Real-Time Evaluation of Radio Access Technology Selection Policies in Heterogeneous Wireless Systems: The AROMA Testbed Approach

Miguel López-Benítez, Nemanja Vučević, Francisco Bernardo, Anna Umbert
Department of Signal Theory and Communications
Universitat Politècnica de Catalunya (UPC)
Barcelona, Spain

{miguel.lopez, vucevic, fbernardo, annau}@tsc.upc.edu

ABSTRACT
This paper presents and describes the real-time testbed for all-IP Beyond 3G heterogeneous wireless networks that has been developed in the framework of the European IST AROMA project. The main objective of the AROMA testbed is to provide an advanced and realistic framework where the benefits of the algorithms developed within the AROMA project for both the radio access network and core network parts, as well as for the management of the end-to-edge quality of service, can be demonstrated. In particular, this paper focuses on the radio access part of the testbed, providing an in-depth description of its implementation and showing performance results with numerous supporting data that demonstrate the potentials and capabilities of the developed tool for the real-time evaluation of Radio Access Technology (RAT) selection policies under realistic scenarios. To this end, the behavior of two innovative RAT selection algorithms recently proposed in the literature has been assessed, analyzed, and compared in order to demonstrate the applicability of the tool.

Categories and Subject Descriptors
I.6.3 [**Simulation and Modeling**]: Applications; I.6.7 [**Simulation and Modeling**]: Simulation Support Systems – *environments*; J.2 [**Computer Applications**]: Physical Sciences and Engineering – *engineering*.

General Terms
Algorithms, Design, Experimentation, Measurement, Performance, Verification.

Keywords
Beyond 3G; common radio resource management; heterogeneous wireless access systems; performance evaluation; radio access technology selection; real-time testbed.

MSWiM'08, October 27–31, 2008, Vancouver, BC, Canada.

1. INTRODUCTION
Future heterogeneous wireless networks, also referred to as Beyond 3G (B3G) networks, are intended to provide a flexible and open architecture to support the coexistence of a wide range of Radio Access Technologies (RATs), applications and services with different Quality of Service (QoS) demands, and user profiles with dissimilar needs, requirements and preferences. This coexistence will force mobile operators to overcome the challenging task of achieving the seamless interoperability of the different existing RATs and managing, in the most efficient way, the pool of available resources provided by each one of the individual RATs. In this context, the term Common Radio Resource Management (CRRM) [1][2][14] is used to designate the set of functions addressed to ensure an efficient and coordinated use of the available radio resources in heterogeneous wireless networks. The aim of CRRM is to take advantage of the coverage overlap that several radio access networks may provide in a certain service area in order to efficiently meet the operator's goals in terms of coverage and QoS, while maximizing the overall capacity of the heterogeneous wireless network.

The CRRM concept embraces several techniques of diverse nature. One important function within the CRRM concept is the RAT selection function, which is in charge of deciding the most suitable RAT to provide connectivity to each user in the radio part of the network. A RAT selection algorithm must define both the initial RAT selection procedure, i.e. the allocation of resources from a given RAT at session initiation, and the procedure for triggering a Vertical Handoff (VHO), i.e. the capability to switch on-going connections from one RAT to another. RAT selection algorithms are not defined by the standardization bodies. Therefore, the development of such kind of algorithms has become an important research topic that has attracted the attention of the research community during the last years. Although this problem has been covered in an important number of papers (see for instance [5][7][8][12]), the proposed algorithms usually have been evaluated using system-level simulators. The utilization of simulation tools is common within the research and industrial communities and can be useful for obtaining preliminary results. Nevertheless, to conduct meaningful and appropriate studies, and to accurately assess the performance of the proposed solutions for mobile communication systems before considering a prototype or full-scale deployment, the evaluation over realistic emulation platforms is becoming essential as a step forward toward the implementation in a real system. Real-time emulators allow reproducing realistic scenarios to test algorithms, strategies, protocols and applications under realistic conditions. In this context, the aim of this paper is to present the real-time testbed that has been developed in the framework of the AROMA project [3] and to show the potentials and capabilities of the developed tool for the real-time evaluation of CRRM policies under realistic heterogeneous wireless scenarios. An overall description of the whole AROMA testbed can be found in [16]. This paper places the emphasis on the radio access part of the tool.

The rest of this paper is organized as follows. First, section 2 provides a brief overview of the whole AROMA real-time testbed and an in-depth description of the radio access part. To illustrate the ability of the presented platform in evaluating CRRM policies, two RAT selection algorithms have been considered in the context of this work; the selected algorithms are described in section 3. Then, section 4 analyzes the behavior of the algorithms under study with numerous results, illustrating the potential and applicability of the presented tool in the evaluation of CRRM policies. Finally, section 5 summarizes and concludes the paper.

2. THE AROMA TESTBED

2.1 General Description

The AROMA testbed allows the emulation of an all-IP heterogeneous wireless network that includes the UMTS Terrestrial Radio Access Network (UTRAN) with High Speed Downlink/Uplink Packet Access (HSDPA/HSUPA) Release-6, GSM/EDGE Radio Access Network (GERAN), and Wireless Local Area Network (WLAN) as well as the corresponding common Core Network (CN) based on DiffServ technology [4] and Multi-Protocol Label Switching (MPLS) [13]. The evaluation platform emulates, in real-time, the conditions that the behavior of the all-IP heterogeneous network, including the effect of other users, produces on the User Under Test (UUT) when making use of real multimedia IP-based applications such as videoconference, streaming services, or web browsing. Such approach allows testing real applications on an end-to-edge (e2e) basis over a complete all-IP heterogeneous network with CRRM algorithms and e2e QoS management policies. The presented tool is therefore a powerful emulation platform that enables advanced CRRM strategies as well as e2e QoS mechanisms to be accurately evaluated in a realistic environment with different real user applications and mobility patterns, which could not be achieved by means of off-line simulations.

2.2 Software and Hardware Platform

The AROMA testbed is implemented with twenty off-the-shelf Personal Computers (PCs). Two of them run Windows operating system (the applications' PCs) and eighteen PCs run Linux operating system. This approach has been proven to be adequate for its capacity to assure appropriate levels of real-time management while guaranteeing a high degree of flexibility. The capacities provided by Linux operating system to interact at low level with the kernel offer the possibility to tune accurately the performance required by the testbed, especially in the issues related with the real-time execution and management. To implement real-time operation a very high computational power is required. These computational requirements are out of the scope of today's off-the-shelf PCs. Then, a cluster of PCs has been constructed to distribute the computational load throughout different processors. To this end, a software tool named Communications Manager (CM) was designed and developed to make this distribution completely transparent.

Figure 1 shows all the entities and connections of the AROMA testbed. Black connections correspond to user data interfaces, whereas red and blue connections correspond to control plane interfaces. The UUT has at its disposal one stand-alone PC to run the application (applications' client), and one stand-alone PC is used to run the main functionalities associated to the User Equipment (UE). To test symmetric services as video-conference and to serve multimedia applications such as web-browsing or streaming, a correspondent node (applications' server) is run in a stand-alone PC. The three mentioned Radio Access Networks (RANs) are emulated using three PCs for UTRAN (two of which implement the HSDPA and HSUPA real-time emulators [6]), one PC for GERAN and one PC for WLAN. The CN has been built using seven Linux PCs acting as routers: three PCs serve as edge routers, two Ingress Routers (IRs) and one Egress Router (ER), and four PCs, identified as Core Routers (CR), interconnect the edge routers. A Traffic Switch (TS) is mainly used to establish different connection configurations between RANs and the IRs in the CN. It captures the UUT's IP packets, passes them to the appropriate RAN (where the UUT is connected to) to make the real-time emulation and re-injects them in the interface of the IR where the RAN is supposed to be connected to. For the emulated users passing through the testbed there is a PC called Traffic Generator (TG) that is in charge of generating real IP traffic to load the CN in accordance to the traffic amount that active users generate in the system. Obviously, generation of this traffic is coordinated with the traffic emulated in the radio part. Finally, a graphical management and configuration tool named Advanced Graphical Management Tool (AGMT) has been developed to configure the initialization parameters, to control the execution flow, to collect logged data and to obtain statistics during the real-time execution of the testbed. The yellow area in Figure 1 includes all the machines controlled by the AGMT.

2.3 Radio Access Network Emulators

The three Radio Access Network Emulators (RANEs) emulating the RATs considered in the AROMA testbed (namely, GERAN, UTRAN and WLAN) have been developed following carefully the corresponding standards. A highly detailed implementation of the specifications developed by the standardization bodies has been carried out, and several realistic and sophisticated models have also been implemented in these modules, which guarantee the accurate evaluation of the system performance. The three RANEs have been designed to cope with the following goals and capabilities:

- *Support for live users as well as fully emulated users*: The emulators are designed to reproduce in real-time the behavior of a relatively large amount of active users, around several thousands of users depending on scenario and traffic configuration. The traffic for both the UUT (real IP traffic) and the rest of users (internally generated by means of traffic modeling) is processed by the emulator. Therefore, the UUT behaves as any other user in the system where processing of the data differs along time depending on the current RAN status, i.e. load conditions, interference, etc.

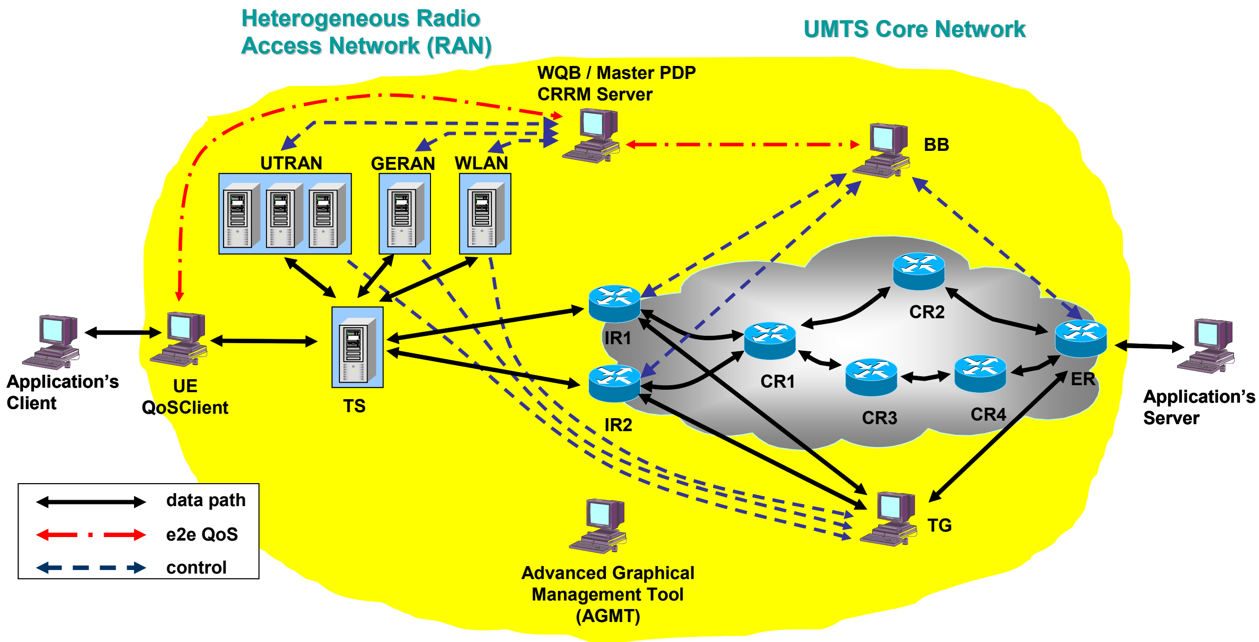

Figure 1. Entities and connections of the AROMA testbed.

- *Emulation of the transmission chain between the mobile terminal and the radio network controller*: The emulators account for the main features of the radio interface as well as specific RAT-dependent Radio Resource Management (RRM) functions. The different functions performed at each level of the protocol stack have been accurately modeled in accordance to the associated specifications. Physical layer emulation has been addressed by means of curves obtained from extensive off-line link level simulations in order to reduce computational requirements while preserving realistic behavior. The functionalities related to higher layers in the protocol stack have been implemented in detail in order to ensure a realistic real-time behavior of the emulators under dynamically varying conditions.

- *Execution of RRM functions and support for CRRM capabilities*: RRM functions implemented in the emulators include essential functions such as admission control, congestion control, radio resource allocation, handover management or transmission parameters management. Although only a single UUT is running real applications on the testbed, RRM algorithms are applied indistinctly over all the traffic generated, including the UUT and also the rest of emulated users. The support of the needed CRRM functions is achieved by means of a communication interface provided by the CM between the emulators and the WQB machine (see Figure 1).

- *Support for different communication scenarios*: The definition of the scenarios takes into account the cell site deployment, radio environment, mobile distribution, user movement, and so on. The considered scenarios are mainly based on the requirements and visions of the four mobile operators that participated in the AROMA project

- *Emulation of all-IP RAN*: The RANEs presented in this paper are integrated in the AROMA real-time testbed, which comprises a complete all-IP beyond 3G heterogeneous wireless network. In all-IP networks, IP transport is employed not only in the CN part, but also in the RAN part. Existing Iub interfaces for UTRAN are kept between base stations and RNCs, but they are supported over an IP-based packet-switched network. As a consequence of such approach, a data block can be lost at Node-B not only because of unfavorable radio conditions but also due to transport network losses or excessive delays. Therefore, a model for emulating the effects and impairments of the IP-based transport in the RAN has been implemented. The envisaged IP-RAN emulation model takes into account losses in the transport network, obtained from non-real-time simulations, as shown in Figure 2. In these off-line simulations, a data block is discarded at RNC if it arrives later than a maximum predefined delay δ_{max}. In order to assure the validity of such approach, the δ_{max} value considered must be lower than the acknowledgment delay at the Radio Link Control (RLC) layer minus the TTI. The loss statistics depend on the traffic and user mobility pattern, the IP-RAN topology chosen, the dimensioning of the network as well as the QoS and IP mobility architecture chosen (over-provisioning, pure Diff-Serv, or QoS routing). These loss statistics obtained from off-line simulations are used to determine, for different scenarios, the probability that an IP packet is lost in the IP-RAN transport network, which is used to decide in real-time whether a packet is discarded due to IP transport impairments.

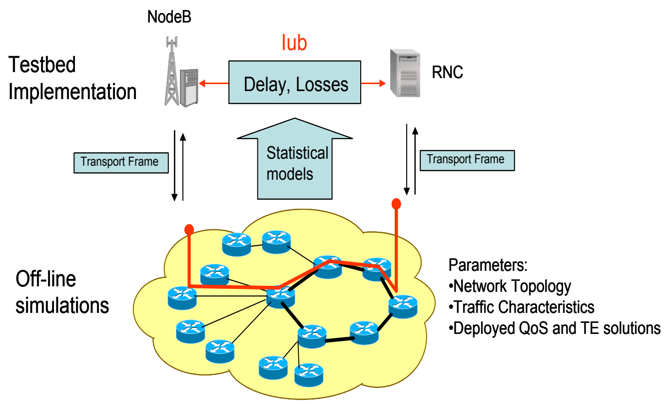

Figure 2. IP-RAN emulation model.

2.4 Interaction Between the RANEs and the Rest of the AROMA Testbed

The interaction between the RANEs and the rest of the AROMA testbed is accomplished through two different planes: a control plane and a data plane. The control plane supports all the functionalities needed to exchange control messages among the RANEs and other modules such as the CRRM, TS, and TG. To this end, the CM abstraction layer provides the logical concept of *flow*. During the initialization phase of the testbed, all testbed modules, including the RANEs, create a flow between itself and all modules to/from which control messages need to be sent/received. Thereafter, modules can write control packets in the flow addressed to the destination module. All this message exchanging process is managed by the CM in a completely transparent way. As shown in Figure 1, the RANEs manage two control interfaces, one with the CRRM PC and other with the TG PC. The control interface between the RANEs and TG is used by the RANE PCs to communicate periodically to the TG the instantaneously experienced traffic load for each service. This information is used by the TG to load the CN with a traffic level according to that experienced in the RANs. On the other hand, the control interface between the RANEs and CRRM is mainly used for session management (activation, deactivation, modification and dropping).

The data plane comprises all the functionalities needed to support the transmission of real IP-packets for the UUT through the testbed. As far as the RANEs are concerned, an interface between each RANE and the TS module is defined. The interaction between each pair of modules is qualitatively illustrated in Figure 3. Real IP-packets coming from the CN are captured by the TS and stored in a buffer. Some descriptive parameters regarding the packet (such as an identifying number or the packet size, among some others) are sent to the RANE by making use of the interface provided by the CM. The RANE maintains a data structure emulating buffers of all the users (UUT and emulated users) that is updated upon the arrival of a new IP packet. The transmission of each packet is emulated taking into account the cell site deployment, number of emulated users, mobility patterns, propagation impairments, and so on. The result of such emulated transmission is communicated back to the TS, through the interface provided by the CM. Then, the TS forwards the packet to the UE or discards the packet, depending on the transmission result obtained in the RANE emulation. The described procedure also applies for IP packets in the upstream direction, i.e. from UE to CN. This procedure is completely managed in real-time.

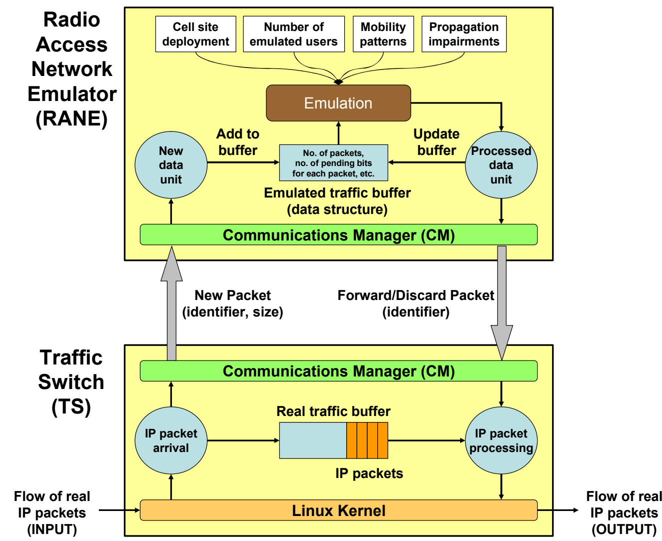

Figure 3. Interaction between RANEs and TS.

3. RADIO ACCESS TECHNOLOGY SELECTION ALGORITHMS

The main purpose of RAT selection strategies is to choose the most suitable access network that each user should be connected to. Such decision must be taken at the session initiation (initial admission), as well as during the entire session lifetime (triggering VHOs between two RATs when they are required).

Several RAT selection algorithms recently proposed in the literature, validated by simulations, have been implemented in the AROMA testbed in order to evaluate their behavior in real-time. The testbed currently incorporates six different RAT selection policies. Two of them have been selected in this work to assess and analyze their performance. The two selected RAT selection algorithms are described in the following subsections.

3.1 Network-Controlled Cell-Breathing

The Network-Controlled Cell-Breathing (NCCB) algorithm is addressed to heterogeneous scenarios where CDMA-based RATs (e.g., UTRAN) coexist with FDMA/TDMA-based systems (e.g., GERAN). The main idea of the NCCB algorithm, as presented in [9] and [11], is to take advantage of the coverage overlap that several RATs may provide in a certain service area in order to improve the overall interference pattern generated in the scenario for the CDMA-based systems and, consequently, to improve the capacity of the overall heterogeneous scenario.

According to the NCCB algorithm, the initial RAT selection decision is taken based on the path loss measurements in the best UTRAN cell, provided by the terminal in the establishment phase. The path loss PL_{CDMA} is computed by measuring the received downlink power from a common control channel whose transmitted power is broadcasted by the network. Path loss measurements are averaged in order to eliminate fluctuations.

Upon the reception of a session activation request, the NCCB algorithm selects UTRAN if the measured PL_{CDMA} is lower than a given threshold PL_{th}. Otherwise, GERAN is selected. In the case that only one RAT has free resources, that RAT will be selected regardless of the value of PL_{CDMA}. The process is illustrated in Figure 4.

Concerning VHOs, the NCCB algorithm acts according to the procedure illustrated in Figure 5. The idea stays the same: keep the high path loss users connected to GERAN and low path loss users to UTRAN depending on how the propagation conditions change throughout the session lifetime. A VHO is triggered upon the relation of the path loss measurements PL_{CDMA} and the path loss threshold PL_{th} with a certain hysteresis margin Δ during M_{up}/M_{down} consecutive samples to avoid ping-pong effects, i.e. consecutive back-and-forth VHOs between two different RATs.

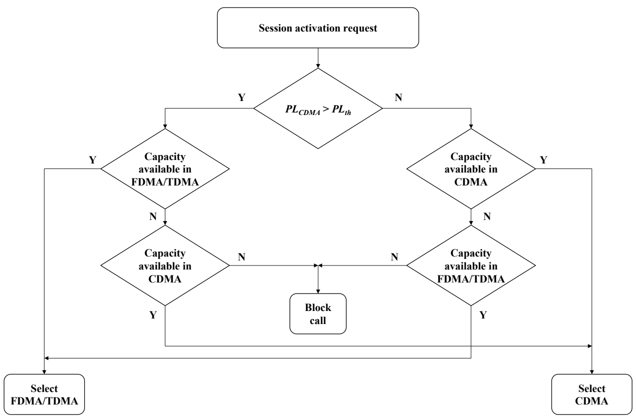

Figure 4. NCCB initial RAT selection procedure.

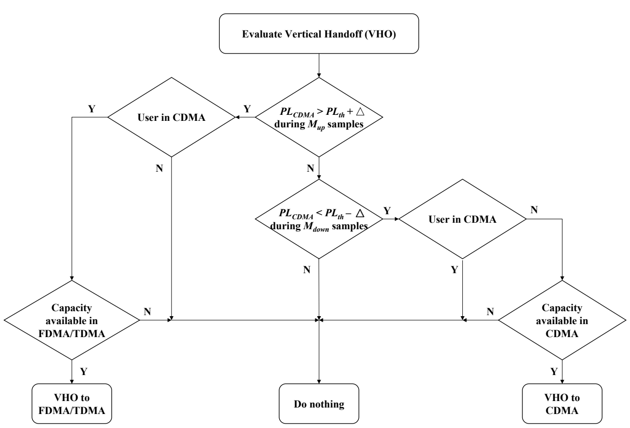

Figure 5. NCCB VHO decision procedure.

3.2 Fittingness Factor

As mentioned in [10], the Fittingness Factor (FF) is a generic CRRM metric that facilitates the implementation of cell-by-cell RRM strategies by reducing signaling exchanges and aims at capturing the multidimensional heterogeneity of beyond 3G scenarios within a single metric. The FF for the j-th RAT to support the s-th service requested by the i-th user with the p-th customer profile ($\Psi_{i,p,s,j}$) is calculated as:

$$\Psi_{i,p,s,j} = C_{i,p,s,j} \times Q_{i,p,s,j} \tag{1}$$

The term $C_{i,p,s,j}$ in expression (1) reflects the capabilities of both the mobile terminal to support a particular RAT (i.e., depending on whether terminal is single or multimode) and the RAT to support a particular type of service (e.g., videophone is not supported in 2G networks). This term is equal to one when the user-to-RAT association is supported by both sides, or zero otherwise. The term $Q_{i,p,s,j}$ in expression (1), referred to as suitability, represents the matching between the user requirements in terms of QoS and the capabilities offered by the RAT (e.g., GERAN may be feasible for economic users, whereas bit rates required by business users may be provided by HSDPA in UTRAN). The term $Q_{i,p,s,j}$ can take any value in the range [0,1] and its exact computation depends on the RAT and the service considered. For conversational/voice services, the suitability is equal to one if the measured path loss is lower than a given threshold L_{max}, which is constant for FDMA/TDMA and varies in case of CDMA according to the instantaneous load factor (in uplink) or base station power (in downlink). For interactive services, the suitability can be qualitatively expressed as:

$$Q_{i,p,interactive,j} = \frac{R^{exp}_{i,p,interactive,j}}{R^{max}_{p,interactive}} \times \varphi_{p,j} \tag{2}$$

where $R^{exp}_{i,p,interactive,j}$ and $R^{max}_{p,interactive}$ are, respectively, the expected bit-rate for RAT j estimated based on the experienced channel quality, and the maximum achievable bit-rate in any of the available RATs. The multiplexing factor $\varphi_{p,j}$ provides an estimation of the average amount of resources that the user may obtain based on the number of active users, multi-slot capabilities, etc. In brief, the suitability of a RAT for an interactive service is computed as the quotient between the expected effective bit-rate for that RAT and the maximum achievable bit-rate in the heterogeneous wireless interface. For details concerning the computation of the FF, the reader is referred to [10].

Based on the above definition of the FF, the RAT selection procedure for both initial RAT selection and VHO decision can be described in several steps as follows:

- FF initial RAT selection procedure:

Step 1) Compute the FF for each candidate cell k_j and each detected RAT j. Since the computation should be done separately for uplink and downlink, both measurements may be weighted by a factor $\alpha_{p,s}$ to obtain a unique numerical value:

$$\Psi_{i,p,s,j}(k_j) = \alpha_{p,s} \cdot \Psi^{UL}_{i,p,s,j}(k_j) + (1-\alpha_{p,s}) \cdot \Psi^{DL}_{i,p,s,j}(k_j)$$

Select the RAT J having the cell with the highest $\Psi_{i,p,s,j}$ among all the candidate cells.

Step 2) Try admission in RAT J and cell k_j.

Step 3) If admission is not possible, try with the next candidate in decreasing order of FF, provided that its FF is greater than zero. If no other candidates with FF greater than zero exist, block the call.

• FF VHO decision procedure:

Step 1) Compute the FF for the current serving cell l_j, and for each candidate cell k_j and each detected RAT j. Measurements should be averaged.

Step 2) If the condition

$$\Psi_{i,p,s,j}(k_j) > \Psi_{i,p,s,servingRAT}(l_j) + \Delta_{VHO}$$

holds during a period T_{VHO} then a VHO to RAT j and cell k_j should be triggered, provided that there are available resources for the user in RAT j and cell k_j.

4. REAL-TIME EVALUATION

This section evaluates and analyzes the behavior of the two considered RAT selection algorithms using the AROMA real-time testbed. The performance of these two policies for the case of initial RAT selection was evaluated and analyzed in [15]. Therefore, this section will focus on the performance of the considered algorithms in the case of VHO decisions for users already admitted and with an on-going active session.

Table 1. Main configuration parameters.

BS parameters	***UTRAN***	***GERAN***
Maximum transmitted power	43 dBm	43 dBm
Thermal noise	-106 dBm	-120 dBm
Common control channels power	30 dBm	43 dBm
Maximum downlink power per user	41 dBm	N/A
Number of carriers	1	3
UE parameters	***UTRAN***	***GERAN***
Maximum transmitted power	21 dBm	33 dBm
Minimum transmitted power	-44 dBm	0 dBm
Thermal noise	-100 dBm	-114 dBm
Downlink orthogonality factor	0.4	N/A
Maximum bit-rate for data (UL/DL, kbit/s)	64/128	118.4/ /236.8
NCCB parameters	***Values***	
Path loss threshold value (PL_{th})	120 dB	
Averaging period for PL_{UTRAN} measurements	1 s	
Hysteresis margin for PL_{UTRAN} (Δ)	1 dB	
No. of samples to trigger VHO (M_{up}/M_{down})	3/3	
FF parameters	***Values***	
Weighting factor ($\alpha_{p,s}$)	0.5	
Averaging period for measurements	1 s	
Hysteresis margin for FF (Δ_{VHO})	0.1	
Time interval to trigger VHO (T_{VHO})	1 s	

The scenario considered in this work is composed of a 8 km by 4 km service area with GERAN and UTRAN coverage (WLAN is not an eligible candidate RAT). Base stations for both technologies are co-located. A cell site deployment with 13 omni-directional uniformly-distributed base stations has been considered. Voice and interactive users, in a proportion 1:4, are moving within the service area at 50 km/h. While emulated users move randomly, the UUT periodically moves in straight line between two pre-selected base stations. The UUT requests a session activation 5 seconds after the testbed is running and the session remains active during the whole emulation. As the UUT is moving between two base stations, different path loss values are experienced during the session lifetime, which allow us to analyze the behavior of the considered RAT selection algorithms as a function of the measured path loss (among other factors). The main configuration parameters are summarized in Table 1. It is worth noting that for the FF algorithm the sensitivity of the receiver has been adjusted in order to obtain the desired values of maximum allowable path loss (L_{max}) for GERAN voice users.

The results obtained with the AROMA testbed are shown from Figure 6 to Figure 12, and are analyzed in the next sections.

4.1 NCCB Algorithm Behavior

Figure 6 shows the VHO decisions taken by the NCCB RAT selection algorithm for the UUT while the UUT moves between Base Stations (BSs) 2 and 3, when the system is loaded with 500 emulated users and different path loss threshold values (PL_{th} = 115, 120 and 125 dB) are considered. At the beginning, the UUT is near BS2. BS3 is reached at time instant around 130 seconds. Then, the UUT turns back to BS2, which is reached again at time instant around 260 seconds. As it can be appreciated, the UUT is initially connected to UTRAN at BS2 since it is the best UTRAN cell and the path loss PL_{CDMA} experienced for that BS is lower than the threshold PL_{th}. As the UUT moves towards BS3, PL_{CDMA} increases for BS2 and decreases for BS3. There exists a point in time in which the experienced PL_{CDMA} for BS2 becomes greater than $PL_{th}+\Delta$, while the decreasing PL_{CDMA} for BS3 is still greater than $PL_{th}-\Delta$. When this situation occurs, a VHO from UTRAN BS2 to GERAN BS2 is triggered by the NCCB algorithm since no UTRAN BS is able to provide a PL_{CDMA} lower than PL_{th}. As the UUT approaches BS3, PL_{CDMA} decreases for BS3. When a value lower than $PL_{th}-\Delta$ is measured, then a VHO is triggered from GERAN BS3 to UTRAN BS3. Therefore, when at least one of the two reachable UTRAN BSs provides a value PL_{CDMA} lower than the threshold $PL_{th}\pm\Delta$, the NCCB algorithm maintains the UUT connected to UTRAN. Otherwise, GERAN is the RAT selected to provide connectivity. As it can be appreciated, this behavior is observed for the three PL_{th} values considered in this example. The only difference among the three cases is the time instants at which the VHOs are triggered by the NCCB algorithm. The time instants depend on the threshold PL_{th} and on the hysteresis margin Δ.

One interesting consequence observed in Figure 6 is that the variation of the threshold PL_{th} (for a constant hysteresis margin Δ) determines the duration of the connection to UTRAN or GERAN as the UUT moves from one BS to the other. For low values of PL_{th} (Figure 6a) the NCCB algorithm becomes more restrictive and the VHO from UTRAN to GERAN is triggered sooner. In this case, the UUT is connected to GERAN during a longer time period. On the other hand, for high values of PL_{th} (Figure 6c) the NCCB algorithm is more permissive and the UUT is moved to GERAN only during a short time period in which the UUT is crossing the cell boundaries. This behavior suggests the possibility of controlling the user distribution between UTRAN and GERAN by simply changing the value of the threshold PL_{th}. To verify this point, Figure 10 shows the average number of active users, i.e. with a session activated. The obtained results show that the user distribution between RATs can be controlled by modifying the threshold PL_{th}. An increase in PL_{th} results in a higher number of users being assigned to UTRAN and a reduction in the GERAN load, and vice-versa. This behavior is verified for different traffic loads. Thus, the threshold PL_{th} can be configured to obtain the desired load distribution. It is worth noting that the results shown in Figure 10 are analogue to those shown in Figures 4 and 5 of [9] and follow qualitatively the same trend.

4.2 FF Algorithm Behavior

Figures 8 and 9 show the behavior of the FF algorithm for a voice service as the UUT moves between BS2 and BS3, when the system is loaded with 500 emulated users and path loss threshold values L_{max} of 110 and 125 dB, respectively, are considered for GERAN voice users. The FF selects the RAT offering the highest FF, i.e. the highest value for $\Psi_{i,p,s,j}$. In this example, when both RATs offer the same value, GERAN is preferred. The suitability for voice can take the values 0 or 1 depending on the relation between the measured path loss and the threshold L_{max} (see definition in [10]). As it can be observed in Figures 8a and 9a, the threshold L_{max} for UTRAN (around 140 dB) is never exceeded, and therefore the UTRAN suitability for voice is always equal to one (Figures 8c and 9c). In GERAN, however, the selected values of sensitivity and maximum transmitted power lead to different values of L_{max} that are exceeded during some time intervals (Figures 8b and 9b). When this situation occurs in both BSs, the suitability of GERAN decreases from one to zero (Figures 8d and 9d). This behavior is only observed for the UL direction in GERAN since the maximum transmission power in UL is more limited than in DL. As a result, the value of the GERAN FF during these time intervals decreases from 1 to 0.5 due to the weighting factor $\alpha_{p,s}$ = 0.5 (Figures 8e and 9e), and UTRAN is selected (Figures 8f and 9f). Therefore, when the maximum allowable path loss L_{max} is exceeded in one of the candidate RATs (in one or both directions), the FF for that RAT decreases and, as result, the alternative RAT is selected for the voice service.

Analyzing Figures 8 and 9 in detail, it is possible to infer how the variation of the threshold L_{max} impacts on the RAT selection decisions. As it can be observed, for low values of L_{max} (Figure 8), the probability of exceeding the limit is high and the GERAN FF is low during a longer interval. As a result, the UUT is connected to UTRAN. As the value of L_{max} increases, the probability of exceeding the limit decreases and the time period during which the UUT is connected to UTRAN becomes shorter. For sufficiently high values of L_{max} (Figure 9), the GERAN FF is in general equal to the value for UTRAN and the UUT is connected to GERAN almost all the time. This behavior suggests the existence of a relation between the value of L_{max} and the user distribution between RATs. To verify this, Figure 11a depicts the average FF for both GERAN and UTRAN as a function of L_{max} for voice in GERAN. The resulting user distribution is shown in Figure 11b. As the value of L_{max} increases, the average FF for GERAN also increases since a higher number of users experience in GERAN a path loss lower than L_{max}. As a result, a higher number of users are allocated to GERAN when the value of L_{max} and also the GERAN FF increases, as shown in Figure 11b.

Regarding the FF algorithm for interactive users, Figure 7 shows the results obtained when an interactive service is considered instead of voice (500 emulated users). As it can be appreciated, the algorithm always allocates the user to the RAT offering the highest FF (Figures 7e and 7f), triggering VHOs whenever they are required. The main difference between Figure 7 and Figures 8 and 9 is that in this case the values of $Q_{i,p,s,j}$ and $\Psi_{i,p,s,j}$ are not limited to 0 or 1; they can take any real value within the interval [0,1] for both RATs. To analyze the behavior of the FF algorithm, Figure 12a shows the average FF for interactive services in GERAN and UTRAN, while Figure 12b shows the user distribution. The presented results correspond to two different cases. The first case considers the availability of 3 carrier frequencies in each GERAN cell. Since one time-slot must be reserved for signaling, 23 time-slots are available for Traffic Channels (TCHs). The second case considers 2 carrier frequencies in each GERAN cell (15 TCHs). For the first case, Figure 12a shows that GERAN, in general, offers a higher average FF than UTRAN. This is due to the bit-rates obtained in GERAN with 2 slots in UL (up to 118.4 kbit/s) and 4 slots in DL (up to 236.8 kbit/s), which are considerably higher than those of UTRAN interactive bearers with 64 kbit/s in UL and 128 kbit/s in DL (see Table 1). As a result, the FF is considerably higher for GERAN. One interesting point in Figure 12a is the higher sensitivity of the UTRAN FF to an increment in the number of users. While the value for UTRAN rapidly decreases as the number of users increases in the first case, the value for GERAN experiences a small variation. This is due to the low number of users admitted in GERAN (see Figure 12b), which forces UTRAN to absorb the increment of users. If the number of admitted users in a given RAT increases, or alternatively the amount of available resources decreases, the value of the multiplexing factor $\varphi_{p,j}$ in expression (2) will decrease, and therefore a reduction of the FF is expected. In effect, this behavior is observed for GERAN in Figure 12a when the number of carrier frequencies per GERAN cell is reduced from 3 (case 1) to 2 (case 2). In this second case, the GERAN FF exhibits a higher sensitivity to the number of users than in the first case due to the smaller amount of available resources. As a result, the number of users admitted to GERAN decreases with respect to the first case, and some users are moved to UTRAN (see Figure 12b). The higher load level supported by UTRAN in this second case is at the origin of the reduction in the UTRAN FF shown in Figure 12a (the amount of UTRAN resources was maintained unchanged in both cases). To conclude, it is worth noting that the curves shown in Figure 12 follow qualitatively the same trend than those shown in Figure 5 of [10].

5. SUMMARY

This paper has presented the real-time testbed for all-IP Beyond 3G heterogeneous wireless networks that has been developed in the framework of the IST AROMA project, showing the potentials and capabilities of the developed tool for the real-time evaluation of Radio Access Technology (RAT) selection policies under realistic heterogeneous wireless scenarios. To this end, elaborated experiments were conducted in order to assess, analyze and compare the behavior of two innovative RAT selection algorithms recently proposed in the literature. The paper provides evaluation results with numerous supporting data that illustrate the applicability of this complex tool in evaluating advanced RAT selection algorithms. They were previously evaluated by means of simplified system-level simulations but not with a highly realistic tool as the AROMA testbed. Therefore, this paper not only describes a highly sophisticated and realistic emulation platform but also shows how it can be used to conduct detailed studies and evaluations that usually could not be performed by means of simple system-level simulations.

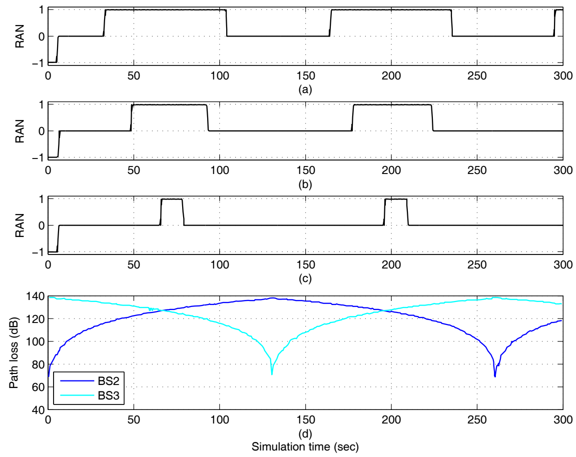

Figure 6. NCCB VHO RAT selection for the UUT for different path loss thresholds PL_{th} = 115 dB (a), 120 dB (b), 125 dB (c), as a function of the PL_{CDMA} measured between the UUT and base stations 2 and 3 (d). The current RAT the UUT is connected to is represented in (a) – (c) by 0 (UTRAN), 1 (GERAN), or –1 (when the UUT is not connected).

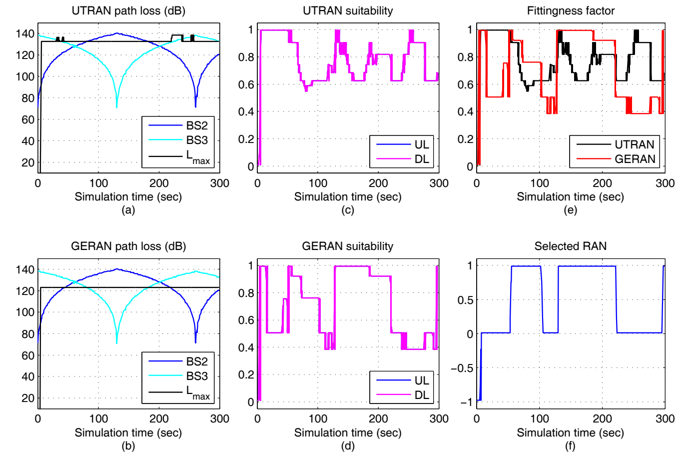

Figure 7. FF VHO RAT selection for interactive service. Graphs (a) and (c) correspond to UTRAN while (b) and (d) correspond to GERAN. Graphs (a) and (b) show the path loss between the UUT and BS2/BS3, including the value of L_{max}. Graphs (c) and (d) show $Q_{i,p,s,j}$. The FF is shown in graph (e). Graph (f) shows the RAT the UUT is connected to.

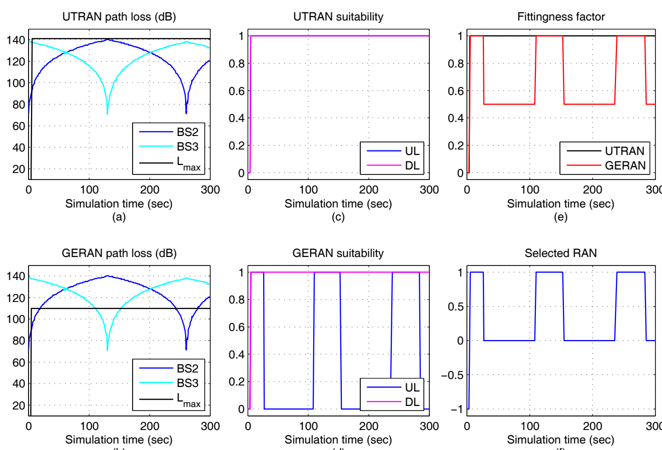

Figure 8. FF VHO RAT selection for voice service (L_{max} = 110 dB). Each graph (a) – (f) represents the same magnitude than in Figure 7.

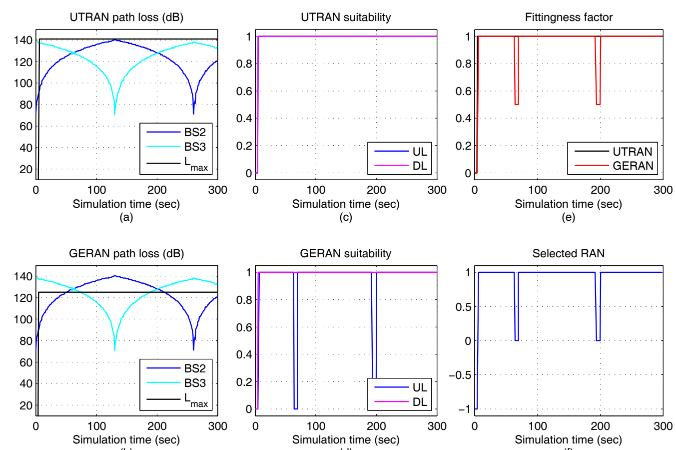

Figure 9. FF VHO RAT selection for voice service (L_{max} = 125 dB). Each graph (a) – (f) represents the same magnitude than in Figure 7.

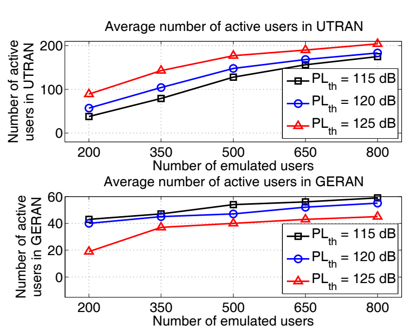

Figure 10. Average number of active users with NCCB. (a) Upper graph corresponds to UTRAN. b) Lower graph corresponds to GERAN.

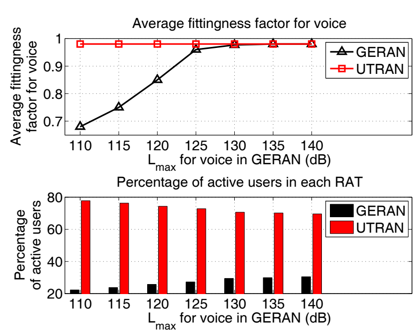

Figure 11. (a) Up: Average FF for voice vs. L_{max} for voice in GERAN. (b) Down: Percentage of active users with FF. 500 emulated users.

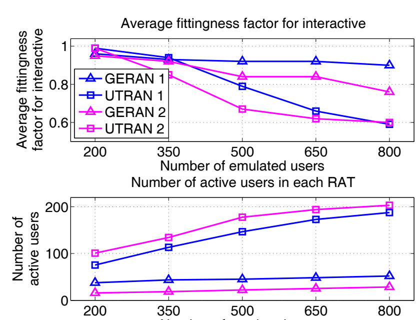

Figure 12. (a) Up: Average FF for interactive. (b) Down: Number of active users with FF. Case 1-2: 3-2 carriers per GERAN cell.

6. ACKNOWLEDGMENTS

This work has been performed in the framework of the IST AROMA Project, and has been supported by the Spanish Research Council under COGNOS grant (ref. TEC2007-60985).

7. REFERENCES

[1] 3GPP TR 25.881, "Improvement of Radio Resource Management (RRM) across RNS and RNS/BSS," v5.0.0, January 2002.

[2] 3GPP TR 25.891, "Improvement of Radio Resource Management (RRM) across RNS and RNS/BSS post-Rel-5," v0.3.0, June 2003.

[3] AROMA Project (Advanced Resource Management Solutions for Future All IP Heterogeneous Mobile Radio Environments), 6th Framework Programme of the European Community, http://www.aroma-ist.upc.edu.

[4] Blake, S., Black, D., Carlson, M., Davies, E., Wang, Z. and Weiss, W., "An architecture for differentiated services," RFC 2475, December 1998.

[5] Lincke, S., "Vertical handover policies for common radio resource management," International Journal of Communication Systems, vol. 18, pp. 527-543, March 2005.

[6] López-Benítez, M., Bernardo, F., Vučević, N. and Umbert, A., "Real-time HSPA emulator for end-to-edge QoS evaluation in all-IP beyond 3G heterogeneous wireless networks," in proceedings of the 1st International Workshop on the Evaluation of Quality of Service through Simulation in the Future Internet (QoSim 2008), p. 12, 3 March 2008.

[7] López-Benítez, M. and Gozálvez, J., "QoS provisioning in beyond 3G heterogeneous wireless systems through common radio resource management algorithms," in proceedings of the 2nd ACM International Workshop on Quality of Service & Security for Wireless and Mobile Networks (Q2SWinet 2006), pp. 59-66, 2-6 October 2006.

[8] Malavasi, F., Breveglieri, M., Vignali, L., Leaves, P. and Huschke, J., "Traffic control algorithms for a multi access network scenario comprising GPRS & UMTS," in proceedings of the 57th IEEE Vehicular Technology Conference (VTC 2003), vol.1, pp.145-149, 22-25 April 2003.

[9] Pérez-Romero, J., Sallent, O., Agustí, R., Wang, L. and Aghvami, H., "A novel algorithm for radio access technology selection in heterogeneous B3G networks," in proceedings of the IEEE 63rd Vehicular Technology Conference (VTC 2006-Spring), vol. 1, pp. 471-475, 7-10 May 2006.

[10] Pérez-Romero, J., Sallent, O. and Agustí, R., "A novel metric for context-aware RAT selection in wireless multi-access systems," in proceedings of the IEEE International Conference on Communications (ICC 2007), pp. 5622-5627, 24-28 June 2007.

[11] Pérez-Romero, J., Sallent, O. and Agustí, R., "Network controlled cell breathing in multi-service heterogeneous CDMA/TDMA Scenarios," in proceedings of the IEEE 64th Vehicular Technology Conference (VTC 2006-Fall), pp. 1-5, 25-28 September 2006.

[12] Pérez-Romero, J., Sallent, O. and Agustí, R., "Policy-based initial RAT selection algorithms in heterogeneous networks," in proceedings of Mobile and Wireless Communication Networks (MWCN 2005), pp. 1-5, 19-21 September 2005.

[13] Rosen, E., Viswanathan, A. and Callon, R., "Multiprotocol Label Switching Architecture", RFC 3031, January 2001.

[14] Tolli, A., Hakalin, P. and Holma, H., "Performance evaluation of common radio resource management (CRRM)," in proceedings of the IEEE International Conference on Communications (ICC 2002), vol. 5, pp. 3429-3433, 28 April-2 May 2002.

[15] Umbert, A., Budzisz, Ł., Vučević, N. and Bernardo, F., "An all-IP heterogeneous wireless testbed for RAT selection and e2e QoS evaluation," in proceedings of the 2007 International Conference on Next Generation Mobile Applications, Services and Technologies (NGMAST 2007), pp. 310-315, 12-14 September 2007.

[16] Umbert, A., López-Benítez, M., Bernardo, F., Vučević, N., Azevedo, R. and Oliveira, A., "The real-time AROMA testbed for all-IP heterogeneous wireless access networks," in proceedings of the 4th International Conference on Testbeds and Research Infrastructures for the Development of Networks & Communities (TRIDENTCOM 2008), p. 10, 18-20 March 2008.