfaces, knowledge management via a Cognitive Pilot Channel and Security solutions); furthermore, ETSI RRS fulfills a key role in the framework of European Regulation, with a focus, among other aspects, on the following:

i) The R&TTE Directive regime in force in Europe is based on declaration of conformity and does include

neither type approval nor registration of the equipment nor equipment identifier (in the US, type approval is still necessary). This self-declaration is preferably a reference to a Harmonised Standard to be developed by ETSI RRS;

ii) Protection of TV bands: In Europe, DVB-T does not show a residual carrier as it is the case in the US (the possibility for detection of the US ATSC signal below noise (i.e., at -114 dBm) is made possible thanks to the residual carrier which is present in the ATSC signal). A corresponding adaptation of sensing based standards needs to be defined for Europe;

iii) Broadcasting, wireless microphones and assignment to radio stations are managed in Europe at the national level. Any sharing scheme based on a database will require some level of integration of the national data.

In order to address the above and other European Regulatory aspects, the Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT) has set up the SE43 group working on *"Technical and operational requirements for the operation of cognitive radio systems in the 'white spaces' of the frequency band 470-790 MHz"*. ETSI RRS is the competence center within ETSI to implement those regulatory requirements.

III. ETSI RRS SYSTEM ASPECTS OVERVIEW AND CR VISION

WG1 has conducted feasibility studies on Cognitive Radio Systems (CRS) concept and potential regulatory aspects of CRS and SDR. The technical concept of CRS developed by WG1 includes the following key elements:

i) Objectives;
ii) Spectrum use scenarios;
iii) Technical requirements;
iv) Spectrum management layers;
v) Architectural approaches;
vi) Enabling technologies.

Several objectives have been identified for CRS in order to ensure the provision of more efficient and flexible use of spectrum. For this purpose, CRS performs three key activities: i) obtain knowledge of the radio operational environment and location, ii) decide on the gathered information and act based on this decision, iii) learn from the results obtained.

Enhancing user experience is one of the main objectives of the CRS. Application examples are cross-operator access, user networks, flexible access to future internet, and connecting to smart spaces. CRS is expected to be beneficial for optimization of the mobile operator network. This could include load balancing, spectrum refarming, and radio resource usage optimization.

CRS deployment examples are categorized according to the following four spectrum use scenarios: i) dedicated spectrum, ii) shared spectrum, iii) secondary usage in dedicated spectrum, and iv) spectrum dedicated for CRS. The first category includes such scenarios as autonomous reconfiguration of software defined multiradio, and reconfiguration of terminals and base stations in a composite wireless network. Shared spectrum scenarios consider deployment of CRS in license exempt bands. Secondary usage in dedicated spectrum considers a scenario where CRS shares the spectrum within the current licensed allocations on secondary basis.

The overall cognitive radio system concept developed by ETSI RRS is depicted in Fig. 2. The figure covers both centralized and decentralized solutions for CR systems, where the centralized, operator-driven solution is targeted for wide area utilization, and the decentralized solution is targeted for local area ad-hoc/mesh networking.

The centralized CRS concept is represented by the Composite Wireless Network (CWN) including Cognitive Network Management System (C-NMS). C-NMS contains such key components as Operator Spectrum Manager (OSM) and Joint Radio Resource Management (JRRM). The decentralized CRS concept is represented by the Cognitive Mesh Network (CMN) controlled by the Cognitive Control Network (CCN).

WG1 has also identified key *enabling technologies* for CRS. They include software defined radio and multiradio, reconfigurable base stations management, spectrum sensing, cognitive pilot channel, cognitive control radio and networking, geolocation, primary protection database, and distributed decision making.

IV. ETSI RRS COGNITIVE RADIO SOLUTIONS

In order to address the stringent requirements stemming from the introduction of CR technology, the WG3 of ETSI RRS has focused on the management of reconfigurable radio systems (encompassing both SDRs and CRs). Specifically, the group has conducted studies on a Functional Architecture (FA) for the management of RRS. This comprised the description of the requirements, of the derived functional building blocks and of the key interfaces among them. In addition, the group has refined and further analyzed the concept of Cognitive Pilot Channel (CPC), which has been originally proposed to facilitate the collaboration between network and terminals in heterogeneous radio environments [5][6], and can be seen as an enabler to support the management of RRS.

The group has investigated the feasibility of standardizing the above concepts and eventually produced two technical reports for the FA [8] and the CPC [7] respectively.
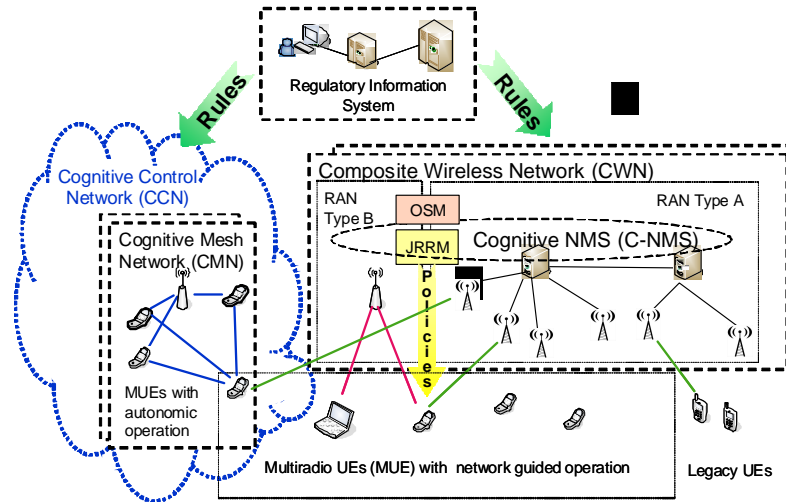
Figure 2: Centralized and Decentralized CR System Concepts.

a)   Cognitive Pilot Channel

The CPC is defined as a channel which conveys the elements of necessary information facilitating the operations of CRS [5]. The CPC provides information on which radio accesses can be expected in a certain geographical area. This information includes operator information, RAT type as well as used frequencies. Exemplary scenarios where the CPC is seen as useful are:

i)   The CPC is used to support a terminal during the start-up phase in an environment where the terminal does not yet know the available RATs and corresponding used frequencies;

ii)   In the context of a secondary system, the CPC is used to exchange sensing information between terminals and base stations in order to perform collaborative/cooperative sensing facilitating the searching of white spaces to start communication;

iii)   The CPC is used for an efficient level of collaboration between a network and the terminals by supporting Radio Resource Management (RRM) optimisation procedures.
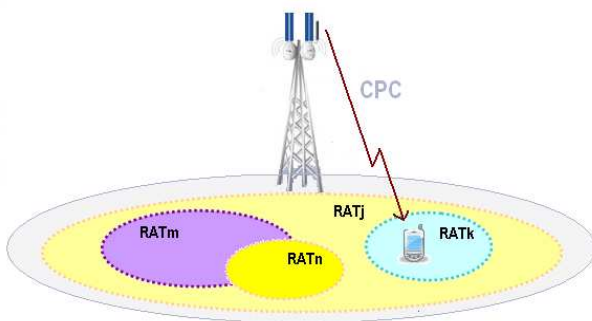

Figure 3: The CPC in a Heterogeneous RAT Environment.

While the basic principle of the CPC is shown in Fig. 3, different CPC deployment approaches are possible:

In the **out-band CPC solution**, where the CPC is conceived as a radio channel outside the component Radio Access Technologies, the CPC either uses a new radio interface, or alternatively uses an adaptation of legacy technology with appropriate characteristics.

In the **in-band CPC solution**, the CPC is conceived as a logical channel within the technologies of the heterogeneous radio environment.

Furthermore, extensions of the above centralised approaches towards more decentralized ones are currently under discussion including a distributed cognitive pilot channel (DCPC) [9] and the Cognitive Control Radio (CCR) [4].

b)   Functional Architecture (FA) for Management and Control of Reconfigurable Radio Systems

In order to define a functional architecture that is able to provide optimized management of radio and spectrum resources, the WG3 of ETSI RRS has collected and reported the following set of requirements:

i)   Personalization, to support various classes of users;

ii)   Support of pervasive computing, enabled by the existence of sensors, actuators and wireless local area networks in all application areas;

iii)   Context awareness, for efficiently handling multiple, dynamically changing and unexpected situations;

iv)   Always-best connectivity for optimally serving equipment and users, in terms of QoS and cost;

v)   Ubiquitous application provision for the applications above;

vi)   Seamless mobility for rendering the users agnostic of the heterogeneity of the underlying infrastructure;

vii)   Collaboration with alternate RATs for contributing to the achievement of always-best connectivity;

viii) Scalability, for responding to frequent context changes.

Accordingly, in order to address these requirements, a proper functional decomposition has been proposed in [8]. The

derived functional blocks, together with the interfaces among them and their distribution between network and terminals is depicted in Fig. 4. Dynamic Spectrum Management (DSM) block is responsible for the medium and long term, both technical and economical, management of spectrum and as such, it incorporates functionalities like provisioning of information for spectrum assignments, spectrum occupancy evaluation and decision making on spectrum sharing/trading.

Dynamic, Self-Organising Planning and Management (DSONPM) caters for the medium and long term management at the level of a reconfigurable network segment (e.g. incorporating several BSs). It provides decision making functionality for QoS assignments, Traffic Distribution, Network performance optimization, RATs activation, configuration of Radio parameters etc. The fundamental objective of the Joint Radio Resources Management (JRRM) block is the joint management of radio resources possibly belonging to heterogeneous RATs and its functionalities mainly include Radio Access Selection, Neighbourhood

Information provision and QoS/bandwidth allocation/admission control. Finally, Configuration Control Module (CCM) is responsible for the enforcement of the reconfiguration decisions typically made by DSONPM and JRRM.

V. ETSI RRS SOFTWARE DEFINED RADIO SOLUTIONS

ETSI RRS considers SDR related standardization for both, Base Stations (BS) and MDs. The BS related work is currently in an early stage and available results are resumed in [10]. The current focus in ETSI RRS WG2 relies mainly on MD SDR related interface standardization between distinct stakeholder domains, such as SDR chipset vendors and MD manufacturers. In this framework, a reference architecture has been derived which outlines the relevant interfaces and concerned building blocks – this architecture, however, is not meant to be normative.
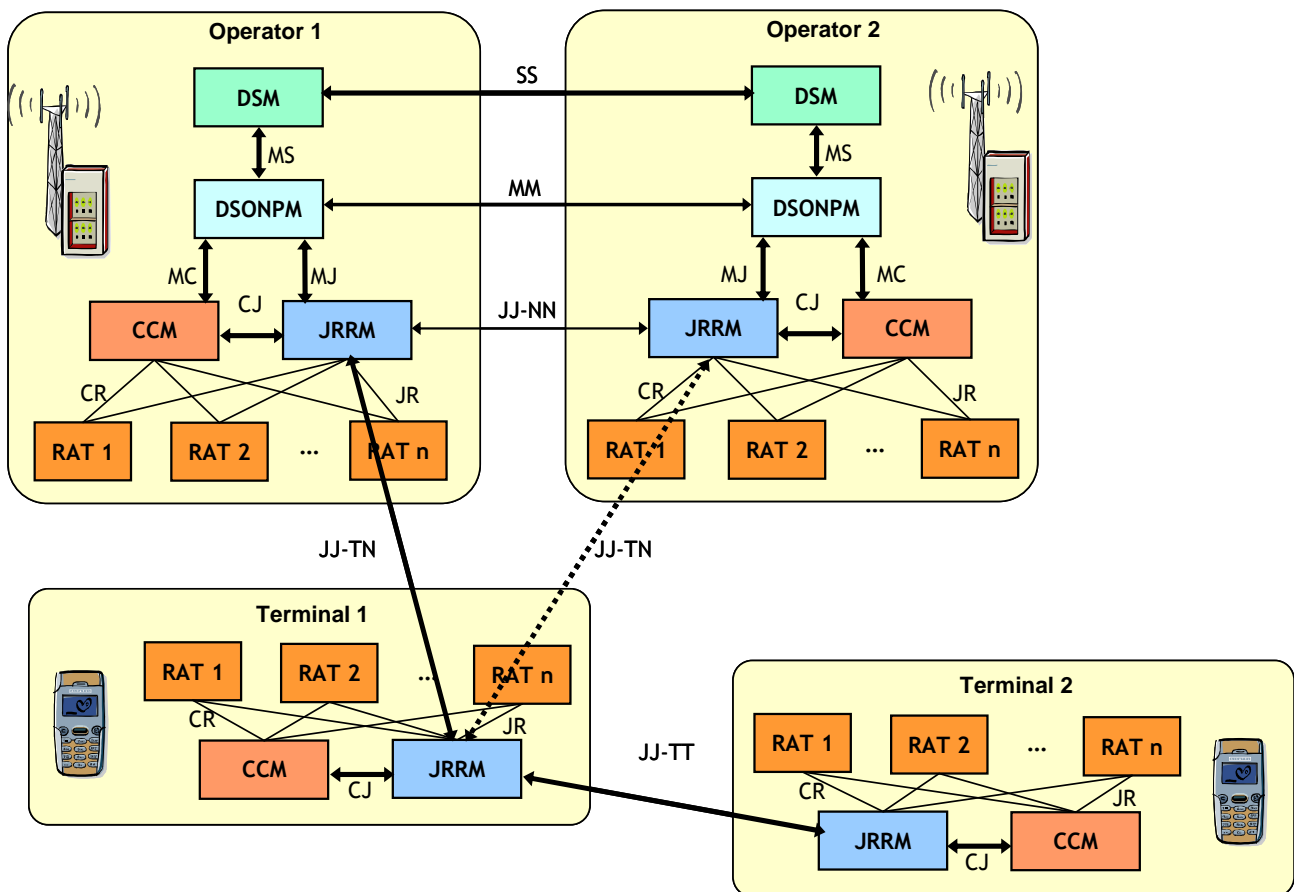

Figure 4: High Level View of the proposed ETSI RRS Functional Architecture.

ETSI RRS has identified a set of requirements related to an SDR MD architecture [11], including i) general architectural requirements, ii) capability requirements, iii) operational requirements, iv) interface requirements and v) other requirements. The capability requirements are highlighted below:

i) **Multiradio configuration capability**: SDR equipment in mobile device is expected to install, load and activate a radio application while running a set of radio systems already;

ii) **Multiradio operation capability**: SDR equipment in mobile device is expected to execute a number of radio systems simultaneously by taking into account temporal coexistence rules designed for their common operation;

iii) **Multiradio resource sharing capability**: SDR equipment in mobile device is expected to execute a number of radio systems simultaneously by sharing computation, memory, communications and RF circuitry resources available on the radio computer platform by using appropriate resource allocation, binding and scheduling mechanisms.

The outcome of the study consists, among others, of the presentation of a functional architecture for SDR equipment as detailed in Fig. 5:
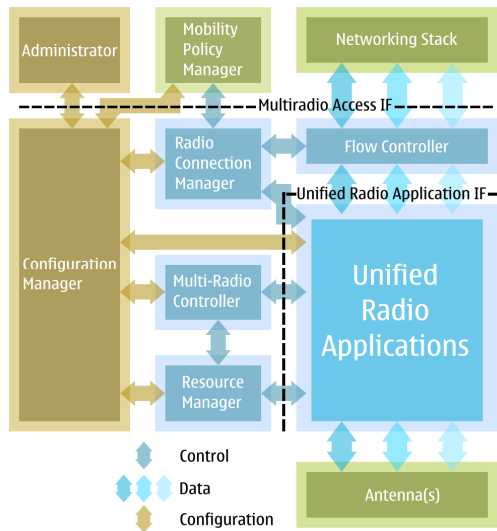

Figure 5: Functional Architecture of SDR Equipment.

The components of this framework have different responsibilities as follows:

i) **Configuration Manager:** (de)installation and (un)loading of radio applications into radio computer as well as management of and access to the radio parameters of those radio applications;

ii) **Radio Connection Manager:** (de)activation of radio applications according to user requests and overall management of user data flows;

iii) **Flow Controller:** sending and receiving of user data packets and controlling the flow;

iv) **Multiradio Controller:** scheduling the requests on spectrum resources issued by concurrently executing radio applications in order to detect in advance the interoperability problems between them;

v) **Resource Manager:** management of radio computer resources in order to share them among simultaneously active radio applications, while guaranteeing their real-time requirements.

b) *SDR Standardization related to Interfaces*

The ETSI RRS WG2 SDR handset reference architecture report [11] identifies four candidate interfaces for standardization:

i) **Multiradio Interface** as the uniform interface for network protocol stacks and other user domain entities to access services of the radio computer;

ii) **Unified Radio Application Interface** at the boundary between the common radio computer platform and the specific radio applications;

iii) **Radio Programming Interface** including software development-time concepts and run-time interfaces between radio software entities and radio computer platform;

iv) **Interface to the Reconfigurable RF Transceiver** to support multiple radio applications, even concurrently.

Among these interfaces, the **Multiradio Interface** has most potential for standardization, and is currently under further studies in ETSI RRS.

The deployment of the **Multiradio Interface** is expected to proceed in phases with platform capability advancing, starting from legacy radio access technologies, gradually moving towards a full SDR:

i) Radio applications use pre-defined fixed resources. Radio applications come from a single source, and a list of concurrently supported radios is provided. Additional CR functionality is introduced by means of parameter management of individual radio applications;

ii) Radio applications have fixed resource requirements. Instead of fixed resources, a worst-case resource consumption budget is attached to each radio. The SDR platform does admission check and resource allocation for concurrently running radios, enabling higher resource utilization at the cost of less determinism;

iii) Radio applications have dynamic resource requirements. In addition to phase 2 capabilities, the resource demand of radios varies based on their type of activity (for instance power-save vs. active data link). Admission control and resource allocation is done whenever a radio changes its behavior classification;

iv) Radio applications come from third-party vendors. This stage mostly affects the security requirements on the platform, as well as the tools to create radios.

The **Multiradio Interface** is described with a static information model and signaling diagrams for dynamic behavior. This is organized in an UML model to allow formal definitions on a rather abstract level, and extension and specialization of the desired elements later on. Fig. 6 shows an example signaling diagram.

Installation of new a radio application is done by passing a package containing all information and software executables needed to run the radio. Loading of any installed radios may be requested into the execution environment. Parameters of loaded radios may be managed to change the behavior of the radio or to obtain information.

Together with relevant control plane services (such as measuring the radio environment) the management plane services may be used to realize various cognitive radio functionalities.
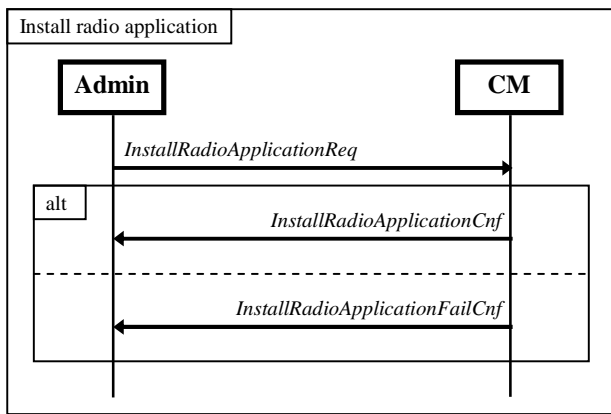

Figure 6: Definition of a service in MURI - Administrator User Requests Installation of a New Radio Application from the Configuration Manager in the SDR Platform.

The information model and service definition for standardization pre-study is ongoing in ETSI RRS. The next step after that is to gather feedback from relevant stakeholders such as chipset and mobile device manufacturers, to determine if there is sufficient interest to begin actual standardization of the multiradio interface.

VI. SECURITY

As a general rule, RRS must validate communication security requirements like Data Confidentiality and Privacy, Availability, Registration, Authentication and Authorization already defined for conventional wireless communication systems. RRS may also be vulnerable to new types of security attacks, beyond the ones already identified for conventional networks.

The SDR reconfiguration capability, as described in section V, where a radio application can be loaded and activated at run time could be exploited by a security attacker to download and activate malicious software modules.

To protect the SDR against these types of attacks, we suggest to adopt Software Assurance processes and functions including a software certification processes, a secure download mechanism, which guarantees the authenticity of the downloaded software, and a secure execution environment in the SDR terminal to guarantee that only trusted software can be activated and executed.

With reference to functional architecture of SDR equipment described in section V, these functions could be implemented by a Software Download Authentication (SDA) component, which can be part of the Administrator and Configuration Manager blocks. SDA may use security functions on the radio, which must be implemented with a suitable level of trust. We may have three levels of interfaces to radio resources: public; group managed; and national (government controlled).

ETSI TC RRS is also investigating security vulnerabilities and threats of Cognitive Radio. Conventional communication systems can only change their transmission parameters and use the RF spectrum bands in the limits implemented in their hardware and firmware architectures. A Cognitive Radio could instead communicate in a wide range of spectrum bands and change its transmission parameters at runtime, on the basis of the sensed radio spectrum environment or the information received from other Cognitive Radio nodes. Because of these capabilities, cognitive radio nodes could increase the risk of harmful wireless interference if the cognitive radio mechanism is disrupted or abused.

As described in section IV.a), cognitive radio networks can be based on the concept of CPC, which can become a vulnerability point by Denial of Service attacks like traffic overload or jamming. Overflow of CPC channel can be controlled through algorithms implemented in the cognitive radio nodes to analyze repetition of cognitive control messages, while jamming of CPC can be mitigated by defining a number of CPC channels in various frequency bands, which could be changed if harmful interference is detected.

The exchange of cognitive control messages could be protected by a distributed authentication protocol and a secure encapsulation protocol to guarantee respectively the sources of cognitive messages and their content. In this area, security solutions designed for the distribution of routing information in mobile ad-hoc networks could be adapted to the exchange of cognitive messages in cognitive radio networks.

VII. OUTLOOK ON FUTURE ETSI RRS TOPICS AND CONCLUSION

Different research lines have been initiated from the academic perspective addressing ETSI RRS aspects. Part of this research is also linked to specific projects such as ICT-E[3] [2]. In the sequel, current research trends are highlighted which have the

potential to become relevant for ETSI RRS and CR/SDR standardization in general.

As far as the algorithmic level is concerned, specific algorithms for autonomous RAT selection using advanced tools of game theory, stochastic analysis and decentralized resource allocation are being studied. The cognitive concepts are exploited to carry out dynamic spectrum assignment based on reinforcement learning mechanisms in order to achieve an efficient spectrum usage in the context of next generation mobile flexible networks based on OFDM.

Spectrum sensing has become also a full dedicated topic research in order to continuously monitor and learn the radio environment. The cognitive radio node senses the spectrum to detect any incumbent spectrum users (ISU) to opportunistically utilize it in the spatial, temporal and frequency domains. The key term to be considered here is 'reliably' detecting the ISU as per the regulatory requirements.

Current directions for spectrum sensing involve localization techniques to generate a radio environment map (REM) and keep track of the ISU in the spatio-temporal manner.

As far as the co-existence of primary and secondary networks, several spectrum measurement campaigns have already been performed in diverse locations in Europe and have shown the potential of exploiting free un-used bands. This has permitted to determine the capacity of cognitive networks through the analysis of the spectrum occupancy degree of the allocated spectrum bands in real wireless communication systems. Some specific time and frequency domain models of the spectrum usage have also been derived.

Researchers from academia are discussing in fact beyond the cellular scenario considering more flexible radio communication like peer-to-peer or private femto or hotspot concepts. All these approaches have in common that neither the precise spectrum usage nor the air-interface parameters are known in advance, e.g. using a LTE-like air-interface in ISM spectrum, provided that general coexistence rules on interference power are fulfilled. Obvious advantages of such a approaches are multi-user capabilities, embedded broadcast, and concepts of interference handling, system bandwidth scalability, and existing FDD and TDD options.

To give a conclusion, it can be stated that this paper has illustrated the SDR and CR framework that is elaborated by ETSI RRS for a heterogeneous wide area (cellular) and short range system scenario. While these studies are reaching a final stage within ETSI RRS, the next step consists in elaborating corresponding normative standards: From December 2009 on, the group is mandated to produce normative standards in the field of CR and SDR (instead of study reports). The existing study results are expected to provide a broad basis for that effort.

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