Resource Modeling for a Joint Resource Management in Cognitive Radio

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Abstract-**Cognitive radio characterizes an ambient aware and software-defined radio system that is capable to autonomously and intelligently adjust the system parameters. It has the potential to optimize the usage of all relevant resources for service-driven wireless communications. We identify four types of resources; these are the radio, the computing, and the radio and user application resources. This paper presents their modeling, including several models for each resource type. The modeling serves as the basis for a joint resource management in a cognitive radio system that may eventually trade-off one resource (type) against the other(s). Two approaches for such a management are presented: a distributed-cooperative and a centralized-integrated. We finally discuss the applicability and utility of the proposed models, and the potentials of a joint resource management in cognitive radio in terms of user satisfaction and revenues.**

Keywords-cognitive radio; joint resource management; resource modeling; software-defined radio (SDR)

I. INTRODUCTION

The current trend in commercial wireless communications is towards user-centric and service-driven and away from RAT-driven wireless communications. A beyond 3G (B3G), or heterogeneous, system, where many radio access technologies (RATs) coexist, offers a wide variety of user services and leverages the introduction of particularized services. In such a scenario, a RAT is chosen from among a set of suitable RATs for the delivery or provision of a desired service, where the RAT selection is a question of (radio) resource management.

B3G systems are dynamic: Users change their positions, preferences, demands, and so forth, network operators modify (extend or diminish) their networks, terminal manufacturers develop sophisticated radio terminals, and service providers introduce new and personalized user services. In parallel with that, new RATs or RAT enhancements, which offer higher bandwidths at lower costs, are investigated and, eventually, realized; recent examples are the introduction and extensions of WLANs, HSDPA and WiMAX.

Software-defined radio (SDR), which was introduced in the early 90s [1], can manage and even exploit a dynamic and heterogeneous radio environment. SDR facilitates the reconfiguration of radio equipment (SDR platforms) by means of changing the RAT-specific software implementation (SDR application) it executes. In other words, radio equipment that follow the SDR approach are not (completely) hardware defined, but rather (partially) software reconfigurable.

The realization of software-defined radios has implications on many players in the wireless world: Manufacturers need to introduce reconfigurable radio equipment that can provide sufficient computing capabilities for the many different radio standards. Network operators should be able to provide and manage a set of RATs for an adequate service delivery to each of their subscribers. Service providers need to develop a high variety of innovative and personalized user service at different QoS (quality of service) levels to be competitive with third parties, which may introduce their own products to the wireless user [2].

Cognitive radio emerged as a follow-up concept to SDR [3]. Cognitive radio can be described as an ambient-aware radio system that intelligently manages the available (radio) resources in a multi-RAT scenario [4]. Although it can be realized without software-defined radio, i.e. assuming multimode terminals, it is more powerful when implemented on top of software-defined radio. This paper addresses reconfigurable SDR equipment and, thus, a cognitive radio implementation that is based on software-defined radio.

More recently the notion of spectrum sharing, referring to a flexible spectrum usage between operators and systems, emerged [5] [6]. For example, a licensed spectrum band may be leased while not used by its owner. Therefore, the corresponding regulatory issues are currently addressed. We believe that this paves the path for an agile spectrum usage.

The prospective flexibility in the spectrum allocation makes the research in software-defined and cognitive radios even more interesting: Spectrum sharing increases the number of bands that SDR equipment can access and so the variety of possible platform configurations. Being able to more flexibly choose the transmission band as well as the transmission technology facilitates a more efficient usage of radio resources.

Apart from the management of the scarce radio resources, the limited and distributed computing capabilities of SDR equipment have to be dynamically managed [7] [8]. Additionally, a dynamic management of the available RAT implementations and service presentations (radio and user applications) and their computing requirements and QoS repercussions is necessary.

This paper introduces a modeling of the radio, the computing, and the radio and user application resources for their joint management in cognitive radio. It extends our previous work [8] in two ways: First, it also considers the radio and user application resource management and provides a more general

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framework for the joint resource management in cognitive radio (section II). Second, it provides a modeling of the radio, computing, and application resources as the basis for such a management (section III). We discuss its applicability before providing an outlook for future research (sections IV and V).

II. JOINT RESOURCE MANAGEMENT

The context of this paper is a cognitive radio system that jointly manages all those resources that are required for SDR communications. Apart from the radio resources, we identify the application and computing resources. The limited amount of any of these resources constrains the capacity of the wireless access: Quality requirements and interference limit the availability of radio resources, the accessibility of applications constrains the service and QoS provisioning, whereas the computing capabilities restrain the execution of these applications. The users become aware of these constraints through QoS degradations or the lack of service versatility, among others. The principal task of the joint radio resource management is to make these limitations transparent to the wireless users and to maximize the revenues of all parties (see section IV).

This section provides a general framework for a joint resource management in cognitive radio. Such a management can be either distributed and *cooperative* or centralized and *integrated*; the following definitions point out the differences.

- *Cooperative resource management*: The resource management entities interchange their individual objectives and decisions, which are then adjusted for the sake of the system's overall benefit.
- *Integrated resource management*: Environmental information is jointly processed to derive the appropriate actions that maximize the system's overall benefit.

These definitions indicate that a cooperative resource management system consists of distributed and cooperative resource management entities, whereas an integrated resource management system features one central entity, the integrated resource management entity (Fig. 1, Table I). A cooperative resource management may be easier to develop and implement, whereas an integrated resource management may provide more efficient results. One approach may be more appropriate than the other under certain environmental conditions or management policies; this, however, is not further analyzed here.

TABLE I. ABBREVIATIONS

RRM$_n$	Radio resource management for RAT *n*
JRRM	Joint radio resource management
CRM$_m$	Computing resource management for platform (type) *m*
JCRM	Joint computing resource management
RARM$_k$	Radio application resource management for RAT implementation *k*
JRARM	Joint radio application resource management
UARM$_l$	User application resource management for user application (type) *l*
JUARM	Joint user application resource management
JARM	Joint application resource management
IRM	Integrated resource management

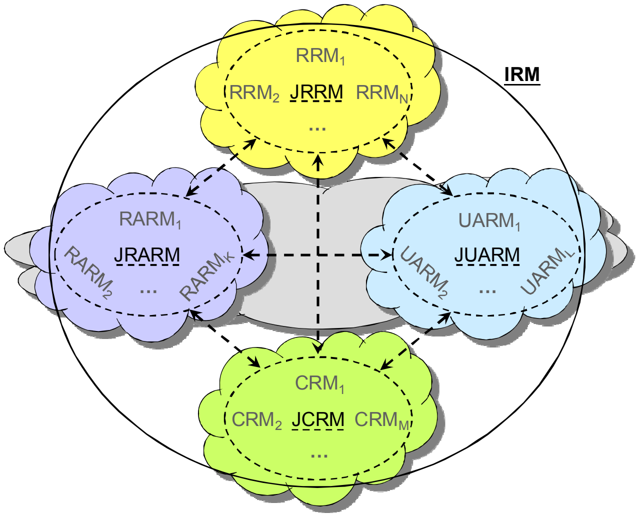

Figure 1. Cooperative/ integrated resource management (dashed/ solid lines).

We may logically separate and independently model the different types of resources, but we must not forget that they are related to each other. In particular, a radio or user application requires some amount of computing resources (radio or user application environment – clouds around JRARM and JUARM in Fig. 1). This amount depends on the particular implementation, being a function of the service and QoS (service environment – long cloud in the background) and the current radio environment (cloud around JRRM). The selection of the appropriate implementations is finally a function of the available computing resources (computing environment – cloud around JCRM).

Only a joint resource management can account for such an interrelation between resources of different types. A cognitive radio system can, moreover, take advantage of this interrelation: It can select the radio and user applications for each SDR platform as a function of the radio, computing, application, and service environments. We therefore argue for a cognitive radio system that implements either a cooperative or an integrated resource management. Resources can only be managed if their states are known; this requires a resource modeling and is the topic of the next section.

III. RESOURCE MODELING AND ITS CONTEXT

This section pretends to establish a suitable system modeling of the radio, the computing, and the two application environments. Subsections *A*, *B*, and *C* assume a cooperative resource management context, whereas *D* discusses the integrated resource management counterpart.

A. Radio Resources and the Radio Cycle

The management of radio resources is of utmost importance in modern radio communications and is a hot topic in cognitive radio as well [4]. This is primarily so because of the rising number of wireless users and their increasing bandwidth demands. Moreover, the fact that many radio frequency bands are, over large time span, underused underlines the importance and the potentials of a *joint*, or *common*, radio resource management in heterogeneous radio environments [9]. The recent research therefore tries to make use of underused spectrum bands, allowing licensed spectrum to be leased to secondary users [5] [6]. The following modeling proposal assumes that such a spectrum leasing is possible, whereas spectrum bands may or may not be pre-assigned to certain RATs.

Fig. 2a shows the *radio cycle*. The radio scene analysis continuously updates the information about owned and leased radio frequencies and their occupation. Therefore, a channel model is necessary. Reference [6] illustrates how a frequency band can be divided into channels. It shows two frequency grids, one for a narrowband radio system and one for a wideband radio system. Since the grids overlap, the frequency grid of the narrowband radio system specifies the channel bandwidth. We adopt this approach, although we do not require that the entire spectrum be divided into channels of equal bandwidths but rather that a channel's bandwidth be a function of the radio systems that may operate in the corresponding band. It could, though, be necessary to merge adjacent channels to make their amount tractable: the smaller the channels the more flexible the spectrum allocation but the more complex the JRRM. We do not address this issue here but rather assume that the modeled spectrum portion is small enough.

A channel is described by a number of parameters, such as *owner*, *leaser*, and *occupation*. If a channel is licensed, its owner is the license holder; otherwise the owner is *public*. If a channel is currently not leased, its leaser is the owner. The occupation of a channel may take discrete values, such as *free*, *low*, *medium*, *high*, and *occupied*, or continuous values, for example, occupation percentage. This metric relates the actual with the tolerable interference. Radio resources can then be modeled as

$$R_r^{(i)} = (\langle\text{start frequency [MHz]}\rangle, \langle\text{end frequency [MHz]}\rangle, \langle\text{owner}\rangle, \langle\text{leaser}\rangle, \langle\text{occupation [\%]}\rangle), \quad (1)$$

where $i \in \mathbf{Z}$ (integer numbers) gives the channel number. The channel numbering can be done arbitrarily; however, a logical numbering, where channels x and $(x+1)$ are adjacent, would be useful for identifying adjacent channels. Here we assume that the RAT suitability for a given channel and the number of (adjacent) channels that a RAT requires are known to the system. It will be included in future versions. The above representation is simple and flexible: Additional channels and channel information can be easily tracked just by extending channel model (1) vertically (additional i's) and horizontally (additional vector elements).

Based on the momentary state of radio resources, primarily described by the 5th element of (1), the JRRM entity would be able to identify over and underused spectrum within its range (of channels i) to eventually derive the appropriate actions that would optimize the joint usage of radio resources.

B. Computing Resources and the Computing Cycle

Software-defined radio characterizes reconfigurable radio equipment consisting of general-purpose processors, digital signal processors (DSPs), and software-reconfigurable processing entities, such as and field-programmable gate arrays (FPGAs). Any processor has a limited amount of computing resources, including processing capacity, inter-processor communication bandwidths and energy. (Although base stations' energy availability may be considered unlimited for practical cases, optimizing their power consumption it is still an important issue.) Management of computing resources is necessary for switching from one radio standard or service to another, or, in other words, for mapping another radio or user application to a given SDR platform. An SDR platform is characterized by the available and occupied computing resources, the RF circuitry and all other features it provides for radio communications and, possibly, non-radio specific computation.

Cognitive radio automates the reconfiguration process of SDR platforms. It thus requires a computing resource management entity that processes the hardware information of its surrounding. Fig. 2b shows the *computing cycle*. The *computing scene analysis* entity of this cycle captures the hardware information and provides it in a suitable format to the JCRM entity. A suitable format, or computing resource management modeling, is proposed in continuation.

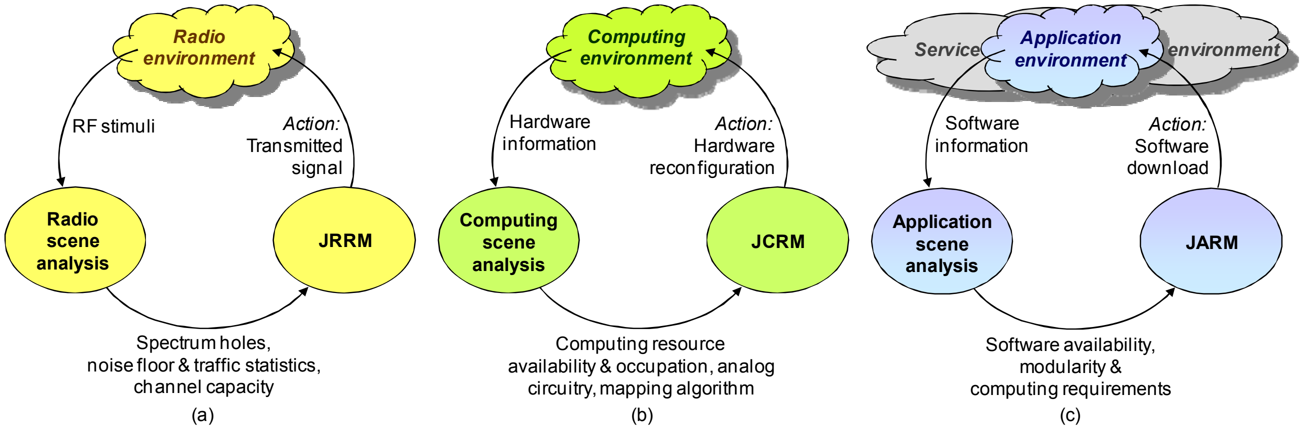

Figure 2. The radio (a), computing (b) and application (c) cycles.

Matrix $R_c^{(i,\,j)}$ models the available computing resources of type "i" for SDR platform "j" ($i, j \in \mathbf{N}$ – natural numbers). More precisely, $R_c^{(i,\,j)}$ is a $X_c(i)$ times $Y_c(i)$ matrix of non-negative real elements $\mathbf{R}^+$ ($X_c(i)$, $Y_c(i) \in \mathbf{N}$). We suggest the computing cycle to consider at least the following computing resources: processing powers, bandwidth capacities, memory resources, and power availability.

The processing powers of the $N(j)$ processing entities of SDR platform "j" can, for example, be represented as

$$R_c^{(1,j)} = (C^j_1, C^j_2, \ldots, C^j_{N(j)}) \text{ [MOPS]}. \tag{2}$$

In [7] we discussed the suitability of million operations per second, or MOPS, as a metric for characterizing the processing powers of SDR platforms. Similarly, a platform's bandwidth capacities can be captured in mega-bits per second (MBPS) as

$$R_c^{(2,j)} = \begin{pmatrix} \infty & B^j{}_{12} & \cdots & B^j{}_{1,N(j)} \\ B^j{}_{21} & \infty & \cdots & B^j{}_{2,N(j)} \\ \vdots & \vdots & \ddots & \vdots \\ B^j{}_{N(j),1} & B^j{}_{N(j),2} & \cdots & \infty \end{pmatrix} \text{[MBPS]}. \tag{3}$$

$B^j{}_{12}$, for instance, is the bandwidth capacity that is available for the directed data transfer from the local data memory of processor "1" to the local data memory of processor "2" of SDR platform "j". We assume direct memory access (DMA) or pointer transfers, where processor internal bandwidths are sufficiently high to be modeled as infinite.

An SDR platform may have a global memory to store the downloaded radio and user applications. The application mapping process then distributes the radio and user applications' functions between the processors' local memories for their distributed processing. The memory availability for program and data can be modeled as

$$R_c^{(3,j)} = (M^j_1, M^j_2, \ldots, M^j_{N(j)}, M^j_{N(j)+1}) \text{ [MB]}, \tag{4}$$

where $M^j{}_1$ through $M^j{}_{N(j)}$ represent the processors' local and $M^j{}_{N(j)+1}$ the platform's global memory resources in mega-bytes (MB). Finally, the energy resources can be modeled as

$$R_c^{(4,j)} = P^j \text{ [mWPS]} \tag{5}$$

if we assume that the total energy of P^j milliwatt per second (mWPS) is shared among all computing resources of SDR platform "j".

Note that the above modeling permits to capture additional computing resources $R_c^{(i,\,j)}$, $i \geq 5$. Also, matrices can be removed or simply ignored when the corresponding resource becomes unlimited for practical issues and does not require its management any more. Focusing on the most relevant computing resources facilitates a more efficient JCRM.

C. Application Resources and the Application Cycle

Radio and user applications basically differ in their utility: The radio application defines the radio functionality of an SDR platform and eventually the transmission mode for service delivery, whereas the user application facilitates use of the service itself. In other words, the radio application defines how data is transmitted and received over the wireless link (OSI layers 1–3), whereas the user application defines how the service is locally presented to the user (OSI layer 7). These applications will be modularly built out of independent processing blocks to be processed following the distributed computing concept and to be individually exchangeable for an easy distribution of new functions.

Fig. 2c shows the *application cycle*. As suggested in Fig. 1, the cognitive radio system may execute one such cycle for the radio and one for the user application. Although the radio and user applications have different functionalities and requirements, the same resource model $R_a^{(i,\,j)}$—a $X_a(i)$ times $Y_a(i)$ matrix of $\mathbf{R}^+$ elements ($X_a(i)$, $Y_a(i) \in \mathbf{N}$)—serves for both.

$$R_a^{(1,j)} = (c^j_1, c^j_2, \ldots, c^j_{M(j)}) \text{ [MOPS]} \tag{6}$$

represents the processing requirements of the $M(j)$ functions of application "j".

$$R_a^{(2,j)} = \begin{pmatrix} b^j{}_{11} & b^j{}_{12} & \cdots & b^j{}_{1,M(j)} \\ b^j{}_{21} & b^j{}_{22} & \cdots & b^j{}_{2,M(j)} \\ \vdots & \vdots & \ddots & \vdots \\ b^j{}_{M(j),1} & b^j{}_{M(j),2} & \cdots & b^j{}_{M(j),M(j)} \end{pmatrix} \text{[MBPS]} \tag{7}$$

captures the platforms' bandwidth requirements, where $b^j{}_{12}$, for example, is the bandwidth that is at least required for the data transfer from function "1" to function "2" in the processing chain, both pertaining to application "j".

The memory requirements are summarized in

$$R_a^{(3,j)} = (m^j_1, m^j_2, \ldots, m^j_{M(j)}, m^j_{M(j)+1}) \text{ [MB]}, \tag{8}$$

where $m^j{}_1$ through $m^j{}_{M(j)}$ represent the functions' program and data memory requirements and $m^j{}_{M(j)+1}$ the application's total memory demand. The application's energy requirement may finally be written as

$$R_a^{(4,j)} = p^j \text{ [mWPS]}. \tag{9}$$

The application resource modeling so far is in line with the computing resource modeling. The application cycle, however, needs to process information about the suitability of an application for service and QoS delivery. This may be modeled as

$$R_a^{(5,j)} = (q^j_1, q^j_2, \ldots, q^j_S), \tag{10}$$

where $q^j{}_k \in \mathbf{R}^+$ indicates the QoS that application "j" can achieve for service k and may be a function of the theoretically achievable bit rate and BER, among others. For each service, we suggest to define a reference QoS value, e.g. $q^j{}_{video} = 1$ for a 128 kbps UMTS implementation. Since we do not scale $q^j{}_k$, we can choose this reference freely, facilitating the definition of $R_a^{(5,j)}$ and accounting for future QoS enhancements.

S stands for the number of services that are considered. It will grow with each new service that is introduced, requiring an update of (10).

Because different RAT implementations or service presentations may require different amounts of resources (6)-(9) or provide different QoS's (10), we treat them as different radio or user applications.

D. Integrated versus Cooperative Resource Management

The proposed modeling serves for characterizing the states of the relevant resources for software-defined radio communications at each moment. It pretends to represent the available resources in a suitable format for a joint resource management, either cooperative or integrated. Fig. 3 shows the cognitive cycles of the integrated resource management approach. The scene analysis entities again collect and process information but provide it to a central entity, the integrated resource management (IRM) entity. This entity then jointly processes the system's state information to make an integrated decision upon its inputs, whereas the logically distributed resource management entities of the cooperative approach coordinate their individual decision.

IV. DISCUSSION

This section discusses the applicability and importance of a resource modeling that accounts for the different types of resources discussed in this article. One such applicability is a cognitive radio system that jointly manages and intelligently uses the limited amount of resources of any kind while ensuring reliable radio communications (Figs. 1-3). Such a cognitive radio systems would eventually try to maximize the benefits or revenues of all involved parties. The wireless user is one of these parties; though non-profitable, his satisfaction may be revenue to others. Below we sketch some relationships between resource management and benefits.

The operators want to maximize the number of users they can serve. Each user that is not admitted due to network capacity limits is lost revenue, directly because the user session cannot be initiated and charged and indirectly because the user may switch to another operator. Hence, JRRM is required [10].

The service providers also compete for users. This requires the introduction of innovative and computing feasible services that attract as many wireless users as possible (keyword: *personalized services*). The JUARM facilitates the selection of a user service presentation and the management of their steadily increasing number.

Once the first radio applications will become available, there will be no limit in designing new or optimized software-implementations of RATs. Many different parties may participate in this design and each one of these parties wants to sell its product. The JRARM will manage the growing amount of radio applications and be responsible for proposing the one to execute on an SDR platform at a given time instant.

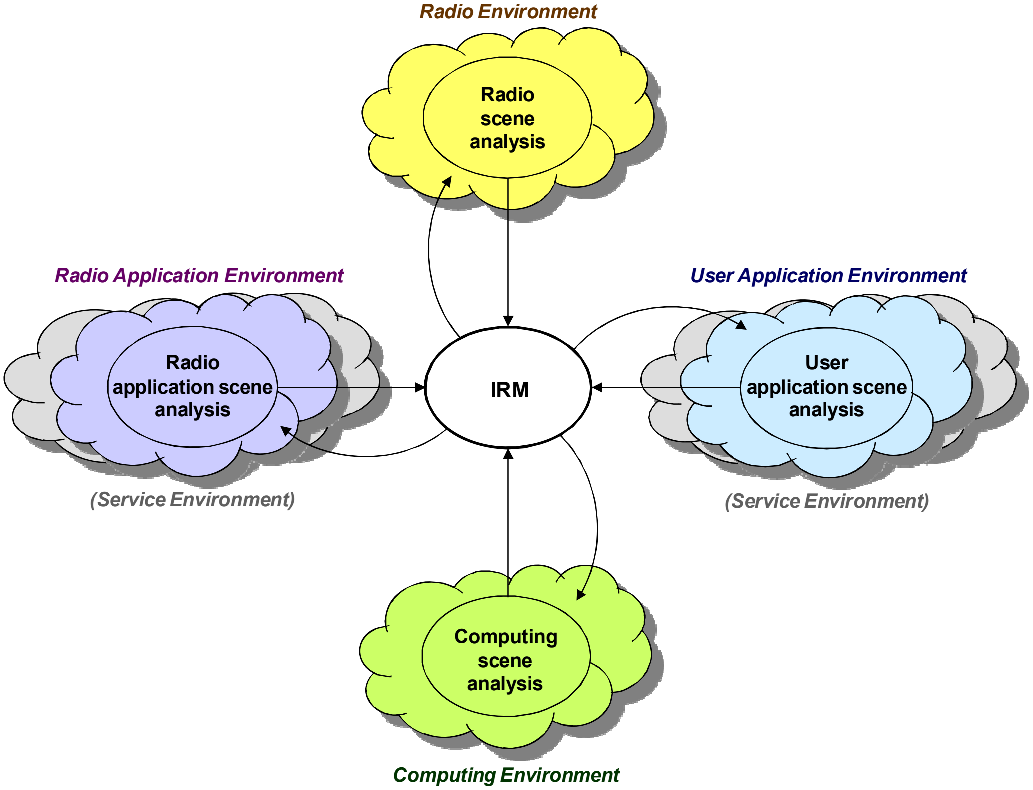

Figure 3. The cognitive cycles of the integrate resource management approach.

The JCRM is necessary for providing the desired user service and QoS whenever possible and as long as desired. Each consumed MOPS or MBPS, for instance, consumes power and costs money. Hence, computing efficient mappings of user and radio applications are very important for direct and indirect revenues.

We conclude that many parameters influence the selection of the radio resources, the radio and user applications, and the computing resources that execute these applications. In the previous paragraphs we have pointed out some relations between revenue and resource management for each resource type independently. Because of the correlation between the resources of different types, we believe that a joint resource management could achieve the greatest benefit. Consider therefore the following scenarios.

A. *Scenario I*

The first scenario pretends to show the importance of a joint resource management, where the usage of the different types of resources is optimized without the users being aware of it. We assume a B3G context, where several radio access technologies coexist and offer a wide variety of different user service at different QoS levels. Moreover, more than one RAT may be suitable for providing a particular service and QoS. A future wireless user will likely not be interested in the specific air interface that provides the service, as long as it is affordable and of good quality. In such a service-driven wireless communications world RATs can be flexibly chosen, giving the cognitive radio system the control it needs for an efficient resource management: It can, for example, distribute the radio and computing loads as a function of the radio, computing, application, and service environments. It can also trade-off the different types of resources against each other.

B. *Scenario II*

This scenario focuses on two users communicating with each other. User *A* has established a voice session with user *B* using the GPRS RAT. During their conversation they decide to switch to a video conference without interrupting the current session. They both notify the network of the desired service upgrade using some protocol, for example sending a message from their terminals. The cognitive radio system realizes that user *A* could be given the desired services at an adequate QoS using either UMTS or WLAN. The WLAN implementation requires less computing resources than the corresponding UMTS implementations. User *A*'s remaining battery capacity suggests a WLAN implementation. User *B*, however, is not within the reach of a WLAN hot spot. Hence, the system decides to access the WCDMA air interface. Since being handheld mobile terminals, which have a small display, a 128 kbps data rate would be enough. A 128 kbps UMTS transceiver implementation is downloaded from the application environment to the mobile terminal of user *B*, whereas user *A* receives the WLAN processing chain. Each radio application is mapped to the available computing resources of the corresponding SDR platform in real-time and without interrupting the voice call. Once both terminals execute the new radio and user applications, they can smoothly switch to a videoconference.

V. CONCLUSIONS AND OUTLOOK

This paper discusses the importance of a joint resource management in cognitive radio and formalizes the cooperative and integrated resource management framework. We have identified four types of resources: radio, computing, and radio and user application resources. Each resource type itself consists of different resources; we have discussed some of them and presented a modeling, which facilitates an easy extension to account for additional resources. Finally, we have discussed the potentials of a cognitive radio system that jointly manages the usage of all relevant resources for software-defined radio communications and, thus, have justified the need for such a modeling.

More research is necessary before a cognitive radio system that implements a joint resource management becomes feasible. First of all, we need to be able to formalize the users' satisfactions or disappointments. Apart from typical performance issues, such as observed bit-rate and BER, economical aspects, such as price-performance ratio, have to be considered as well. Furthermore, we need policies that concretize the particular objective of a joint resource management implementation. These policies should be fair to all parties in a competitive world. All these aspects and many others need to be solved to be able to wisely trade-off one resource (type) against the other(s). On the other hand, the cognitive radio system could figure this out by itself during its learning process. Therefore, it is essential to keep track of the state of all relevant resources to be able to process the consequences of decisions.

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