

Cooperative Resource Management in Cognitive Radio

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Abstract—Cognitive radio is generally understood as an intelligent wireless communication system aiming at the efficient utilization of radio resources. We argue for the extension of its scope to also address the management of computing resources, including processing and bandwidth capacities of SDR platforms, and present a cooperative resource management framework: The joint radio resource management (JRRM) and the computing resources management (CRM) entities interchange information to cooperatively decide if and what kind of terminal reconfiguration would be the most appropriate in each situation. Therefore, the cognitive radio system continuously observes the radio *and* the computing environments.

We discuss a realistic case study and present a simple CRM algorithm. Simulation results show that such a cooperative resource management approach can achieve important improvements over the JRRM by itself. In particular, our proposal considerably reduces the number of lost user sessions due to inappropriate reconfiguration decisions and, thus, serves more wireless users.

Keywords—cognitive radio; computing resource management; cooperative resource management; ubiquitous wireless access

I. INTRODUCTION

A heterogeneous mix of radio access technologies (RAT's) will characterize future wireless communications. The emerging 3G systems, for example, neither pretend to substitute the worldwide available access to 2G services nor directly compete with wireless local area networks (WLAN's). Instead, these RAT's will coexist, complementing each other: 2G systems offer worldwide roaming for carrying voice traffic and low-volume data. 3G systems will offer higher data rates for many different classes of multimedia services. WLAN's locally offer very high data rates at lower cost. That is, 2G can be used around the globe for basic wireless communication services, whereas a switch to WLAN or 3G may be necessary to obtain advanced multimedia services. This view of cooperative rather than competitive networks facilitates the personalization of services and the ubiquitous wireless access [1].

Software radio or software-defined radio (SDR) [2][3], coined in the early 90s, introduces flexibility to radio communications. It facilitates the dynamic change from one radio access technology to another (total reconfiguration). Also, particular modules, or processing blocks, can be interchanged

(partial reconfiguration) to respond to changes in the environmental conditions (channel, economics, business models). Therefore, the signal processing chains for radio communication are to some extent defined in software and executed on programmable hardware.

The cognitive radio concept [4][5] arose as an extension to software-defined radio to automate the reconfiguration of SDR equipment, including SDR mobile terminals and network elements. A cognitive radio system continuously monitors the radio environment and decides about the reconfiguration of SDR equipment within its coverage area. Cognitive radio has the potential to locally balance the communication load between the available radio access technologies to, principally, maximize the network capacity. The locally operating cognitive radio systems can be coordinated to facilitate the ubiquitous wireless access at the global level.

The general understanding of cognitive radio is that of an intelligent wireless communication system aiming at the efficient usage of radio resources [6]. This work approaches the extension of the cognitive radio's scope to include the management of *computing resources*, which refer to the hardware that implements the (software-defined) signal processing chains for radio communications. That is, we classify a cognitive radio as an intelligent wireless communication system aiming at the efficient usage of radio and computing resources.

This paper proposes a cooperative resource management framework for cognitive radio system. The framework is general enough to be applied for trading off communication against computation. Spectrum scarcity and limited interference tolerance are the major reasons for the efficient allocation of radio resource. The limited computing capabilities and the energy consumption of SDR equipment, on the other hand, require the efficient usage of computing resources.

We consider a simpler scenario to present our principal idea, which is to show that the awareness of the computing environment can constructively aid the reconfiguration decisions of cognitive radio systems. In particular, simulations show that such a cooperative resource management can improve on the user disappointment due to lost sessions while balancing the communication load.

The rest of the paper is organized as follows: In section II we discuss our approach to resource management in cognitive radio and introduce the cooperative resource management

framework. Section III presents the simulation set up, including a simple though realistic case study, and analyzes the results. We derive conclusions in section IV.

II. RESOURCE MANAGEMENT IN COGNITIVE RADIO

Joint radio resource management (JRRM) is a timely research topic in wireless radio communication [7]. It principally addresses B3G and 4G systems, characterized by the coexistence of different radio access technologies. JRRM basically refers to the coordination of the spectrum management of the different RAT's that are accessible in a specific area. Its objective is to exploit a heterogeneous radio environment to maximize the overall system capacity while providing adequate quality of service (QoS) levels [8].

As mentioned in the introduction, cognitive radio so far principally addresses the JRRM [6]. We argue for the extension of its scope to manage not only the scarce radio resources but also the limited computing capacities. Therefore, Fig. 1 presents the extended cognitive cycle, which concretizes Mitola's cognition cycles [4][5]. The right cycle in Fig. 1 is due to [6]. It features the *radio-scene analysis* and the JRRM. This cycle is also known as the basic cognitive cycle. The left cycle is our extension proposal. It contains two intelligent entities that are responsible for the *computing-scene analysis* and the *computing resource management* (CRM). The next paragraphs detail their functionalities.

The radio-scene analysis entity senses the radio environment within the cognitive radio system's coverage area. It provides the information about the currently used and available radio resources, amongst others, to the JRRM entity (JRRME). In parallel, the computing scene is analyzed. In particular, the information about mobile terminals' hardware resources is collected, classified due to available RF circuitry, and passed to the CRM entity (CRME). The network provides the information about the available radio infrastructure and software downloads, as well as the computing requirements of the latter. The CRM and JRRM entities then synchronously cooperate to decide upon an appropriate action. For instance, if the radio resources of RAT *A* are overused, whereas those of RAT *B* are

not (right cycle) and if the network infrastructure and mobile terminals facilitate a reconfiguration to RAT *B* (left cycle), the action could be the request of the reconfiguration of some mobile terminals from RAT *A* to RAT *B*. Each action modifies the computing and the radio environments and the system observes these changes.

The extended cognitive cycle of Fig. 1 considers the reconfiguration of SDR mobile terminals. It can easily be extended to aid the reconfiguration of network elements as well. Furthermore, although we focus on the physical layer here, all OSI layers may be subject to reconfiguration. Moreover, a reconfiguration of (some or all OSI layers of) a mobile terminal may require an end-to-end coordination of several communication layers. A terminal reconfiguration may even invoke the reconfiguration of some network entities to, for instance, adjust the downlink transmission data rate to the terminal's reception capacity in the current configuration.

This paper studies the influence of computing resource management on the communication load balancing and therefore considers the following cooperation between the CRM and JRRM entities: The CRME informs the JRRME about the supported RAT's in the cell or cells that are within the coverage area of the cognitive radio system. The JRRME then defines the objective and passes it to the CRME, which tries to realize this objective. More precisely, on the basis of the radio scene analysis, the JRRME decides how many terminals should be reconfigured from one particular RAT to another, where some JRRM algorithm causes this decision. The CRME requests the reconfiguration of selected SDR mobile terminals on the basis of the *computing scene analysis*.

We believe that being able to trade off radio against computing resources could become one of the major achievements of cognitive radio and will, thus, explore different types of cooperation in future work. For example, the CRME may also define its objective(s), such as *minimize the energy consumption of some SDR equipment*. The CRM and JRRM objectives are then jointly processed to make the most appropriate decision in each situation.

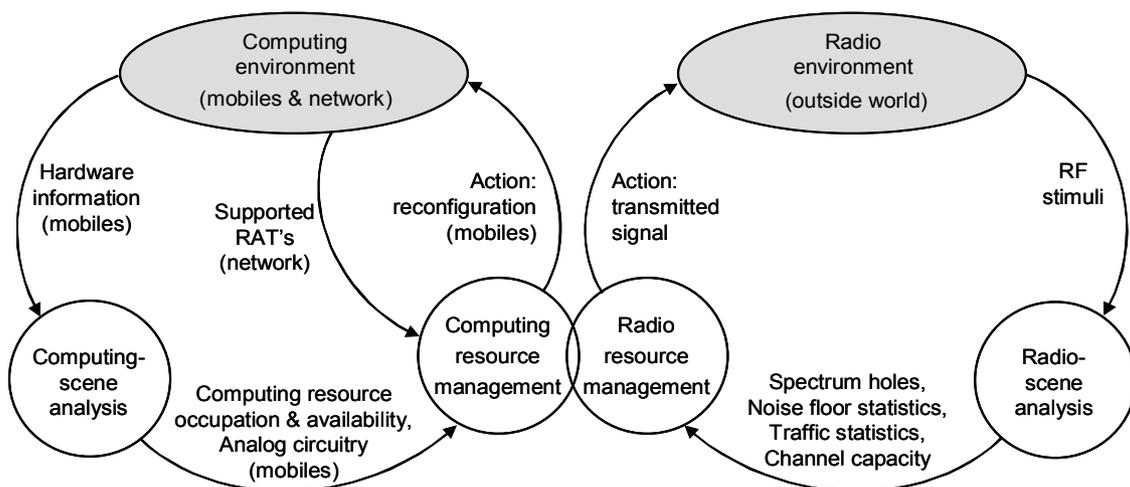


Figure 1. Extended cognitive cycle.

The radio and computing environments are non-stationary in practice; the users' behaviors and the actions taken by the cognitive radio system are the main reasons for this. Moreover, the computing requirements of SDR processing chains are typically a function of the channel conditions, movement characteristics, and so forth. The evolution of RAT components, such as new coding techniques, may additionally modify the computing requirements. Therefore, the extended cognitive cycle, or the learning-by-observing process, runs continuously.

III. SIMULATIONS

A. Use-case Scenario

The spectrum scanning at a certain time and area with 2G and 3G coverage shows that the number of GPRS sessions is elevated (radio scene analysis). This is a typical scenario in crowded areas where many users simultaneously initiate their sessions using the GPRS RAT. The computing scene analysis in parallel observes that the number of registered, but not necessarily communicating, GPRS users is very high in this area. As a result, the cognitive radio system searches for alternative RAT's to increase the network capacity and, thus, potentially satisfy more users. It recognizes that the UMTS radio resources are underused (radio scene analysis) and that the necessary infrastructure, including software downloads, is available (computing environment) and so chooses to reconfigure some of the active terminals to use the WCDMA air interface. This would balance the traffic load between the two standards so that penetrating 2G mobile terminals, as opposed to SDR mobile terminals, could still initiate their GPRS sessions.

B. Objective and assumptions

The JRRM decides that some number of SDR-GPRS mobile terminals should be reconfigured to use the UMTS air interface. We do not consider a particular number here, but rather try to reconfigure 1000 SDR-GPRS terminals. This high number can be justified considering a large area and time span. The objective is thus to reconfigure any of these terminals that has sufficient capacity to execute the SDR-UMTS signal processing chain. (Additional RAT- or non-RAT-specific applications running on an SDR mobile terminal could be a reason for insufficient capacities.)

We assume that the 1000 SDR-GPRS platforms contain the analog RF circuitry that is necessary to access the WCDMA air interface. We can make this assumption because not doing so would not sacrifice the performance of our approach, which is aware about the available RF circuitry (Fig. 1). We address the digital signal processing part at the physical layer of an UMTS receiver and assume that additional computing resource for implementing the higher OSI layers and the UMTS uplink transmitter are sufficiently available.

C. Cognitive Radio Systems and CRM Algorithms

We consider two cognitive radio systems. The first executes the basic cognitive cycle. We call it basic cognitive radio system. The extended cognitive radio system implements the extended cognitive cycle of Fig. 1. The systems apply different

CRM algorithms: Algorithm 0, which is the baseline algorithm, is implemented within the JRRME entity of the basic cognitive cycle. Algorithm 1 is embedded in the CRME.

1) Algorithm 0

No hardware specific information is available to the basic cognitive cycle. Therefore, algorithm 0 reconfigures all terminals, where those that have insufficient processing capacities to execute the SDR-UMTS signal processing chain loose their currently running session. The system chooses the 384 kbps UMTS realization because the current channel conditions facilitate such a high-data rate implementation.

2) Algorithm 1

Algorithm 1 uses the supplied hardware information. It reconfigures mobile terminals as a function their hardware capacities and the available reconfiguration information. This information is successively accumulated during the reconfiguration process: If a mobile terminal loses its session due to an unsuccessful reconfiguration (*infeasible mapping*, which means that the system's computing or timing constraints are not met), terminals of these characteristics are not considered again for reconfiguration. This way the CRME learns which terminals can and which cannot be feasibly reconfigured (learning-by-observing).

The system, furthermore, dynamically chooses the particular UMTS realization as a function of a terminal's processing capacity. It therefore specifies the thresholds T_{128} and T_{384} as the minimum processing capacity that is necessary for executing the 128 and 384 kbps UMTS receiver processing chains. The CRME then selects the 128 kbps (384 kbps) realization if the terminal's total processing capacity C_T satisfies $T_{128} \leq C_T < T_{384}$ ($C_T \geq T_{384}$), whereas in case of $C_T < T_{128}$ no action is requested for the corresponding terminal. Later we specify the exact values of the two thresholds T_{128} and T_{384} .

Some services may not be maintained at the same quality when implementing the 128 kbps instead of the 384 kbps UMTS receiver. If this occurs, the corresponding downlink transmitter is informed to adjust its transmission rate (end-to-end coordination, see section II).

D. Simulation Setup

1) SDR Platforms

We consider several mobile terminals of different architectures and computing capacities. To constrain the number of possible SDR mobile terminals, we assume that each terminal consists of three homogeneous processors, for example, three digital signal processors, which are interconnected by a homogeneous communication network. Fig. 2 shows the three platform models that are addressed in this study. The computing capacity of a mobile terminal consists of the total processing capacity $C_T = 3 \cdot C$ in Mops (million operations per second) and the total bandwidth $B_T = 6 \cdot B$ in Mbps (mega-bits per second). C_T and B_T are the available computing resources after the projected deallocation of the SDR-GPRS transceiver functions.

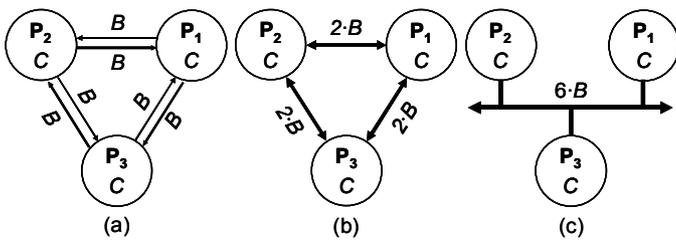


Figure 2. SDR platform models: I full-duplex (a), II half-duplex (b), and III bus (c) architectures.

We consider several values for C and B to simulate terminals with different computing resources' availabilities and randomly generate 1000 SDR platforms. Parameters C , B , and the platform type, which are independently chosen on the basis of uniform distributions in [2700, 2750, ..., 3450] Mops, [200, 300, ..., 1400] Mbps, and [I, II, III], characterize an SDR platform.

2) SDR Applications

Fig. 3 shows the chip- and bit-rate processing chains and their computing requirements of two software-defined UMTS downlink receiver realizations, which support the raw data rates 128 and 384 kbps. Table I resumes the 20 SDR functions f_1 to f_{20} .

We obtained the processing and bandwidth demands from [10]–[13] and from available implementations, considering that the processing requirement is the number of multiply-accumulate operations times the required processing frequency. Table I reveals some implementation characteristics.

The two processing chains require a minimum processing capacity of 8301 and 9403 Mops. Because the total processing

capacity $C_T = 3 \cdot C$ of an SDR platform takes the values 8100, 8250, 8400, ..., 9300, 9450, ..., 10 350, the extended cognitive radio system straightforwardly specifies thresholds T_{128} and T_{384} as 8400 and 9450 Mops.

TABLE I. SDR FUNCTIONS

Label	Denomination; implementation characteristics
f_1	Digital down conversion ; @ 65 MHz
f_2, f_3	Sampling ; output @ 61.4 MHz = $16 \cdot$ chip rate
f_4, f_5	Filtering ; channelization & matched filters
f_6	Chip & slot synchronization ; 2 matched hierarchical real correlators, each @ $4 \cdot 3.84$ MHz [10] [12]
f_7	Interpolator/ Decimator
f_8	Frequency adjust
f_9	Frame synchronization ; 32 256-chip real correlators @ 1.5 kHz [10] [12]
f_{10}	Cell ID detection ; descrambling & correlation [10]
f_{11}	RAKE receiver ; 4 fingers, SF = 4 & 8 [10] [11]
f_{12}	Physical channel demapping ; [13]
f_{13}	2nd deinterleaving ; [13]
f_{14}	Physical channel desegmentation ; [13]
f_{15}	Radio frame desegmentation ; [13]
f_{16}	1st Deinterleaving ; [13]
f_{17}	Rate matching ; [13]
f_{18}	Turbo decoding ; 4 iterations [10] [13]
f_{19}	Transport block concatenation & code block desegmentation ; [13]
f_{20}	Cyclic redundancy check ; [13]

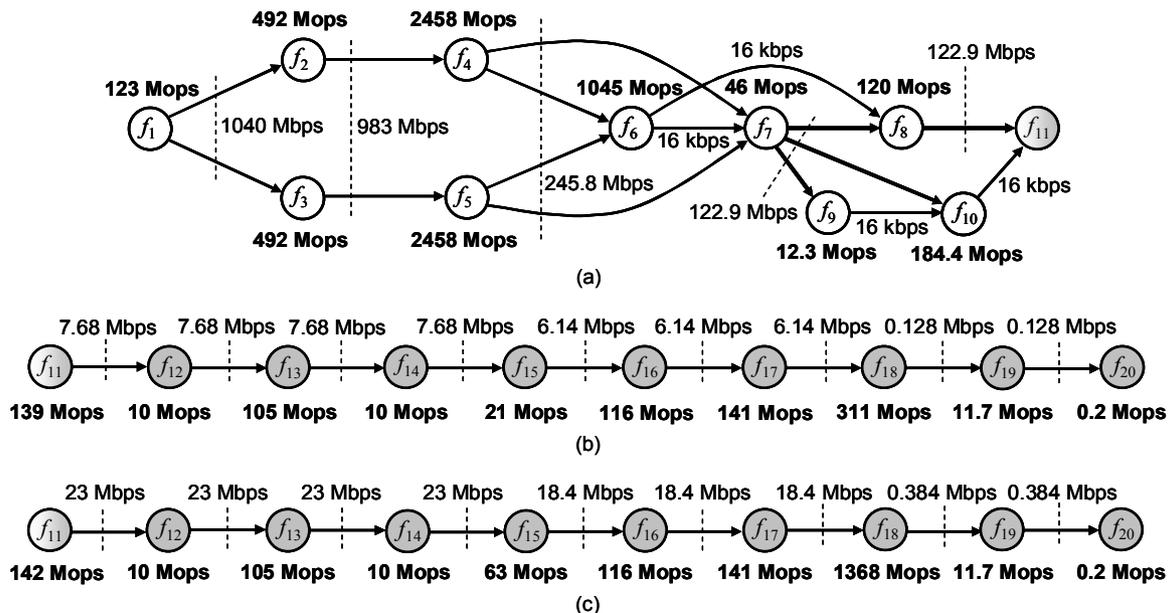


Figure 3. UMTS task graph: Chip- and bit-rate processing requirements for the 128 kbps (a, b) and the 384 kbps (a, c) UMTS receiver realizations.

3) Application Mapping

The mobile terminals of this case study are equipped with the ordered version of the t -mapping algorithm [9], which maps the downloaded SDR processing chain to the platform's available computing resources. The SDR functions are mapped one by one to all processors minimizing the sum between the computation and the communication costs. A bandwidth is reserved if two communicating processes are mapped to different processors; otherwise, the data is accessed via shared memory. The mapping of each SDR function to all N processors results in N different mapping options of the entire processing chain. The algorithm then chooses the least-cost solution.

The low complexity of this mapping approach greatly facilitates its implementation. Since being non-optimal, it not always finds a feasible solution. A feasible solution, or *feasible mapping*, reserves no more than 100% of any computing resource and, hence, meets the RAT-specific computing constraints. In particular, a feasible mapping can meet the timing constraints because time is an implicit resource [9].

E. Simulation Results

Fig. 4 shows the number of lost sessions as a function of the CRM algorithm and SDR platform index. Not processing any hardware specific information results in constantly losing sessions. Therefore, the grey curve (Alg. 0) does not saturate, as opposed to the black curve (Alg. 1). Additional simulations have shown that the black curve saturates at 228 lost sessions.

During the learning process the CRME accumulates the mapping information of the tested (C, B) instances as a function of the platform architecture. Fig. 5 illustrates the complete mapping information. The dark grey areas indicate infeasible mappings for the corresponding (C, B) instances. That is, for any of these (C, B) instances the mapping approach cannot feasibly solve the given problem. In case that a feasible mapping exists, it is the mapping algorithm that fails. Further discussion is beyond the scope of this paper.

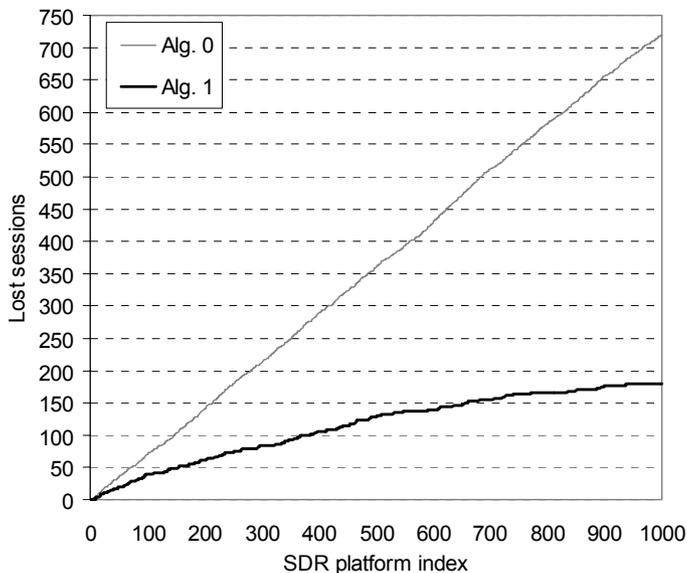


Figure 4. Number of lost sessions as a function of the SDR platform index.

Figs. 5a–c show that the computing resource allocation is a function of the platform architecture. These results reflect the flexibility of the bus system (Fig. 2c) over the half-duplex architecture (Fig. 2b), which is more flexible than its full-duplex counterpart (Fig. 2a). We have studied these three architectures, which represent a small excerpt of the variety of possible mobile terminals, to highlight the importance of providing the information about a platform's architecture to the CRME.

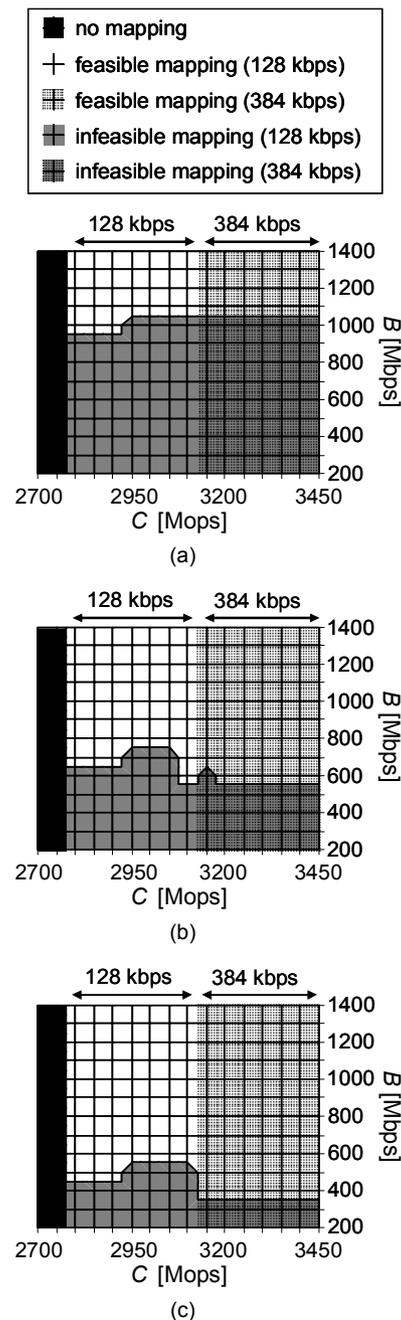


Figure 5. Feasible and infeasible mappings as a function of (C, B) for the full-duplex (a), half-duplex (b), and bus (c) architectures.

TABLE II. TOTAL NUMBER OF SUCCESSFUL RECONFIGURATIONS AND LOST SESSIONS

Alg.	Total number of successful reconfigurations		Total number of lost sessions
	128 kbps	384 kbps	
0	-	281	719
1	227	281	180

Table II contains the final results of this study. Applying algorithm 0 results in 719 lost sessions, whereas the number of lost sessions is 180 with algorithm 1. The number of successful 384 kbps UMTS reconfigurations is 281 for both cognitive radio systems. The extended cognitive radio system additionally achieves the reconfiguration of 227 SDR-GPRS mobile terminals to the 128 kbps UMTS realization. These results indicate the improvements that can be achieved with our cooperative resource management proposal. More sophisticated CRM algorithms and cooperation strategies may be necessary in more dynamic scenarios, where the diversity of terminal architectures, software implementations, service and QoS requirements, and mapping algorithms, amongst other, may be considerably higher.

Finally, this study has shown that the RAT selection should also be a function of the available computing resources. Although some services require a particular RAT (realization) to comply with the corresponding QoS agreements, users often prefer a lower QoS than no service at all. These aspects foster our belief that in the near (4G) future the ubiquitous wireless access problem will be a JRRME-CRME cooperative management rather than an infrastructure problem.

IV. CONCLUSIONS

This paper stresses the importance of cooperative resource management in cognitive radio. We have presented a framework that facilitates the cooperation between the joint radio resource management and the computing resource management. JRRM is already considered a cognitive task, whereas CRM is rather novel in this context. A case study has demonstrated that the proposed cooperative resource management can achieve severe improvements over the joint radio resource management by itself.

The presented simulations have addressed the communication load balancing. Nevertheless, in section II we have indicated that the framework is suitable for trading off radio against computing resources. We will explore this further in future work, considering additional computing resources, such as battery power and memory, as well as other terminal architectures and software issues. Software issues include modularity, software architectures, and execution environments. These aspects claim for more sophisticated and dynamic learning mechanisms, making the cognitive process more complex but also more powerful.

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