

On Integrating Radio, Computing, and Application Resource Management in Cognitive Radio Systems

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Abstract

Cognitive radio is an emerging concept that facilitates the intelligent usage of radio resources in heterogeneous radio environments. It automates the reconfiguration of software-defined radio (SDR) platforms, which stand for reconfigurable mobile terminals and network elements. This paper introduces a novel approach to resource management in cognitive radio. We call it integrated resource management (IRM) because it integrates the radio resource or spectrum management, the computing resource management of SDR platforms, and the application resource management of SDR applications, which define a platform's radio functionality. Our cognitive radio system thus executes three cognitive cycles: the radio, the computing, and the application cycles. We present a general framework that facilitates the introduction of integrated resource management algorithms. Simulation results, based on a heterogeneous radio scenario and a simple integrated resource management algorithm, indicate the achievable improvements of our proposal.

1. Introduction

The coexistence of heterogeneous radio access technologies (RAT's) characterizes modern 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 or personal area networks (WLAN's, WPAN's). These radio access technologies rather complement each other: 2G systems offer worldwide roaming for carrying voice traffic and low-volume data. 3G systems offer higher data rates for many classes of multimedia services. WLAN's locally offer very high data rates at lower costs for accessing

global information, whereas WPAN's wirelessly interconnect personal devices.

Additional RAT's will be introduced in the future. B3G, or beyond 3rd generation, is the commonly used term that describes them as a whole. That is, B3G characterizes a heterogeneous radio environment rather than a new generation for radio communications. B3G-RAT's may evolve over time, for example, when introducing new (de-)coding techniques or optimized implementations in general. Although, today's state-of-the-art RAT's will once become obsolete and replaced by new ones, we believe that the radio environment will remain or even become more heterogeneous.

An ambient aware (radio) resource management is necessary to fully exploit the heterogeneous and dynamic wireless access networks of today and tomorrow. This leads to cognitive radio [1] [2]. Cognitive radio, coined in the late 90s, is an intelligent wireless system and, so far, basically coordinates the spectrum management of the different RAT's that are accessible within a certain geographical area [3]. A cognitive radio system should be able to autonomously distribute the radio load to optimize the spectrum usage due to the network operators' policies and operator-user agreements, amongst others.

The cognitive radio concept is based on software-defined radio (SDR). Software-defined radio, or software radio as it was originally coined, facilitates the dynamic switch from one RAT to another [4]–[6]. Therefore, the signal processing chains for radio communication are to some extent defined in software (SDR applications) and executed on programmable or reconfigurable hardware (SDR platforms) [7]. This hardware-software decoupling facilitates the independent development of SDR platforms and applications and will leverage the design of both: SDR platform manufacturers can improve the performance and reconfigurability of their platforms without depending on the application designer; a third party,

which cannot access today's radio market, may become an SDR application designer.

The SDR concept, though mostly applied to the physical layer processing of radio access networks, is applicable to all OSI layers of the entire radio system [6] [8]. In other words, any digital signal processing block may be software-defined, although its implementation is constrained by the processing powers of DSP's (digital signal processors), microprocessors, FPGA's (field-programmable gate arrays), and the like. Despite of the advances in microelectronics, the high complexities of digital signal processing algorithms require that an SDR application's signal processing blocks be mapped to an SDR platform's processing devices following the distributed computing concept [7]. This explains the need for computing resource management in software-defined and cognitive radios. The vast variety of future SDR applications, being modularly built and rebuilt from several functional blocks, calls for an appropriate application resource management.

This paper introduces a novel approach to resource management in cognitive radio. We call it integrated resource management (IRM) because it integrates the radio resource or spectrum management, the computing resource management of SDR platforms, and the application resource management of SDR applications. An SDR platform stands for an SDR mobile terminal or a reconfigurable network element, whereas an SDR application is a software-defined signal processing chain for the transmission, or the reception, or both over the radio link.

Many arguments for such an integrated resource management can be found. The following list contains just a few of them:

- the numerous B3G-RAT's,
- the ever-growing bandwidth demand,
- the expected commercialization of SDR platforms and applications,
- the vast variety of SDR platforms, each consisting of several processing entities,
- the modularity of SDR applications.

The rest of the paper is organized as follows: Section 2 describes our cognitive radio system proposal. We discuss a simple cognitive radio scenario and the corresponding simulation results in section 3. Section 4 summarizes the contribution of this work.

2. Cognitive Radio System Proposal

The general understanding of cognitive radio is that of an intelligent wireless communication system aiming at the efficient usage of radio resources in heterogeneous radio environments [3]. In other words,

a cognitive radio system automates the joint radio resource management (JRRM) of the available RAT's within its coverage area. Different policies may be followed, although the general interest is to maximize the overall system capacity while providing adequate quality of service (QoS) levels.

Our cognitive radio system proposal extends the current scope of cognitive radio in that it integrates the radio, computing, and application resource management. Fig. 1 illustrates our proposal. It features three cognitive cycles: the radio cycle, the computing cycle, and the application cycle. The rest of this section discusses these three cycles and their unifying entity, the integrated resource management entity (IRME).

2.1. Radio Cycle – Radio Resource Management

The *radio scene analysis* entity within the radio cycle observes the radio environment and provides information about spectrum holes, traffic and noise floor statistics, and the current channel capacity to the integrated resource management entity. In other words, it feeds the IRME with the necessary information about the current radio environment. Based on this continuous information flow, the IRME is able to optimize the usage of radio resources at each moment. In this sense, the concept of spectrum sharing arose. For example, currently unused spectrum (spectrum holes) may be leased to another party for its momentary usage [9] [10].

The IRME action, which translates to a transmitted signal at some frequency and modulation type, changes the radio environment. The radio scene analysis entity then observes this change and closes the radio cycle. This radio cycle corresponds to the basic cognitive cycle presented in [3].

2.2. Computing Cycle – Computing Resource Management

The computing cycle principally consists of the computing scene analysis that provides the information about the computing environment to the IRME. In particular, the computing environment is scanned for the occupied and available hardware resources for radio communications of (SDR) mobile terminals and reconfigurable and non-reconfigurable network elements. The principal computing resources are the platforms' processing and bandwidth resources of the digital circuitry as well as the analog circuitry, including the RF part. Additional computing resources are physical memory capacities and battery powers. These computing resources should be properly

managed. One major reason for this is that a mobile subscriber or a network operator is very interested in optimizing the power consumption of its computing devices.

The mapping of another SDR application to an SDR platform reconfigures the platform from one operating mode to another. Mapping is thus the interface between the SDR application and the SDR platform. Because a mapping algorithm should be locally available on each SDR platform, we consider it part of the computing environment.

The IRME's action, which may initiate the reconfiguration of particular SDR mobile terminals or reconfigurable network elements, can modify the computing environment. The computing scene analysis entity captures these changes and forwards them to the IRME.

2.3. Application Cycle – Application Resource Management

An SDR application is a software-defined signal processing chain for radio communications, such as a software-defined chip- and bit-rate processing chain of

a UMTS receiver. Each SDR application consists of several SDR functions. These functions characterize digital signal processing blocks, which may be (individually) implemented in one way or another. Many SDR functions embody dynamic algorithms with highly variable processing requirements. The processing requirement of the turbo decoder, for instance, is a function of the number of iterations, which can be dynamically adjusted as a function of the momentary channel conditions (radio cycle) to achieve the desired BER at the minimum computing cost.

We expect that future application environments will contain a number of SDR applications, supporting many different multimedia services and QoS's. The modularity of software-defined radio permits an easy exchange of SDR functions and augments the number of available SDR applications. This modularity permits an easy introduction of new SDR function, resulting in a highly dynamic application environment. We therefore suggest that the application environment is continuously scanned for available SDR applications and functions. The application scene analysis entity collects this information, processes it, and provides it to the IRME.

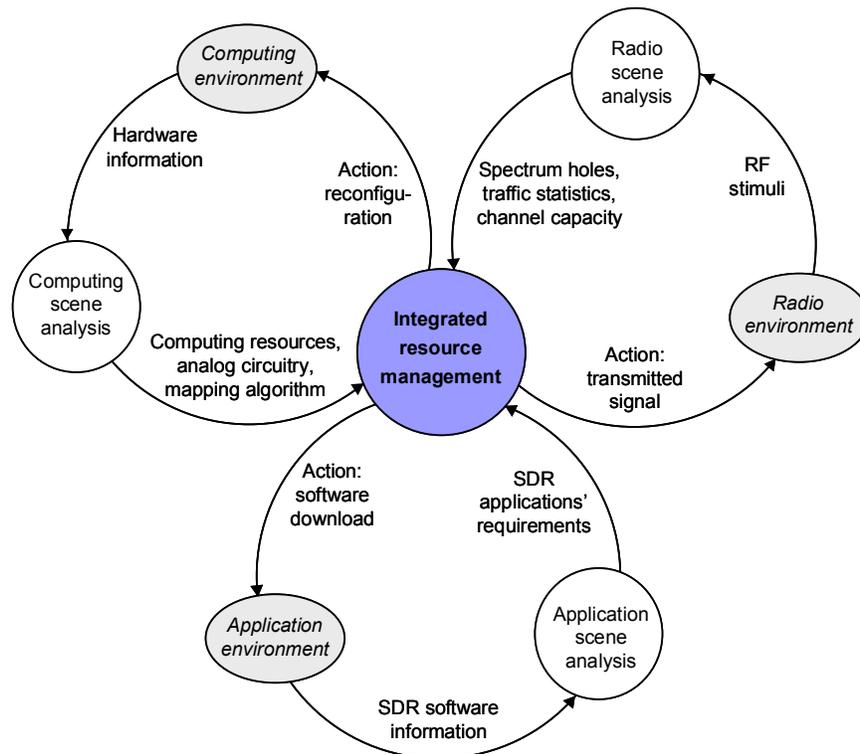


Figure 1. Cognitive radio system proposal: Integrated resource management joining the radio, the computing, and the applications cycles

Once the IRME has received the updated information about SDR applications and their requirements, it can make the proper decisions and initiate the necessary software downloads [11]. For each software download, the corresponding SDR application is downloaded from some data base within the application environment to the designated SDR platform of the computing environment. (This interaction between the application and computing environments is not shown in the figure.) Once downloaded, the SDR application is mapped to the platform's computing resources before defining the platform's new radio functionality. This indicates that the computing and the application cycles cannot operate completely independently; neither can the radio cycle be fully separated from them. Instead, this logical separation needs a synchronization point, which is the IRME.

2.4. Integrated Resource Management

The integrated resource management entity is the brain of our cognitive radio system: On the one hand, the IRME synchronizes the three cognitive cycles. On the other hand, and much more important, it contains the necessary intelligence to jointly process all the environmental information and to decide upon appropriate actions while being aware of the possible consequences. The necessary information can be previously injected to the IRME or obtained during the learning process of the system in operation. The probably most effective way to foster a system's intelligence is to apply both techniques: provide some previous information and let the system learn (intelligence, in fact, stands for the capability to learn).

A straightforward way of learning is *learning-by-observing*, meaning that the appropriateness of a decision is analyzed after making this decision to deduce whether it was a right or a wrong one. Other learning techniques, such as reinforcement learning [12], are much more powerful and should be considered in this context. Their discussion is, however, out of the scope of this document.

3. Simulations

We simulate a heterogeneous radio scenario and apply a simple integrated resource management algorithm to prove the above concepts. In line with section 2 we first describe the radio scenario, followed by the computing characteristics, the application instances, and the resource management algorithms. Simulation results are discussed thereafter.

3.1. Radio Scenario

These simulations analyze the effect of integrating the three cognitive cycles of section 2 on the intelligent reconfiguration of SDR mobile terminals. We therefore simulate the following heterogeneous radio scenario, where the cognitive radio system of Fig. 1 controls an area with both GPRS and UMTS coverage (Fig. 2):

- 5000 active SDR mobile terminals (SDR-MT's), which are distributed over a large time span; they enter, remain, and exit the system's boundary.
- Each user initiates or runs a session in some mode, e.g. GPRS, and observes up to 3 horizontal handovers (HHO's between the two Node-B's), vertical handovers (VHO's from GPRS to UMTS or vice versa), or QoS up- or downgrades (QoSX – change to another UMTS data rate) as a function of the terminal's current position and the user's service request. A VHO or QoSX requires a terminal reconfiguration from one operating mode to another. If this fails, the user session is lost.
- The target mode probability of a handover or QoSX is 0.4 for GPRS, 0.3 for 64kbps-UMTS, 0.2 for 128kbps-UMTS, and 0.1 for 384kbps-UMTS.

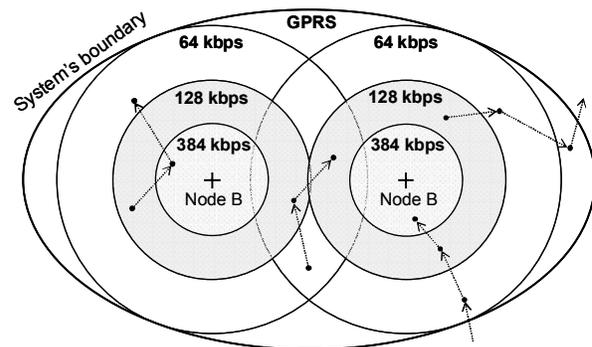


Figure 2. Radio scenario – the cognitive radio system's coverage area

3.2. Computing Characteristics

In this case study we do not address the management of network elements but rather assume full network support in terms of computing resources. The architecture and computing resources of SDR mobile terminals and the assumed mapping algorithm are presented in continuation.

3.2.1. Architecture and Computing Resources. The 5000 SDR mobile terminals are of the same architecture but varying computing resources (Fig. 3). P_1 , P_2 , and P_3 are the processing capacities of processors P_1 , P_2 , and P_3 and are, for simulation

purpose, independent random variables that are uniformly distributed in [2700, 2800, ..., 3800] Mops (Million operations per second). B is the bus bandwidth that is available for the data transfers between the three processors. It takes the constant value of 3000 Mbps (mega-bits per second).

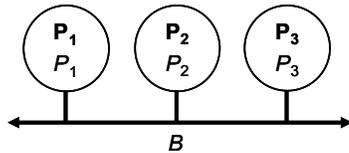


Figure 3. SDR mobile terminal architecture and its computing resources

The 4-tupel (P_1, P_2, P_3, B) describes a platform's remaining processing and bandwidth capacities after de-mapping the SDR functions of the currently running mode and before mapping the SDR functions of the next mode. Other RAT- or non-RAT specific software may remain running during a terminal's reconfiguration. Hence, although the 5000 SDR-MT's may be initially homogeneous and identical, e.g. $P_1 = P_2 = P_3 = 3800$ Mops and $B = 3000$ Mbps, they become heterogeneous and non-identical during operation as a function of the users' preferences (software downloads, user-operator agreements, etc.).

We assume that each terminal contains the analog RF circuitry that is necessary to access the GPRS and WCDMA air interfaces.

3.2.2. Mapping Algorithm: t -mapping. Each SDR-MT is equipped with the t -mapping algorithm [7]. It locally maps the downloaded SDR processing chain to the platform's available computing resources. In particular, it maps each SDR function to all available processors to locally minimize 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 direct memory access. 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, which must be feasible; otherwise it is useless. A feasible mapping, or *feasible reconfiguration*, 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.

Only an optimal mapping approach can guarantee a feasible reconfiguration in case it exists. However, such an algorithm has a non-polynomial (NP) runtime and is thus impractical in software-defined and cognitive radios. The t -mapping's low complexity greatly facilitates its implementation. Since being non-optimal, it does not always find a feasible solution [7].

The algorithm's internal SDR platform modeling assumes $P_1 \geq P_2 \geq P_3$. Then, and due to the symmetry of the SDR-MT architecture of Fig. 3 only about a sixth of all simulated SDR-MT's have to be examined and memorized by the cognitive learning mechanism within the IRME (section 3.4).

3.3. Application Instances

The SDR applications are 3 UMTS downlink receivers, each comprising 20 SDR functions. Figs. 4 and 5 illustrate these SDR functions and their computing requirements for the data rates of 64, 128, and 384 kbps. Also shown are some implementation details, which are due to [13]–[15] and available implementations. An SDR function's processing requirement is the number of multiply-accumulate operations times the required processing frequency. Likewise, a bandwidth demand is the product of the corresponding sampling frequency and the implemented bit-precision.

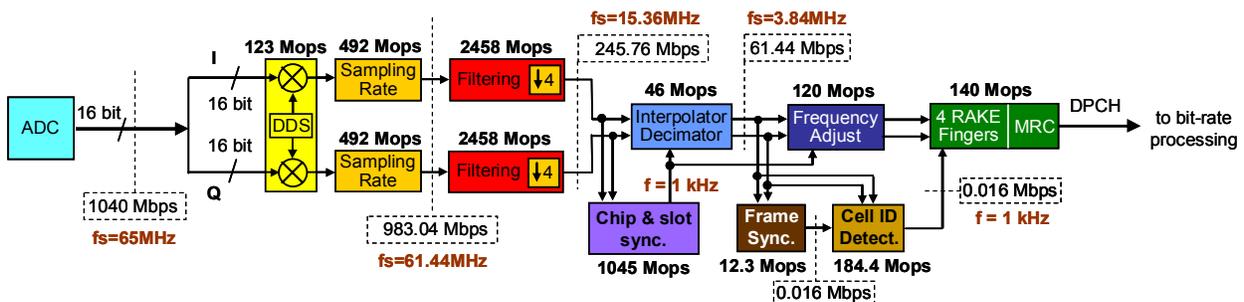


Figure 4. Chip-rate computing requirements of a UMTS downlink receiver

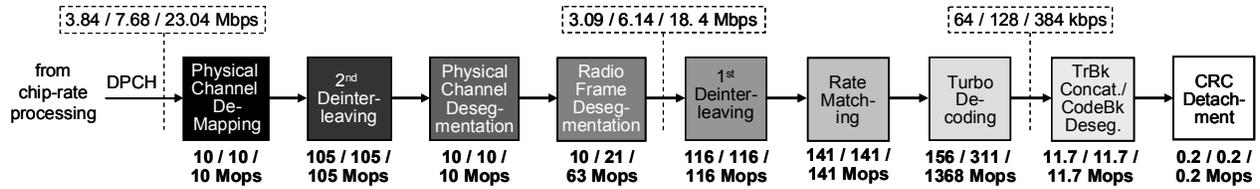


Figure 5. Bit-rate computing requirements of a 64 / 128 / 384 kbps UMTS downlink receiver

The total processing requirements of these SDR applications are $p_{64} = 8130$, $p_{128} = 8300$, and $p_{384} = 9400$ Mops. The corresponding GPRS processing chain requires about a tenth of these processing requirements and can thus be easily mapped to any SDR-MT of this study.

The processing and bandwidth resources of Fig. 3 are dedicated to these receiver chains. We assume that additional computing resource for implementing the higher OSI layers and the UMTS or GPRS uplink transmitter are sufficiently available.

3.4. Resource Management Algorithms

We apply two resource management algorithms: a simple integrated resource management algorithm (IRMA) and a baseline algorithm (BSLA). The BSLA assumes the execution of just the radio cycle and is thus unaware of the available computing resources and the applications' requirements.

3.4.1. Integrated Resource Management Algorithm.

The IRM algorithm reconfigures an SDR mobile terminal as a function of its computing capacity, the available software downloads and the SDR applications' computing requirements, and the radio resource availability at the user's current position. First of all, the IRME defines the following rules as a function of a platform's total processing capacity P_T and the SDR applications' processing requirements p_i ($i \in 64, 128, 384$):

- 384 kbps UMTS if $P_T \geq p_{384}$,
- 128 kbps UMTS if $p_{128} \leq P_T < p_{384}$,
- 64 kbps UMTS if $p_{64} \leq P_T < p_{128}$,
- GRPS if $P_T < p_{64}$.

The IMRA chooses the best possible solution as a function of the above rules, the radio scene analysis and the accumulated mapping information. The best possible solution refers to selecting the SDR application that supports or nearly supports the desired QoS. We assume that the users are willing to accept a possible QoS degradation whenever necessary to maintain the current session.

A mapping of an SDR application to an SDR platform is either feasible or infeasible. If infeasible, this session is lost and the next platform of the same

characteristics will not be considered again for executing this SDR application but rather the next lower one in terms of processing requirements. This mapping information is accumulated during the system's execution. Hence, the cognitive radio system learns which SDR applications can and which cannot be feasible mapped to the different SDR-MT's (learning-by-observing).

3.4.2. Baseline Algorithm. The baseline algorithm chooses the SDR application due to the radio scene analysis, that is, as a function of the radio resource availability at the SDR-MT's current position and the user's QoS request. An infeasible reconfiguration again translates to a lost user session. Since ignoring the computing and radio cycles, the BSLA cannot apply the above learning mechanism. It still may implement some cognitive learning algorithm that processes the supplied radio resource information. We can consider this out of the scope here because it affects both resource management algorithms.

3.5. Simulation Result and Discussion

Fig. 6 shows the evolution of the number of lost user sessions due to infeasible reconfiguration requests. We observe that the curve representing the BSLA continuously increases, whereas the learning capability of the IRMA leads to saturation. More precisely, Fig. 6 illustrates that the IRMA-curve begins saturating before the 2000th SDR-MT. In a dynamic radio scenario (of the future), where many wireless subscribers make use of a wide variety of multimedia services, this can be considered a fast saturation. Such a fast saturation, or adaptation to the surrounding environment, is highly desirable, especially when bearing in mind that the radio, computing, and application environments change at a steadily increasing pace.

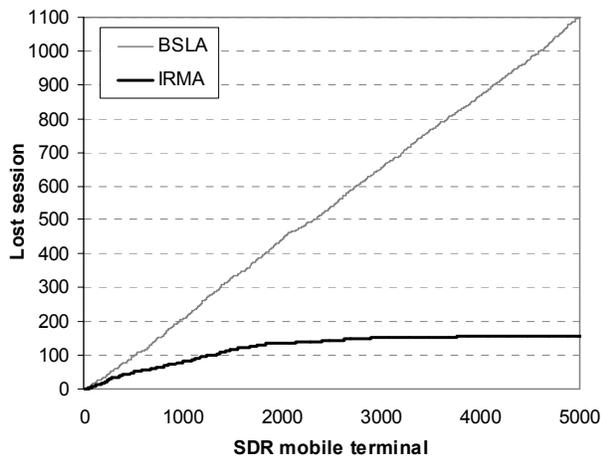


Figure 6. Evolution of the number of lost sessions

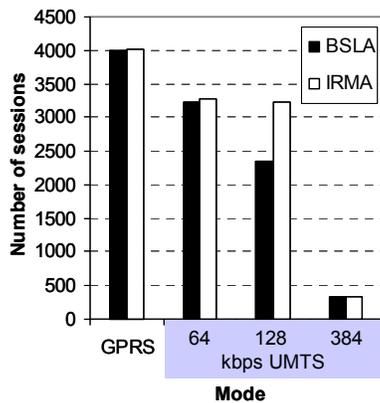


Figure 7. Total number of sessions per mode

The total number of terminal reconfigurations is 11 006; 9907 and 10 847 are feasible in case of the BSLA and IRMA. Fig. 7 shows that the total number of feasible reconfigurations due to the IRMA is, for any mode, equal or higher than the total number of feasible reconfigurations due to the BSLA. This reflects that the IRMA may sacrifice the QoS only for the sake of connectivity. In other words, whenever the new mode that the radio scene analysis suggests or requests for a given SDR-MT is feasible, the IRMA reconfigures the terminal to this mode.

4. Conclusions

This paper introduces the concept of integrated resource management in cognitive radio. Our cognitive radio system proposal executes the radio, the computing, and the application cycles. It integrates the radio, the computing, and the application resource management and, thus, extends the scope of the

original cognitive radio concept, which basically addresses the joint radio resource management.

We have discussed a simple simulation scenario to indicate the achievable improvements of our proposal in respect to a cognitive JRRM by itself. A more complex simulation scenario or more powerful cognitive algorithms would, most probably, reinforce our approach. On the other hand, we believe that it is necessary to define a general framework before introducing powerful cognitive algorithms or addressing complex simulation scenarios. The presentation of such a framework is this paper's contribution.

5. Acknowledgment

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