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A Real Time Emulator Demonstrating Advanced Resource Management Solutions

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Abstract The E2R-II prototyping environment, as part of the E2R-II project, is a framework that pretends to demonstrate the most promising radio resource management proposals that are developed within the project. Such demonstrations have been based on a dedicated proof-of-concept environment, which serves for validating the work in the areas of cognitive networks, reconfigurable terminals, enhanced radio resource and spectrum efficiency, and dynamic and robust reconfigurations. In this framework, this paper presents a real time demonstrator running IP-based applications for the validation of ASM/JRRM algorithms. Such a demonstrator tries to reproduce in a realistic way a B3G heterogeneous radio access network, which considers different RATs (UTRAN, GERAN, WLAN), interfacing a common Core Network. This demonstrator serves for testing the ASM/JRRM strategies that are proposed within the E2R project. In addition, the E2R ASM/JRRM demonstrator incorporates the capacity to evaluate the QoS experienced by the user when using real applications under controlled conditions of the used RAT and the CN.

Keywords Real time emulation · Advanced Spectrum Management (ASM) · Joint Radio Resource Management (JRRM)

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1 Introduction

The steady evolution of wireless technologies allows operators delivering more and more advanced multimedia services. In parallel, the regulatory perspective on how the spectrum should be allocated and utilized is tending towards a more flexible spectrum usage. More precisely, we observe a cautious introduction of more flexibility in spectrum management together with economic considerations on spectrum trading. These new paradigms are driven by the growing competition for spectrum and the requirement for its more efficient usage [1].

This scenario can only be fully accomplished by further enhancing the Radio Access Networks (RANs) towards Cognitive Network (CN) complemented with Cognitive Radio-based technologies. On the one hand, a CN has a cognitive process that can perceive current network conditions, and then plan, decide, and act upon those conditions. The network can learn from these mechanisms and use this knowledge to derive future decisions [2]. On the other hand, Cognitive Radio (CR) technology allows individual radios to make choices about their frequency use based upon the radio environment [3].

A number of techniques have been identified, proposed, and analyzed in recent years to cope with heterogeneous wireless networks with flexible spectrum management capabilities [4]. Joint Radio Resource Management (JRRM) is the process that enables the management (allocation, de-allocation) of radio resources (time slots, codes, frequency carriers, etc.) within a single or between different radio access systems for a fixed spectrum band allocated to each one of these systems. In turn, Advanced Spectrum Management (ASM) is the process that enables the dynamic management (allocation, de-allocation, sharing) of spectrum blocks within a single or between different radio access systems in order to adapt to the current demand of radio resources. These baseline strategies target the most efficient radio resource utilization, while providing a "seamless experience" to the mobile users. Taking these as the objectives for a more dynamic spectrum allocation, the different resource optimization techniques need to be integrated into a coherent framework, while bearing in mind that the use cases pose individual problems of resource utilization, each requiring a different approach to achieve the optimal allocation.

The complete picture of a multi-operator, multi-RAT, multi- cell, multi-user, and multi-service scenario can only be fulfilled in a mature deployed and operational network (on a per-operator basis), with real users generating a high enough load into the network so that the benefits of the ASM/JRRM strategies become relevant. This is neither feasible today nor in the mid-term. On the other hand, a pure simulation approach to assess the benefits of the developed algorithms is not enough. Hence, a trade-off needs to be reached, with some of the elements being emulated (following a sufficiently realistic emulation model) and having the capability to be run in real time. In that case, the impact on real IP-based applications and services together with the algorithms' implementations needs to be validated so that a sufficient proof of concept is provided.

The E2R-II prototyping environment is a framework defined in the E2R-II (End-to-End Reconfigurability—Phase 2) project [4] that serves for demonstrating the most promising ideas that have been developed within this project. Such demonstrations have been based on a dedicated proof-of-concept environment that validates the work in the areas of cognitive networks, reconfigurable terminals, enhanced radio resource and spectrum efficiency, and dynamic and robust reconfigurations. This paper presents a component of this framework that constitutes the validation tool for ASM/JRRM solutions.

In particular, we present a real time demonstrator running IP-based applications for the validation of ASM/JRRM algorithms. In addition to the quantified performance indicators, a valuable outcome of the testbed is the capability to assess the subjective QoS perceived by the user (sometimes referred to as QoE—Quality of Experience). In order to provide insights into the capabilities of the emulation platform, an ASM algorithm enhancing the spectrum utilization is described and evaluated. The rest of the paper is organized as follows: Sect. 2 describes the demonstrator architecture, including the different building blocks as well as the implementation aspects. Section 3 introduces a specific Advanced Spectrum Management algorithm as an illustrative case study, presenting some of the results obtained with the demonstrator. Finally, Sect. 4 summarizes the conclusions.

2 ASM/JRRM Demonstration Framework

2.1 Objectives and Requirements

The main objective of the E2R-II ASM/JRRM demonstrator is to show the benefits of the developed ASM and JRRM algorithms and proposed QoS management techniques. Basically, the demonstration framework emulates, in real time, the impact of the heterogeneous wireless network, including the effect of the other users, on a reference user (denoted as UUT—user under test), while making use of real IP-based applications (e.g. videoconference, web browsing, and video streaming). The prototyping framework aims to capture features that are not easily achievable by means of conceptual studies or system level simulations. Furthermore, an open Application Programming Interface (API) is defined. This API facilitates testing any ASM/JRRM algorithm that is defined according to some specified rules.

The ASM/JRRM demonstration framework is based on a stand-alone real time emulator platform that emulates the GERAN, UTRAN, and WLAN radio access networks (RANs), including all the relevant QoS entities. The proposed approach considers that the required functions that are to be included in each RAN emulation model and in the overall demonstrator architecture must be identified from the kind of scenarios we envisage to test. The processing of the UUT data traffic changes during time as a function of the RAN, the RAB (Radio Access Bearer) and the provided QoS at each instant of the demonstration.

The possibility to interface the demonstrator with real radio equipment in the general E2R-II framework reinforces the real time processing requirements and introduces the need to develop specific APIs and interfacing mechanisms to deal with these issues. Such APIs should be generic and flexible enough to accommodate the management and interfacing requirements from external equipment for most of the demonstrations related with ASM/JRRM issues.

2.2 Architecture

The E2R-II ASM/JRRM demonstrator architecture reflects the required functionalities that are necessary to ensure its capacity of demonstrating the foreseen scenarios and situations. It should provide a flexible framework where the identified proofs of concepts have the room to be implemented. Several key assumptions, related with the QoS management that is done in the different subsystems for each user, must be taken into account in accordance with the considered scenario.

Figure 1 shows the conceptual architecture of the demonstrator and in the following lines a short description is given. The principal building blocks of the E2R-II real time demonstrator (E2R-RTE) are:

- *RAT emulation modules.* A set of modules that emulate UTRAN, GERAN, and WLAN technologies.

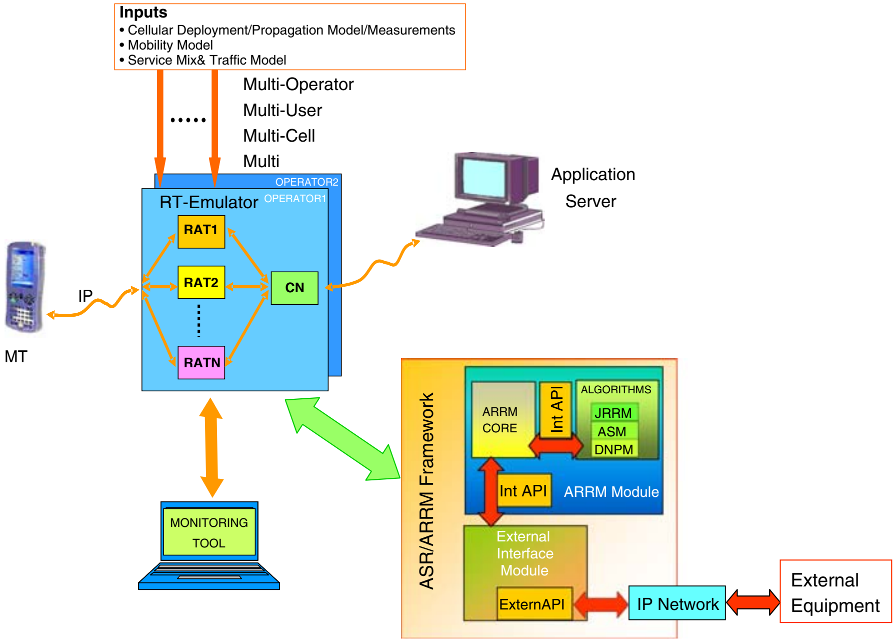

Fig. 1 Demonstrator architecture

- *Traffic Capture & RAN Switching Module.* Real IP packets that are coming from and going to the application under test are captured in the corresponding network interfaces, before being delivered to the radio processing modules at the user plane. This module is properly configured on the basis of the negotiated Traffic Flow Templates (TFT). The RAN Switching capabilities are required to deliver the user data and the signaling traffic to the currently connected RAN. The session management control entities manage this module at run-time.
- *Core Network.* The Core Network is based on real state-of-the-art IP routers that are implemented on PCs running Linux. Diffserv mechanisms are included to provide QoS in the core network Core Network which is managed by a bandwidth broker node.
- *ASM/JRRM Framework.* This module is in charge of the QoS management for heterogeneous RANs. It includes: (a) The JRRM Core module, which incorporates essential functions to manage the admission and congestion control, outer and inner loop power control, handover (vertical and horizontal) management and control, radio resource allocation and transmission parameter management. It periodically updates the path-loss information related with the users' positions. This module interfaces with the RAN emulators in order to capture the relevant information of base stations (BSs) and user' terminals under different RAT conditions. It finally controls the provided QoS of all active users in the demonstration session. (b) Internal API. The interaction between the demonstrator and any ASM/JRRM management entity is exclusively carried out through this specific API. It allows obtaining information from the demonstrator and changing the configuration of the selected parameters at run time. It captures the information from the demonstrator and can change the configuration of selected parameters at run time. The API functions are openly designed and are able to manage any parameter that is described in a particular configuration file, as long as the demonstrator supports such a parameter manipulation.

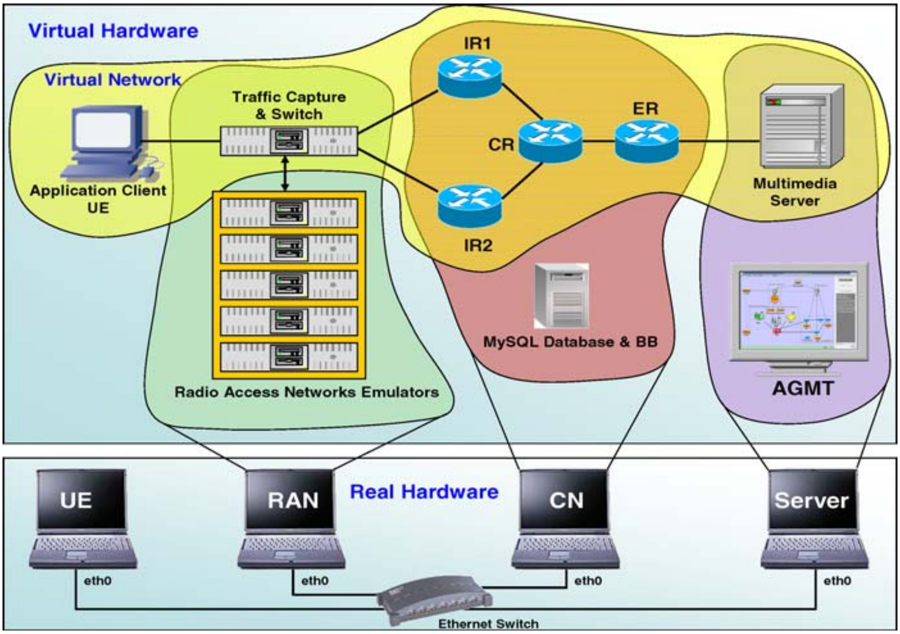

Fig. 2 Demonstrator implementation

(c) ASM module, where the ASM/JRRM algorithms to be tested will be incorporated. The previously defined API interfaces with the rest of the emulator and provides the inputs to these algorithms and sends their outputs to the specified emulation modules. (d) The External Interface Module constitutes the interface between the emulator and external equipment. It is capable to facilitate full access to the demonstrator and the management functionalities due to the API specifications.

- *Advanced Graphical Management Tool (AGMT).* This tool facilitates the management of the configuration files for initialization purposes. It furthermore sets up the scenarios, centralizes the collection of statistics, and carries out the overall system control.

2.3 Implementation Details

All the system has been built by using the Communication Manager (CM), which provides interfacing and execution control tools among the different emulation software modules and controls their execution [5]. The current version of the demonstrator runs on cluster of 4 laptops with P4 processors clocked at 3.4 MHz. Linux Fedora Core 3 is the operating system that runs on each laptop. We identify one laptop to be in charge of traffic switching and the emulation of the Heterogeneous Radio Access Network (RAN). A second laptop carries out the emulation of the network elements that should deal with the emulation of the UMTS Core Network (CN), whereas the remaining two work as the user terminal and application server (UE and Server). Figure 2 illustrates this. The 4 routers that emulate the Core Network have been implemented using the routing capabilities of Fedora Core 3, running as four virtual machines. These have been created using VMware over the CN identified laptop. This is the basic configuration, which can be easily extended, for example, if more computing capacity

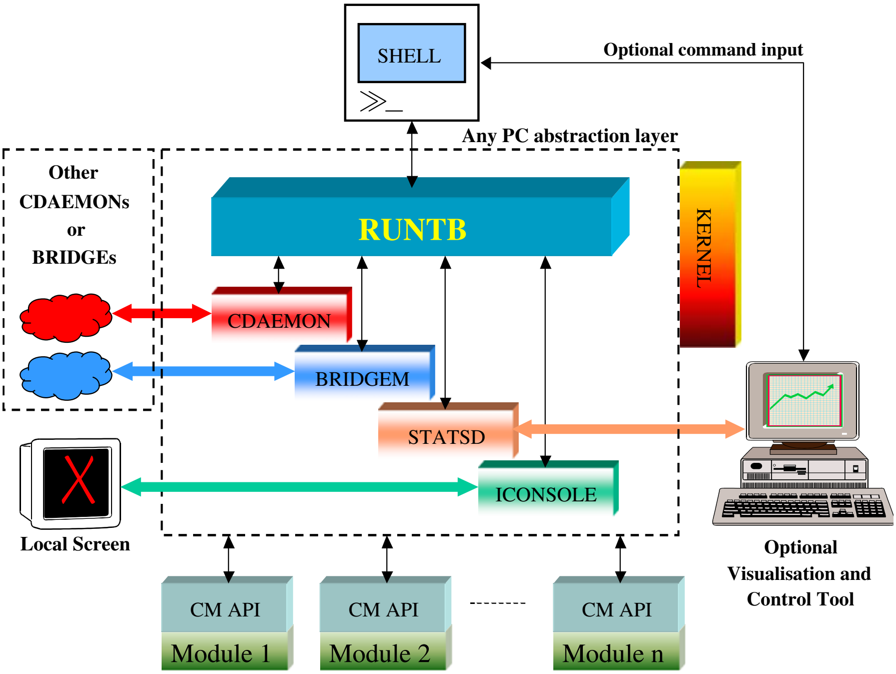

Fig. 3 Communication manager

is required to process additional users. In this case, additional laptops would carry out part of the computational load of the RAN emulation.

Software produced by different programmers running together on a distributed environment needs to be structured according to a common framework. The CM is one possible solution to integrate the different software pieces of an application. The hierarchy of CM software is shown in Fig. 3. The top-most element is the SHELL that offers a manual command-based interface to control the application. It is just the tool to allow the user to set-up the application context and operate on it. The SHELL can interface to any other tool with a friendlier interface (e.g. graphical application management) through a network connection, just to allow a remote management. For proper operation, it requires a daemon (RUNTBD) running on each one of the machines where the application will have one or more software modules running. This daemon is in charge of starting the remaining CM daemons that perform other tasks (CDAEMON, BRIDGEM, ICONSOLE and STATSD as shown in Fig. 3) and also starts the different software modules that the application requires on a given machine.

- CM daemon (CDAEMON) is not operated by user. It provides to CM API a front-end to support application software modules requirements in terms of resource allocation.
- CM ICONSOLE daemon is neither managed by the user. It opens a new window, separated from window where RUNTBD is running to display system messages but also messages originated at modules.
- CM BRIDGEM provides transparent communication between modules running in the different machines. Each BRIDGEM uses the IP addresses information provided within the connection configuration file to establish a link with any other BRIDGEM in the system.

- CM STATSD is the daemon allowing the capture of statistics of the behavior of the application being executed.
- Additionally, and not shown in the figure, CM incorporates two important elements, SYNCS and SYNCD (server and client respectively). They allow synchronizing the local time of all the machines to the time of a single one of them (the time server) by means of a packet-based current time exchange mechanism.

Therefore CM offers the possibility to seamlessly distribute the software pieces across several machines that have a network interface (or any other interface), thus running the application in parallel to improve performance or meet the given timing constraints. The application itself is not aware of how many machines are being used to run the different software blocks that compose it. The CM thus hides the platform details to the application and executes it in soft real-time offering timing control of software modules. CM provides a centralized method to start, stop, debug, and monitor the whole application running in a cluster of processors and gathering multiple forms of data provided by modules to be observed in real-time, or post-processed after the application has finished its execution.

The CM features a set of system-independent functions to the software modules of an application. The capabilities offered by these functions are considered as part of the platform abstraction layer provided by CM. On the other hand, the interaction between the stand-alone demonstrator and any ASM/JRRM management entity is exclusively carried out through the Int API of Fig. 1, which is detailed in next sub-section.

2.4 Int API Description

The definition and implementation of an API has been one of the key issues to facilitate the incorporation of new ASM/JRRM management algorithms into the demonstrator and to integrate external equipment.

Since the type of parameters that can be exchanged with the demonstrator belong to an arbitrarily long alphabet, which is not necessarily completely defined at the API implementation time, the API functions are designed to be open and able to manage any of the parameters that are described in a particular configuration file. This requires that the demonstrator supports such a parameter manipulation. Therefore, the core API functions are multi-purpose. They may perform many generic but related tasks to reduce the number of functions in the library.

Before using this API, it is necessary to adapt any ASM/JRRM management entity to use the available information through the previously defined parameters. Once this is done, it is possible to integrate the management entity (ASM/JRRM algorithm) with the E2R-RTE. The first method to achieve this integration is to link the API library during the process of creation of the ASM/JRRM executable code. This is illustrated in Fig. 4a. In this case the management entity includes an API implementation that is in charge of interacting with the demonstrator hardware and software. The link between the two parts of the application will be exclusively carried out by means of the API functions. Another possible API utilization offers a simplest integration of the ASM/JRRM software with the demonstrator, as shown in Fig. 4b. In this case the interaction between the API and any other software entity is done through a network interface. Although the commands exchanged through such an interface carry the same information as the parameters that are passed to the API functions, this second approach facilitates integrating the API within the software, which can hardly be fulfilled using a C library of a UNIX-like platform. The External Interface Module does the adaptation between the external and internal APIs.

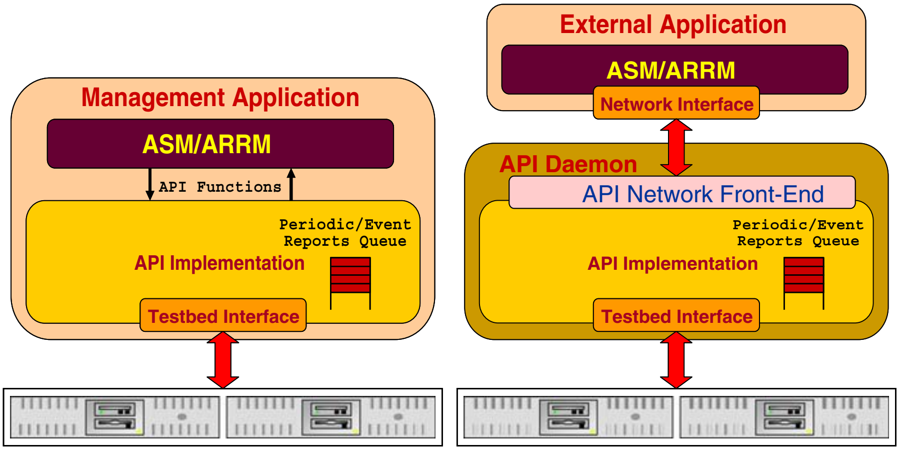

Fig. 4 E2R-RTE ASM/JRRM API. Case A: internal. Case B: external

The information data is sent to and received from external equipment through the IP network using a TCP/IP socket connection. It is established for the information transfer between the external equipment and the E2R-RTE demonstrator as a flexible mechanism that can cope with the data transfer requirements.

3 Case Study: ASM Algorithm

The objective of the Advanced Spectrum Management (ASM) methodology is to find the appropriate spectrum allocation that satisfies the maximum number of users at all periods of time. ASM has been studied extensively in the last few years [4,6–8]. The proposal illustrated in this paper introduces a detailed characterization of the interaction between WCDMA cells, leading to a more accurate interference representation. Consequently, it is able to increase the system performance by a smart distribution of frequencies over cells. This process can lead to an either global or local release of some RAT frequencies, which could then be temporarily used by other RATs; this involves applying inter-RAT ASM algorithms. The suggested strategy is based on the coupling matrix concept, which intends to reflect the inter-cell interactions depending on the current traffic distribution as a function of time and space. This matrix serves as a smart indicator that can be used to capture the macroscopic and the microscopic patterns of all scenarios [9].

The proposed ASM algorithm intends to derive a suitable spectrum allocation in a given scenario (i.e. mapping of carriers to cells). When relevant variations in the traffic distribution occur (i.e. some of the cells that share the affected carriers are experiencing high interactions and should no longer use the same carrier) a new allocation should be found. The detection of this event is a very important issue in the overall ASM methodology to guarantee the required QoS levels. The different steps of the ASM algorithm in the uplink of a WCDMA system are summarized in the following:

1. Evaluate the coupling matrix for the different cells using the path loss of each mobile with respect to the different cells and the service characteristics (see [8] for details). Assuming K cells in the scenario, the coupling matrix has a KxK dimension and each element is defined as:

$$C_{j,l} = \begin{cases} 0 & \text{if } l = j \\ \dfrac{S_{l,j}}{1 - S_{j,j}} & \text{otherwise} \end{cases} \tag{1}$$

The term $S_{l,j}$ reflects the impact of cell l over cell j. It is defined as:

$$S_{l,j} = \sum_{i_l=1}^{n_l} \frac{L_{i_l,l}}{L_{i_l,j}} \frac{1}{\frac{W}{\left(\frac{E_b}{N_o}\right)_{i_l} R_{b,i_l}} + 1} \tag{2}$$

where i_l represents the i-th user connected to the l-th cell, n_l is the number of users connected to the l-th cell, $L_{i_l,l}$ the total propagation loss between the i_l user and the l-th cell, W the total bandwidth, and $(E_b/N_o)_{i_l}$and R_{b,i_l} the requirements of the user in terms of E_b/N_o and bit rate, respectively.

2. Evaluate the spectral radius (i.e. the maximum eigenvalue) of the coupling matrix.
3. If the spectral radius is above a certain threshold, which is equivalent to having a high outage probability, then continue with step 4 in order to modify the carrier to cell allocations; otherwise, finish the procedure.
4. For each cell j determine the number of frequencies to be allocated as:

$$F_j = \min\left(\left\lceil \frac{S_{j,j}}{\beta} \right\rceil, F\right) \tag{3}$$

   where F is the maximum number of available frequencies and β a control parameter of the algorithm. Notice that the term $S_{j,j}$ as defined in (2) will be a measure of the total intra-cell load in cell j. Then, by equally splitting this load among the allocated frequencies F_j, (i.e. assuming a load balancing approach), the load in each frequency would be $S_{j,j}/F_j$. For a proper operation, depending on the amount of inter-cell interference and the specific conditions, it is necessary that this load is below some threshold β in order to ensure that there is enough power available to meet the E_b/N_o requirements. Consequently, the limit $S_{j,j}/F_j < \beta$, together with some considerations regarding the fact that the number of frequencies must be an integer number, yields the relationship given in (3).
5. Distribute the frequencies among the cells in a way that the 1st frequency is allocated in all cells, the 2nd is allocated in all cells requiring at least 2 frequencies, the 3rd in all cells requiring at least 3 frequencies, and so on.

The performance of the proposed ASM algorithm has been evaluated on the E2R-RTE demonstrator under a scenario that considers a service area of 13 UTRAN cells. Results are included in terms of:

- Quantitative KPI (Key Performance Indicators) extracted from the real time emulation in different scenarios and conditions when applying the proposed ASM algorithm.
- Qualitative QoE (Quality of Experience) measurements extracted from real time observations of the perceived quality for different IP-based applications (e.g. video streaming and interactive game).

3.1 Quantitative KPI Results

As an example of quantitative KPI results we observe the different behavior of the proposed ASM algorithm when considering two different values for β. The considered service area includes up to 13 UTRAN cells where up to three different bands are available. The service mix in the scenario assumes that 50% of the users run a videostreaming application at

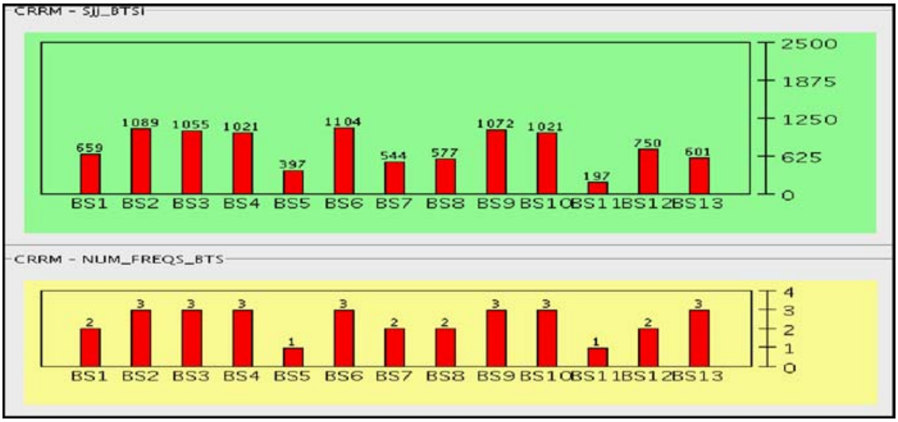

Fig. 5 S_{jj} values (scaled by 1000) and number of carriers in the different cells for $\beta = 0.5$

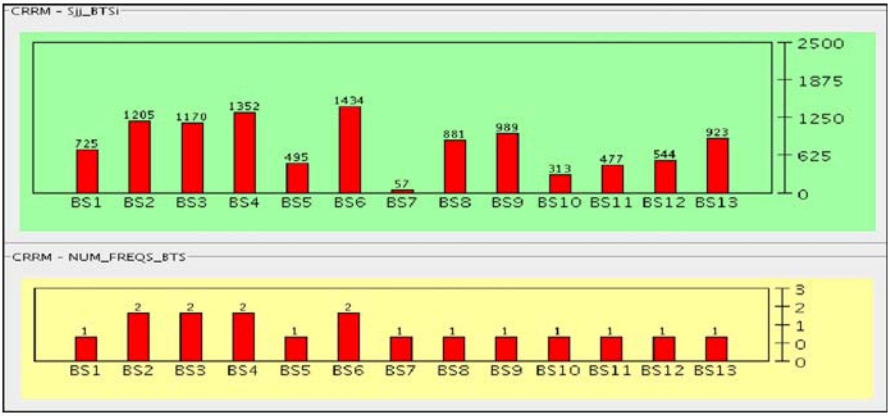

Fig. 6 S_{jj} values (scaled by 1000) and number of carriers in the different cells for $\beta = 1.0$

128 kbps, 25% of the users a videophone application at 64 kbps, and 25% browse the web at 24 kbps in average. Figures 5 and 6 show the $S_{j,j}$ value (scaled by 1000) in the upper graph and the current number of frequency bands assigned to each cell in the layout in the lower graph for $\beta = 0.5$ and $\beta = 1.0$, respectively.

From Fig. 5 we can observe how the number of frequency bands assigned to each cell varies between 1 and 3, the latter being the maximum number of available frequencies whereas the $S_{j,j}$ value reflects the load existing in each cell. Notice that for $\beta = 0.5$ an important number of cells use the three carriers. On the contrary, Fig. 6 shows that the system dynamics lead to a generally smaller number of carriers that are allocated to the different cells. This is achieved at the expense of increasing the overall interference existing in each frequency. Nevertheless, for the current load conditions, it is still possible to provide the service at an acceptable QoE level, as it will be discussed in the next sub-section. Notice also that with $\beta = 1.0$ the operator would have more facilities to release some of the available carriers so that they can be leased or used by a secondary market, thus achieving a better spectral utilization. In this case it would be possible to release 2 carriers of the cells BS7 to BS13 (Fig. 6).

Fig. 7 QoE estimation. Picture **a** (*left*): original, Picture **b** (*right*): degraded

3.2 QoE (Quality of Experience) Measurements

Several procedures have been developed in the recent years to provide the estimation of the perceived quality from some objective measurements using specific algorithms. The MOS (Mean Opinion Score) protocols for video and audio QoS evaluation are specified in the ITU-T (International Telecommunication Union), where the typical schemes use subjective tests (opinion scores) that are mathematically averaged to obtain a quantitative indicator of the system performance.

The procedure we apply for a videostreaming service consists in comparing an original video with its processed version, which the user under test receives from the application server through the E2R-RTE. Therefore we propose the Video Quality Metric (VQM) that correlates these two videos using the perception of a normal end user. Figure 7 shows a screenshot of the two versions of an example video.

Picture B shows an important degradation in comparison to the original video of picture A. These pictures were extracted from a one minute video, where the original video obtained a VQM qualification of 4.5 (maximum 5) and the degraded one a VQM score of 3.3.

This QoE evaluation framework facilitates providing some results on the perceived QoS as a function of the proposed ASM/JRRM algorithm parameters: We could observe a small reduction in the averaged VQM parameter of 4.2 to 3.9 by increasing the “interference tolerance” β from 0.5 to 1.0. The corresponding results are not shown due to space limitations. This difference in the QoE is due to the higher average value of the load factor of the different cells existing with $\beta = 1.0$. Such a small reduction reveals the suitability of the approach. So, if VQM score of 3.9 is good enough, the third frequency of BS7-BS13 can be temporarily leased to other operators, increasing the spectrum efficiency (see Sect. 3.1).

4 Conclusions

This paper presents the main features of a real time demonstrator that has been developed within the E2R-II prototyping framework. Starting with an overview of the architecture model, we have described the emulator’s major functions and procedures, especially those related with the ASM/JRRM strategies. We have detailed some of its modules and interfaces, with special emphasis on the APIs. Finally, we have proposed a methodology to capture the perceived QoS by an end user using relevant IP Multimedia applications.

We have presented a case study that deals with the analysis of a particular ASM algorithm. This scenario reveals the possibilities of a more efficient usage of the available spectrum by releasing unused carriers without significantly degrading the perceived QoS.

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X. Revés was born in Sarroca de Lleida (Spain) in 1974. He received the Telecommunication Engineering degree from the Universitat Politècnica de Catalunya (UPC), Spain, in 1998. From 1999 he was with the Department of Signal Theory and Communications at the UPC, first as a PhD student and from 2001 to 2006 also as Assistant Professor. His PhD research is focused in radio communications, with special emphasis on DSP platforms including hardware and software architectures, software radio technologies and analogue/digital transceiver front-end architectures. Until 2006 he has been participating in several projects of technological transfer to industry, including the European FUSE program. He has also been involved in the European Framework Program projects AR-ROWS, EVEREST and E2R. In 2006 he joined Gigle Semiconductor, a fables semiconductor company, where he designs and develops DSP algorithms for high speed communications.

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