SPHERE – A Simulation Platform for Heterogeneous Wireless Systems

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Abstract— **This paper presents SPHERE, a Simulation Platform for HEterogeneous wiREless systems, and describes its motivation, methodology and implementation approach. This advanced system level simulation platform emulates simultaneously the transmission of GPRS, EDGE Multi-slot, HSDPA and WLAN at the packet level, which allows conducting novel investigations on common radio resource management for beyond 3G systems or on the optimization of radio resource management techniques. This paper presents the simulation platform, validates it and introduces its research potential.**

Heterogeneous Access Networks, Simulation Platform, System Level, Common Radio Resource Management

I. INTRODUCTION

Once commercial 3G deployments are well on their way, research activities on the definition of beyond 3G (B3G) or fourth generation (4G) systems have started for a few years. There is a strong research consensus in that B3G or 4G systems will be characterized by the integration and joint management of various Radio Access Technologies (RATs), including current 2G/3G/3.5G cellular networks, WLAN, broadcasting systems and any potential new technology that might appear in the future. In this context, an important challenge in the path towards B3G heterogeneous wireless systems is to guarantee the interoperability and efficient management of the different RATs with the aim to guarantee the required Quality of Service (QoS) level and increase system capacity. As a result, strong efforts are being undertaken in the research community to define and optimize a Common Radio Resource Management (CRRM) framework [1].

The increasing complexity of current and future mobile wireless technologies requires the implementation of adequate platforms to evaluate and optimize their performance. Before considering a prototype or full-scale deployment, the use of simulation platforms is becoming increasingly common within the research community due to its cost/benefit ratio. However, it is important that to conduct meaningful and appropriate studies, such simulation platforms implement accurately the entities and process under evaluation. The implementation of such advanced simulation tools has become a very challenging task when investigating CRRM techniques since different RATs need to be simultaneously emulated in a single platform. Different research projects have been looking at the development of heterogeneous simulation platforms. For example, the work reported in [2] investigated different traffic distribution policies among a variety of RATs. However, the work was conducted at the session level and the simulation platform employed did not model each RAT's radio interface or the radio propagation effects. As a result, although the simulation platform allowed an investigation on load balancing schemes, it was not able to accurately determine final user perceived QoS values given its limitation on the radio modeling side. Related investigations on traffic distribution algorithms in heterogeneous wireless networks were presented in [3]. To conduct their investigations, the authors implemented a simulation tool that takes into account propagation models and some specific RAT-features although it does not model the complete radio transmission process. A different approach was considered in [4] where the authors considered an analytical model that relates the experienced CIR to the user perceived throughput. Nevertheless, the increasing complexity of mobile and wireless communication systems increases the difficulty of studying the performance of new techniques through analytical models. In fact, analytical studies usually require many simplifications and approximations that limit the accuracy and reliability of the obtained results. Important European projects, such as EVEREST, have also conducted advanced research work on heterogeneous wireless systems and CRRM techniques (EVEREST considered a GERAN-UMTS-WLAN scenario). This project has developed an interesting real-time emulator to demonstrate potential benefits of CRRM mechanisms [5]. This approach differs from the considered in this project where interest is place on system performance of CRRM techniques. Another significant heterogeneous wireless project is WHYNET project [6]. This project intends to develop a wireless hybrid network testbed to assess cross-layer interactions in heterogeneous wireless systems. However this project is more centered on sensor and mesh networks rather than focusing on CRRM in cellular systems.

The previous discussion has highlighted the availability of a variety of simulation tools devoted to conduct research on heterogeneous wireless systems. As explained, the modeling detail of these tools strongly depends on the type of work being conducted. Although each presented simulation platform is valid within their research framework, to the best of the authors' knowledge, there is not any simulation platform available that implements at the packet/slot level different RATs and enables their simultaneous and parallel emulation.

In this context, the University Miguel Hernández and the Polytechnic University of Valencia have developed a novel, ambitious and scalable radio simulation platform for heterogeneous wireless systems, named SPHERE (Simulation Platform for HEterogeneous wiREless systems), under a common national research project. The platform currently integrates four advanced system level simulators, emulating the GPRS (General Packet Radio Service), EDGE (Enhanced Data-rates for GSM/Global Evolution), HSDPA (High Speed Downlink Packet Access) and WLAN RATs. The unique simulation platform emulates all four RATs in parallel and at the packet level, which enables an accurate evaluation of the final user perceived QoS through the implementation of novel CRRM and RRM mechanisms. The radio interface specifications of these four technologies have been faithfully implemented in the SPHERE simulation platform, which works with a high time resolution (in the order of some milliseconds). This modeling approach validates the capability of the SPHERE simulation platform to dynamically and precisely evaluate the performance of RRM/CRRM techniques. The platform has been developed following a modular and scalable design, which guarantees an easy adaptation of the platform configuration to specific requirements, and allows the rapid integration of new RATs. In particular, the research team is considering the future expansion of the platform to also emulate the UMTS and Mobile WiMAX radio interfaces.

The interest of the SPHERE platform and the research being conducted is highlighted by the support of important companies in the mobile and wireless industries, such as Motorola, Swisscom Innovations and Telefonica I+D, to the research project developing SPHERE.

II. RADIO ACCESS TECHNOLOGIES

As it has been previously said, the SPHERE simulation platform currently emulates GPRS, EDGE, HSDPA and WLAN transmissions. This section briefly summarizes the main characteristics of these radio interfaces with regard to SPHERE.

A. GPRS

The GPRS radio interface is based on a combined FDMA/TDMA multiple access mechanism and a FDD scheme. The GPRS standard can be modeled as a hierarchy of logical layers with specific functions. Prior to transmission, data packets are segmented into smaller data blocks across the different layers, with the final logical unit being the Radio Link Control block which has a duration of 20ms. The resulting RLC data blocks are then coded and block-interleaved over four normal bursts in consecutive TDMA frames. Although GPRS is based on a single modulation scheme it defines four different coding schemes (see Table I.) that have all been emulated within SPHERE.

A GPRS TDMA frame is equal to 4.615 ms and is divided into eight 0.577 ms time-slots. Such time-slots impose the SPHERE time resolution for the GPRS radio interface. GPRS defines a temporal hierarchy with higher order structures such as super- and hyper-frames that have not been implemented in SPHERE since the platform is aimed at radio resource management investigations.

TABLE I. GPRS TRANSMISSION MODES

Mode	**Modulation**	**Code Rate**	**Bits per Radio Block**	**Bit Rate (kbps)**
CS-1	GMSK	1/2	181	9.05
CS-2	GMSK	≈ 2/3	268	13.4
CS-3	GMSK	≈ 3/4	312	15.6
CS-4	GMSK	1	428	21.4

B. EDGE

The EDGE radio interface is based on the same multiple access scheme as GPRS, but considers different transmission modes (Modulation and Coding Schemes, MCS), all implemented in the SPHERE platform following the description in Table II. The main difference to GPRS is the introduction of 8PSK, a multilevel modulation that theoretically increases EDGE data rates by a factor of three.

TABLE II. EDGE TRANSMISSION MODES

Mode	**Modulation**	**Code Rate**	**Family**	**Bits per Radio Block**	**Bit Rate (kbps)**
MCS-1	GMSK	0.53	C	1×176	8.8
MCS-2	GMSK	0.66	B	1×224	11.2
MCS-3	GMSK	0.85	A pad.	1×272	13.6
			A	1×296	14.8
MCS-4	GMSK	1.00	C	2×176	17.6
MCS-5	8-PSK	0.37	B	2×224	22.4
MCS-6	8-PSK	0.49	A pad.	2×272	27.2
			A	2×296	29.6
MCS-7	8-PSK	0.76	B	4×224	44.8
MCS-8	8-PSK	0.92	A pad.	4×272	54.4
MCS-9	8-PSK	1.00	A	4×296	59.2

The EDGE transmission modes are divided into three different families, namely A, B and C. Each family has a different basic payload unit of 37 (and 34), 28 and 22 octets respectively. Different code rates within a family are achieved by transmitting a different number of payload units within one radio block. For families A and B, 1, 2 or 4 payload units can be transmitted per radio block, while for family C, only 1 or 2 payload units can be transmitted. These families are designed to allow a radio block to be retransmitted with a transmission mode, within the same family, different from that used in the original transmission; this option is not possible in the current GPRS standard. A block received in error can be resegmented and retransmitted using a more robust transmission mode within the same transmission family.

The GPRS and EDGE transmission procedures are very similar, although some differences for high order modes are appreciated. When 4 payload units are transmitted (MCS-7, MCS-8 and MCS-9), these are split into two separate blocks. These blocks are in turn interleaved over only two bursts, for MCS-8 and MCS-9, and over four bursts for MCS-7. All the other MCSs can only transmit a single block that is interleaved over four bursts. When switching to MCS-3 or MCS-6 from MCS-8, three or six padding octets are, respectively, added to fill a radio block. Identically to GPRS, the transmission of a whole EDGE radio block requires 20 ms.

C. *HSDPA*

HSDPA is based on a CDMA multiple access scheme and considers both a FDD and TDD component, although SPHERE only emulates the FDD one. The FDD mode operates at a chip rate of 3.84 Mcps, which results in an approximated bandwidth of 5 MHz. In the time domain, a Transmission Time Interval (TTI) of 2 ms is defined. A TTI is further divided into three 667 μs slots. In the code domain, channelization codes at a fixed spreading factor of 16 are used. Multi-code transmission to a single user during a TTI is also allowed.

HSDPA achieves high data rates of up to 14 Mbps by means of adaptive modulation and coding (AMC), fast scheduling mechanisms (each TTI) and a powerful Hybrid ARQ mechanism. AMC or Link adaptation (LA) is a process of paramount importance to optimize system functioning. Its operation is based on user equipment reporting the channel state either cyclically or in a triggered-based manner by means of the Channel Quality Indicator (CQI). The definition and processing of the CQIs is explained in detail in [7]. Numerically, CQI varies from 1 to 30, increasing its value when the channel quality augments. To model the radio channel quality, the simulations reported in this paper considered several look-up tables (LUT) matching the SINR as a function of the BLER; in particular, one for each CQI such that the maximum CQI can be calculated considering a specific QoS. These LUT also include the effect of the HARQ retransmission with chase combining.

The available number of codes has also been carefully taken into account and, in the same way, power consumption of all the control channels has been considered to determine the available power per user. Assuming code multiplexing of *n* users per TTI, *n* HS-SCCH channelization codes should be allocated, whereas the available power is equally divided among the *n* users. The maximum number of HS-SSCH codes has been set to 4.

D. *WLAN*

Current WLAN standards do not contemplate the same level of radio resource management functionality than mobile systems. However, extensions that support a more advanced RRM framework have been developed in standardization bodies. In this context, SPHERE implements the 802.11e specification, which provides more advanced MAC mechanisms to support QoS. This standard specifies two access mechanisms, the Enhanced Distributed Channel Access (EDCA) and the HCF controlled channel access (HCCA). According to the literature, the optimum system operation corresponds to the case in which both access mechanisms work together, and this is the philosophy followed in SPHERE.

At physical layer both WLANs 802.11b/g versions have been implemented. Table III summarizes the list of properties for both specifications. In SPHERE, user equipments are simply characterized by the receiver sensitivity (*S*) and the transmission power which has been set to 100 mW (20 dBm).

TABLE III. WLAN PHY MAIN CHARACTERISTICS

Scheme	**Mod.**	**Max PHY Data Rate (Mbps)**	**Max MAC Data Rate (Mbps)**	**Family**	**S (dBm)**
DSSS	BPSK	1	0.8	.11b	-94
	QPSK	2	1.2	.11b	-92
	CCK	5.5	3	.11b	-91
	CCK	11	5.4	.11b	-89
OFDM	BPSK	6	4.1	.11g	-82
	BPSK	9	5.8	.11g	-81
	QPSK	12	7.1	.11g	-79
	QPSK	18	9.4	.11g	-77
	16QAM	24	11.0	.11g	-74
	16QAM	36	13.3	.11g	-70
	64QAM	48	16.8	.11g	-66
	64QAM	54	17.8	.11g	-65

III. THE SPHERE PLATFORM

Fig. 1 shows the scenario modeled by the SPHERE platform which includes the GPRS, EDGE, HSDPA and WLAN radio interfaces. As shown in Fig. 1, the SPHERE platform does not only model the radio interface of the four technologies but also implement various RAT specific RRM features and a centralized CRRM entity. This entity directly collects specific RAT information (e.g. load, channel quality conditions, etc) and interacts with the RRM entities implemented at each RAT.

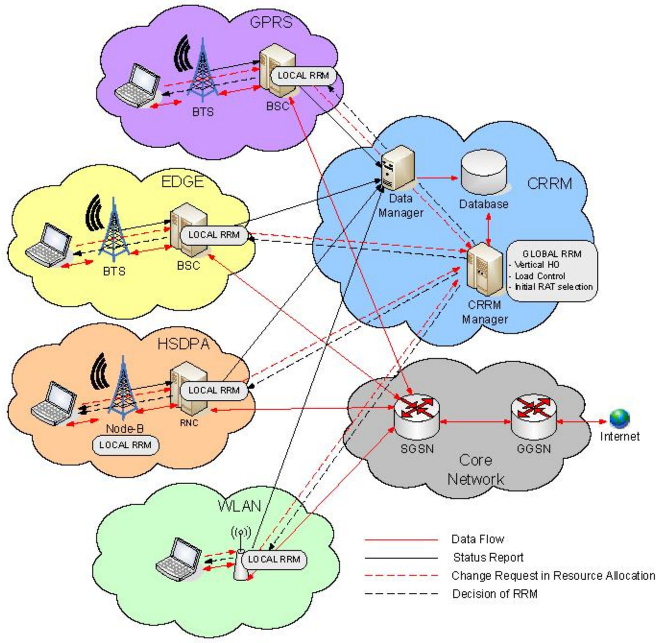

Figure 1. SPHERE heterogeneous scenario

A logical structure of the SPHERE simulation platform, which is a discrete-event system level simulator concentrated on the downlink performance, is shown in Fig. 2. The components shown in this figure, their features, interactions and data flow will be described in the following sections. Finally, the potential of the platform to conduct advanced research on the design, evaluation and optimization of CRRM and RRM techniques will be demonstrated.

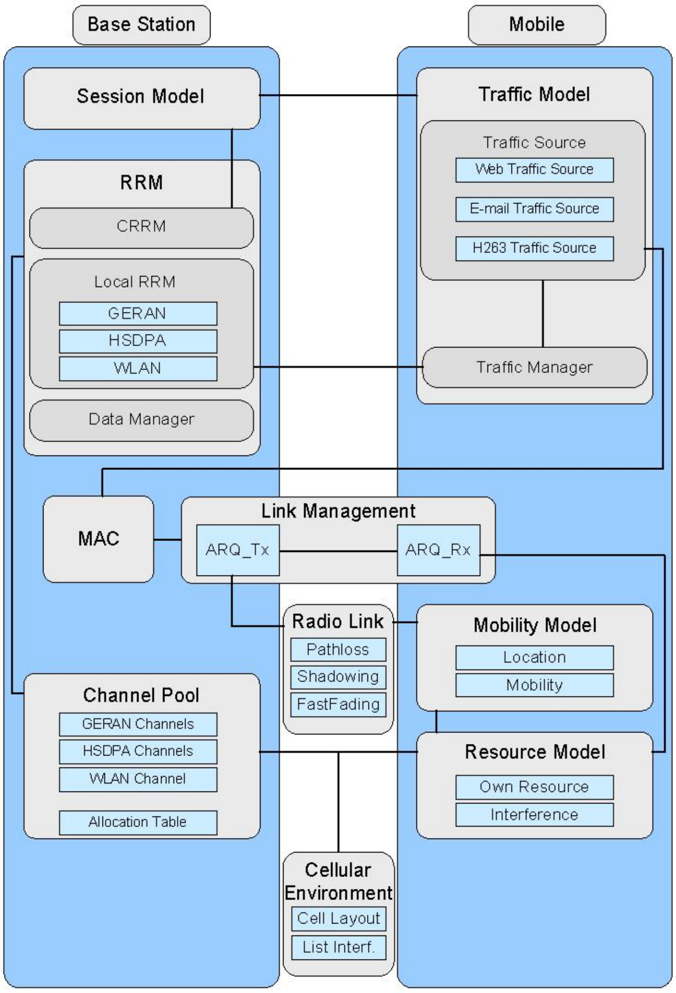

Figure 2. SPHERE logical structure

A. *Cellular Environment*

The *Cellular Environment* entity is a system module storing the location of each base station and the interfering relations among them; this information is needed to estimate the experienced interference levels. The cellular layout can be modified offline at any time to change the system configuration under study. Currently, the SPHERE platform considers a cell layout of 27 omni-directional cells. In order to avoid border effects, a wrap-around technique has been applied. Three-sectorized cell sites have also been modeled. A basic scenario has been defined considering two concentric coverage cells with increasing cell radii. The smaller one, of 50m, represents the coverage area of the WLAN technology. The second coverage radius of 500m includes HSDPA, EDGE and GPRS.

B. *Radio Link*

This module models the radio propagation conditions between transmitter and receiver and is a generic entity employed by any wireless link established. It characterizes the three radio propagation effects, namely path loss, shadowing and fast fading.

The path loss model provides an average measure of the signal attenuation over a given distance. For cellular systems, the path loss (in dB) reported in [8] has been considered:

$$L_p = \left(40 - 16\cdot 10^{-2}\Delta h_b\right)\log_{10} d - 18\log_{10}\Delta h_b + 21\log_{10} f + 80 \quad (1)$$

Where d is the distance in km between the base station transceiver and the mobile terminal, f is the carrier frequency in MHz and Δh_b is the base station antenna height, measured in meters from the average roof top level. In HSDPA typical values for these parameters are Δh_b=15m and f=2000 MHz, leading to

$$L_p\left(dB\right) = 128.1 + 37.6\log_{10} d \quad (2)$$

This model is applicable to frequencies ranging from 1.5 GHz up to 2 GHz. As a result, a carrier frequency of 1.8 GHz has been assumed for GPRS and EDGE. This change in the frequency parameter results in the following path loss equation

$$L_p\left(dB\right) = 127.2 + 37.6\log_{10} d \quad (3)$$

For WLAN, the following path loss model has been implemented [9]:

$$L_p(dB) = 145 + 35\log_{10} d \quad (4)$$

Various works have demonstrated the importance of an adequate shadow modeling to conduct appropriate RRM investigations [10]. In fact, the shadowing effect results in additional signal attenuation due to obstacles in the path between transmitter and receiver. Measurements have shown that the shadowing loss can be modeled as a random process with a normal distribution of mean 0 dB and standard deviation between 4 and 12 dB depending on the propagation environment. The SPHERE platform considers an urban or suburban environment and, as a result, a shadowing standard deviation equal to 6 has been set. The shadowing is a spatially correlated process so that the shadowing loss experienced by a mobile at a given position is correlated to that experienced at a nearby position. Although the authors are actually working on migrating the shadowing models to that used in [10], the current version of the SPHERE platform models this spatial correlation as detailed in [11], with a de-correlation distance of 20 m.

Fast fading modeling is also important when considering technologies, such as EDGE and HSDPA, that base their radio operation on link adaptation techniques [12]. In these RATs, transmission conditions are modified depending on the current channel characteristics. For the sake of simplicity, in SPHERE only a simple block fading model is considered, i.e. the fast fading stays constant over a coherence time interval and each sample is statistically independent. Hence, in addition to the path loss and shadowing value of each radio block, in SPHERE a third multiplicative factor is considered when determining the received carrier: the fast fading coefficient. This factor is of unit mean and follows the probability density function:

$$f_\psi(\psi) = \frac{M}{(M-1)!}(M\psi)^{M-1} e^{-M\psi} \quad (5)$$

Here, M denotes the number of resolvable independent multi-paths at the receiver. In GPRS and EDGE M is set to 1 and in HSDPA M=3.

C. Base Station

As shown in Fig. 2, the Base Station entity is responsible for the Medium Access Control (MAC) and RRM functions. It also controls the channel pool where the status of all channels per RAT is maintained. In the Base Station is also located the session generation process. Once a new mobile is active in the system, the CRRM entity chooses its initial RAT depending on a specific policy. When a mobile station requests a channel from a given RAT, the channel pool of the serving base station is examined to search for an available channel. If a free channel is available on the requested RAT, the mobile station is assigned a randomly chosen channel or based on some quality metrics [13]. If a free channel is not available on the requested RAT, the mobile station is assigned a channel from a different RAT, depending on the CRRM scheme under consideration, or it is placed in a queue until a transmitting mobile ends its transmission and releases its channel. For users in GPRS and EDGE queues, a First-Come First-Served (FCFS) scheduling policy is applied so that channel requests are satisfied in the same order as they appear. Users in the HSDPA queue can be served either in a round robin fashion, according to the Max C/I criterion, which selects at any moment the user with better transmission quality, or following the proportional fair algorithm. In WLAN, real-time traffic is delivered through HCCA with a FCFS policy, whereas best effort users mutually contend to get the channel control being served using the EDCA protocol.

Apart from the scheduling, other implemented RRM functionalities include Link Adaptation for GPRS, EDGE, HSPDA and WLAN, multi-channel operation for GPRS and EDGE, multi-code allocation in HSDPA and call admission control in all technologies.

Link adaptation (LA), also referred to as Adaptive Modulation and Coding (AMC) in HSDPA, is an adaptive RRM technique that periodically estimates the channel quality conditions and selects the optimum transmission mode based on a predefined selection criterion. For web browsing and email services, the transmission mode that maximizes the throughput is selected. For H.263 video service, in GPRS and EDGE the algorithm proposed in [14] has been used since it outperforms the former in several key aspects affecting real-time operation. In the case of multi-channel transmissions, the channel quality conditions are estimated over all channels simultaneously assigned to a single user and their average value is used to estimate the optimum transmission mode according to the established selection criterion. In HSDPA, the mobile directly reports its channel conditions to the base station by means of the CQI. With this information, the base station knows the maximum allocable number of codes as well as the modulation and coding scheme. The final allocation shall always be as higher as possible but not exceeding the transmission mode reported by the user. Automatic Rate Fallback (ARF) is the implemented LA algorithm for WLAN; ARF and other algorithms with similar operating concepts have been widely implemented in many WLAN products although they are not included in the IEEE standards. In ARF, the sender deduces the channel conditions by measuring the numbers of consecutively successful and failed transmissions. The sender adjusts its modulation mode and data rate in accordance with these measurements.

Multi-channel or multi-code mechanisms based on some innovative schemes currently under investigation have been incorporated into the SPHERE simulation platform for the GPRS-EDGE and HSDPA radio interfaces. In these schemes, the number of channels or codes that a base station can simultaneously allocate to a single user depends on factors such as the capability of the terminal, the system load, the availability of radio resource, the requested service type and the considered multi-channel allocation policy.

The research team behind the SPHERE simulation platform is currently working on the development of CRRM schemes. Such schemes, briefly analyzed in section VI, base their RAT selection on utility functions and operating parameters, such as the RAT load, required service and its QoS parameters, interference levels and effect on active transmission, etc. The authors are also working on adaptive CRRM schemes interacting with a RAT RRM functions to compensate or penalize inadequate CRRM decisions. In the current implementation, a RAT selection can be performed for each new session, periodically, or every time a new packet is generated. It is important to highlight that RAT changes are done dynamically in the SPHERE platform and that the radio transmission can be immediately resumed with the newly selected RAT at the stage where the radio transmission ended using the previous RAT. The platform has also been prepared to consider the case in which a user handles different application sessions through various RATs.

D. User traffic behavior

User traffic demands are usually described at two levels: session-arrival process and traffic models. Session-arrival processes, also referred as traffic generation, are usually modeled as a birth-death process, which can be characterized by the following parameters: busy hour call attempts (BHCA), arrival distribution, mean session duration, duration distribution, etc. On the other hand traffic models describe the source behavior within a session. They vary depending on the type of service and they can be described by parameters such as: average active/inactive times, time distributions, data rate, packet length distribution, etc. In SPHERE, the session-arrival has been implemented at the base station, while the traffic models are controlled by the mobile station for optimizing the code.

1) Session Model

Three different services have been implemented in SPHERE, namely web browsing, real-time H.263 video transmissions and email. Cellular subscribers are usually considered to have independent behavior one from each other, which results in exponentially distributed inter-session arrival times. For each one of the implemented services a specific inter-session time is defined, which allows controlling the traffic load.

2) *Traffic Model*

Despite considering downlink transmissions, the current version of the SPHERE platform implements the traffic models at the mobile station. This has been done to optimize the simulation code.

The web browsing service follows the model described in [15]. It follows an ON/OFF pattern where a web browsing session starts with the submission of a web page request by the user. The time interval needed to transfer the requested web page is referred to as active period. When the transfer is completed, the user will take some time to read the information before initiating another request. This time corresponds to the inactive period. The implemented model is based on the HTTP 1.0 standard where a different TCP connection is established for the transmission of each object in a web page. In this case, the active ON time has been considered as the time needed for the transmission of a single object of a web page, while the active OFF time represents the time elapsed between closing a TCP connection and opening a new one to transfer another object of the same web page. The implemented web browsing traffic distributions are shown below:

TABLE IV. PARAMETERS OF THE WEB BROWSING TRAFFIC MODEL

Parameter	**Mathematic Distribution**	**Probability Distribution Function**	**Constants**
Object Size	Pareto	$f(x)=\frac{\alpha k^{\alpha}}{x^{\alpha+1}}$	k=1000 α=1,0
Active OFF Time	Weibull	$f(x)=\frac{b\,x^{b-1}}{a^{b}}e^{-(x/a)^{b}}$	a=1,46 b=0,382
Inactive OFF Time	Pareto	$f(x)=\frac{\alpha k^{\alpha}}{x^{\alpha+1}}$	k=1 α=1,5
Number of Objects per Web Page	Pareto	$f(x)=\frac{\alpha k^{\alpha}}{x^{\alpha+1}}$	k=1 α=2,43

The email traffic model also follows an ON/OFF pattern [16]. The model assumes that incoming messages of a user are stored at a dedicated email server. This server keeps the emails in a mailbox until the user logs onto the network, following the session model previously described, and downloads the emails. When the user opens the mailbox, the headers of the available messages are downloaded. The user scans then through these headers and downloads the emails she/he is interested in. When the user finishes downloading a message (active period), she/he will read it (inactive period) before downloading the next message, and so on. The employed email traffic distributions are shown below.

Real-time services have also been included in SPHERE through the emulation of real-time H.263 video transmissions following the model presented in [17]. This model takes into account the three different frame types considered in the H.263 standard, namely I, P and PB. The model characterizes the size and duration of the video frames, the correlation between both parameters for each video frame, and the transition probability between different video frame types. The modeling is performed at two levels. The first one establishes the frame type to generate. I-frames are periodically created, while a Markov chain drives the transition generation between P- and PB-frames. Once the frame type is selected, the model determines the size and the duration of the video frame to be transmitted. The reader is referred to [17] for a detailed analytical described of the real-time H.263 video traffic model.

TABLE V. PARAMETERS OF THE EMAIL MODEL

Parameter	**Mathematic Distribution**	**Probability Distribution Function**	**Constants**
Email Size	Weibull	$F(x)=\begin{cases}1-e^{-e^{-k_1 x^{c_1}}}, & F(x)\le 0,5\\ 1-e^{-e^{-k_2 x^{c_2}}}, & F(x)>0,5\end{cases}$	k_1=17,6 c_1=3,61 k_2=2,04 c_2=0,37
Inactive Period	Pareto	$F(x)=1-\left(\frac{k}{x}\right)^{\alpha}$	k=30 α=0,5

E. *Mobile station*

1) *Mobility Model*

The implemented mobility model considers a suburban scenario where users move at constant speed. The initial position of a mobile station within a cell is randomly set according to a random uniform distribution. The discrete nature of event-driven simulations has been reflected in the mobility model through the definition of the time at which a mobile's movement is updated. The length of each step is constant and equal to the decorrelation distance used for the shadowing model; the position of a mobile at a particular time between two random positions is extracted by interpolation. The direction of each step is randomly established by adding a random angle to the previous direction. The random angle is obtained from a normal distribution with zero mean and a variance dependent on the mobile speed. The mobility model, leading to a long-term uniform user's density within a cell, was shown to be consistent with an analysis performed on real data provided by a mobile operator.

2) *Resource Model*

The resource model entity is basically responsible for controlling the radio transmission parameters of a channel currently assigned to a user and for estimating the experienced channel quality conditions, in this case carrier to interference ratio. For WLAN systems only the received power is calculated since it is the only value needed to obtain the maximum allocable bit rate.

The GPRS and EDGE CIR level is estimated as follows:

$$CIR_{GPRS/EDGE}=\frac{\frac{P_i}{L_P^{ii}\cdot L_S^{ii}}\psi_i}{\sum_{j\in\Omega}\frac{P_j}{L_P^{ij}\cdot L_S^{ij}}\psi_j+N_0\cdot W} \qquad (6)$$

where P_i is the power transmitted by the reference cell (cell i) to the user of concern, L_P^{ii} and L_S^{ii} are the path loss and shadowing loss over the link between transmitter and receiver at the reference cell, Ω is the set of active co-channel interferers, P_j is the transmission power of each one of the interfering channels, L_P^{ij} and L_S^{ij} are the path loss and shadowing loss over the link between the active transmitting interferers in cells j and the interfered receiver at the reference cell i, and N_0•W represents the thermal noise at the receiver in the reference cell, with N_0 being the noise spectral density and W the bandwidth of the transmission channel. Finally ψ models the fast fading effect.

In CDMA-based systems, such as HSDPA, channelization codes for the users of the same cell are perfectly orthogonal. However, due to multi-path fading, this orthogonality decreases and some intra-cell interference component is observed. Intra-cell interference on a CDMA system is modeled by an orthogonality factor [18], which is usually denoted as α. In absence of multi-path fading, the codes are perfectly orthogonal, so $\alpha = 1$. In the worst case $\alpha = 0$, meaning that orthogonality is entirely destroyed. Typical values of α are between 0.4 and 0.9. Thus, the HSDPA CIR level can be expressed as follows:

$$CIR_{HSDPA} = \frac{\dfrac{P_i}{L_P^{ii} \cdot L_S^{ii}} \psi_i}{\dfrac{(P_{Ti} - P_i/C_i)\cdot(1-\alpha)}{L_P^{ii} \cdot L_S^{ii}} \psi_i + \sum\limits_{j \in \Omega} \dfrac{P_{Tj}\psi_j}{L_P^{ij} \cdot L_S^{ij}} + N_0 \cdot W} \quad (7)$$

where P_i is the addition of the power transmitted in all the C_i channels allocated by the reference cell to the user of interest, P_{Ti} is the total power transmitted by the reference cell, Ω is the set of cells interfering the user and P_{Tj} is the total power transmitted by these interferers. In this expression, the parameters P_{Ti} and P_{Tj} also include the base station power reserved for other channels different from the HSDPA High Speed Downlink Shared Channel (HS-DSCH). The power allocated to each control channel has been extracted from [19]. ψ also models the fast fading effect.

In WLAN the received power is calculated as:

$$P_{Rx} = \frac{P_i}{L_P^{ii} \cdot L_S^{ii}} \quad (8)$$

It is worth noting that the WLAN interference from the rest of Access Points has not been considered in the SPHERE platform since the distance between WLAN transmitters is high enough to neglect it.

F. *Link Management*

The Link Management module is responsible for handling the radio transmission and emulating channel errors.

1) *Transmission Process*

GPRS controls the radio transmission of RLC blocks through an Automatic Repeat reQuest (ARQ) protocol, described in specification 3GPP TS 04.60, that is implemented in SPHERE. This ARQ protocol is based on the numbering of the blocks and a selective repeat principle with sliding transmitting and receiving windows. The transmitter sends blocks and the receiver sends acknowledgment messages acknowledging correctly received blocks and requesting the retransmission of erroneously received blocks. The transmitting and receiving ARQ windows have a size of 64 RLC blocks. The reporting period, which defines how regularly the receiver sends acknowledgment messages, has been set to 16 blocks. No block losses and errors on the transmission of the acknowledgement messages have yet been considered in SPHERE. A similar ARQ protocol has been implemented for EDGE, with varying window sizes according to the number of channels simultaneously assigned to a single user; the window sizes range vary from 64 to 1024 radio blocks. For EDGE transmissions, a 32 radio blocks has been selected.

In HSDPA, retransmission of erroneous transport blocks is performed by an N-channel stop-and-wait (SAW) ARQ protocol. In stop-and-wait schemes, the transmitter handles the transmission of a single block until it has been successfully received. In SPHERE, a maximum of 8 channels can be set up simultaneously since this is the value suggested in the standard. Block size is determined by the reported CQI. As for GPRS and EDGE, no transport block losses or errors on the acknowledgement messages have been emulated.

For WLAN, the SPHERE platform also implements an ARQ protocol. In this case only one channel SAW is employed. The transport block is a fixed-length IP packet of 1500 bytes although it is possible to perform fragmentation to improve channel utilization.

2) *Channel Errors Emulation*

For GPRS and EDGE, in order to decide whether a radio block is received in error, the experienced CIR is computed in the four TDMA frames used to transmit such block. After completing the transmission of a whole radio block, the four associated CIR values are averaged and a single CIR_{avg} value is obtained. This CIRavg value is then mapped to a BLock Error Rate (BLER) value ($BLER_0$) by means of a Look-Up Table (LUT) such as the ones proposed in [12]. LUTs are used as a means of interfacing link and system level simulations using the link level analysis as a source of information for the system level. The link level performance is then represented by a simplified model consisting of a set of LUTs mapping the CIR to a given link quality parameter such as the BLER. Different LUTs need then to be produced for different operating conditions, e.g., transmission mode, mobile speed and propagation environments (typical urban or rural area). Once a $BLER_0$ value is obtained from the adequate LUT, a random process is used to decide whether the radio block is correctly received.

For HSDPA, the experienced CIR is computed in each slot of a TTI. After completing the transmission of a whole transport block, the three associated CIR values are averaged and a single CIR_{avg} value is obtained, which represents the quality experienced by the transport block. In the same way as in the GPRS-EDGE case, a LUT is employed to map the CIR value in a BLER value and to decide whether a block is correctly received. When a transport block is received in error, it is not discarded but stored in the receiver buffer and combined with retransmissions according to a specific method. When Incremental Redundancy (IR) is employed, retransmissions are typically not identical to the original transmission. Another possibility is to use the Chase Combining (CC) scheme in which retransmitted blocks are identical to that of the first transmission. After several transmissions, the resulting effective CIR value (CIR_{eff}) is representative of the global quality experienced by the data stored in the receiver buffer after the combination process. The value of CIR_{eff} is used to decide whether the information is received in error. To this end, a random number X_0 between zero and one is drawn from a uniform distribution prior to the first transmission of a transport block. This random number is mapped to a CIR value by means of the corresponding LUT. The CIR value is then established as the minimum effective CIR (CIR_{min}) that must be obtained at the receiving side to consider that the information is correctly decoded. Each time a transport block is transmitted, the decision is taken by comparing CIR_{min} with the CIR_{eff} obtained after the combination of the current transmission and previous transmissions (if any) of the transport block. When $CIR_{eff} \geq CIR_{min}$, the transport block is assumed to be successfully received. However, if $CIR_{eff} < CIR_{min}$, the transport block is then assumed to be received in error.

When modeling WLAN it is unusual to make use of LUTs as in cellular systems. Rather, the concept of sensibility is employed. If a certain physical transmission mode is given and the mean received power is over its specific sensibility then the transmitted block will be properly received, otherwise the block is dropped.

IV. RRM AND CRRM INVESTIGATIONS

Once the SPHERE simulation platform has been described, this section is devoted to validate the implemented platform and show its potential for conducting novel CRRM and RRM investigations. In particular, this section briefly presents EDGE, HSDPA and WLAN RRM work conducted using the SPHERE platform and initial CRRM investigations considering a heterogeneous scenario made up of the GPRS, EDGE and HSDPA radio interfaces.

A. Platform Validation

The objective of this section is to validate the SPHERE platform by means of simulation results. For a rigorous validation, it would be desirable to compare the results obtained by SPHERE with the results from another source where a similar heterogeneous scenario was simulated. However, as no source for comparison has been found, this section compares the SPHERE results with the maximum possible performance of each RAT to prove the obtained results are within the expected range.

Figure 3 shows the Cumulative Distribution Function (CDF) of the throughput for the different RATs implemented in SPHERE. The EDGE RAT has been simulated considering different multi-slot configurations. These values have been obtained by simulating the diverse RATs of the system independently, i.e. not simultaneously, and considering a load of 15 users per cell in each simulation (3 for web-browsing, 3 for email, 3 for H.263 at 32 kbps, 3 for H.263 at 64 kbps, and 3 for H.263 at 256 kbps). In the simulation of WLAN, user's mobility is restricted to their 50m cell radius.

As it can be observed from Figure 3, the performance per RAT does not overpass their maximum theoretical value, which validates the current implementation of the SPHERE platform. In fact, the performance is lower than the maximum theoretical values given the low cell radius, high transmitting power and high cell load used to conduct these simulations. These conditions increase the interference levels which in turn increases the experienced BLER, decreases the throughput performance and promotes, in adaptive radio interfaces such as those modeled in SPHERE, the use of transmission modes with high error protection and lower bit rate. Figure 3 also shows that the HSDPA throughput performance is improved when using IR instead of CC. This improvement is due to the higher IR probability of successfully decoding retransmitted blocks given that it sends additional redundancy information with each retransmission.

Results clearly show that the SPHERE platform offers a considerably wide range of transmission capabilities, highlighting its suitability for analyzing CRRM policies in a heterogeneous wireless framework. From such perspective, and given that EDGE under multi-slot operation increases the transmission bit rate 'variety', each EDGE multi-slot configuration could be considered as a different RAT for the CRRM policies implemented in heterogeneous systems. This results in a heterogeneous wireless framework with a larger set of radio access alternatives that offer a wider set of transmission capabilities.

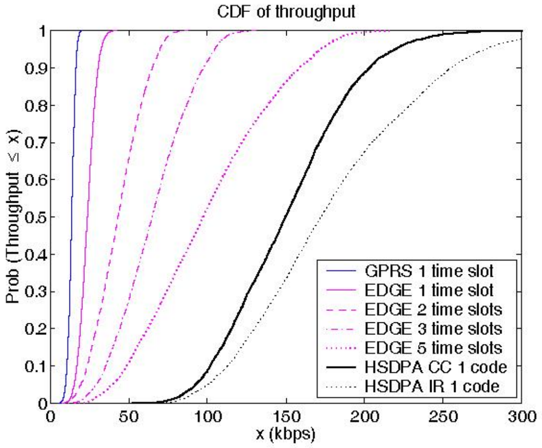

Figure 3. SPHERE throughput cdf

When analyzing the mean throughput performance, the results do not vary significantly per traffic service in a given RAT. Despite similar performance, user satisfaction is not similarly maintained for each RAT since each service has different QoS expectations. Consequently user satisfaction parameters per traffic service have been defined. Web-browsing and email users are assumed to be satisfied when they download a web page or an email in less than 4 seconds, as specified in 3GPP TS 22.105. Video users are supposed to be satisfied every time a video frame is entirely received before a new one is generated, i.e. no part of the video frame is discarded. The user satisfaction is therefore defined as the percentage of times that a web page, email o video frame transmission results satisfactory for the end user. Table VI shows the obtained results. In general, for a given service, the user satisfaction increases as the selected RAT offers better capabilities. However, it can be observed that for some H.263 users, EDGE using 5 slots obtains better user satisfaction than

HSDPA despite its lower throughput performance. This is due to two main reasons. First of all, it is important to note that the defined user satisfaction parameter for video transmissions is based on the bit rate and not on the throughput since transmission errors have not been accounted in the parameter's definition. Also given the real-time nature of H.263 video transmissions, retransmissions of erroneously received data blocks for EDGE and GPRS have not been allowed. On the other hand, up to four retransmissions have been allowed for HSDPA to take profit of HARQ capabilities. As a result, given that the experienced BLER is quite high for the considered operating conditions, HSDPA requests several retransmissions of a transport block and therefore less video frames are transmitted before the next one is generated than considering EDGE with 5 slots.

TABLE VI. USER SATISFACTION (%)

	Web	**Email**	**H.263 32 kbps**	**H.263 64 kbps**	**H.263 256 kbps**
GPRS	0.0	44.5	0.4	0.3	0.0
EDGE (1S)	53.8	53.9	87.9	43.0	0.0
EDGE (2S)	64.1	55.7	99.9	85.9	0.2
EDGE (3S)	74.4	59.7	100.0	98.9	0.6
EDGE (5S)	84.7	71.9	100.0	100.0	15.9
HSDPA	99.8	98.8	99.9	99.7	95.9
WLAN	100.0	100.0	100.0	100.0	100.0

As QoS requirements increase, RATs with higher bit-rates are required in order to obtain an acceptable degree of satisfaction. For the most demanding service, i.e. H.263 video transmission with a mean bit-rate of 256 kbps, only HSDPA and WLAN are able to offer an acceptable satisfaction level to the users for the considered operating conditions. On the other hand, for services with low QoS requirements such as background services, RATs with limited capabilities can fulfill the user expectations.

B. *EDGE multi-channel operation*

The authors are currently working on novel multi-channel operation mechanisms designed to effectively distribute the scarce available resources among users, according to the system state and the user's needs based on some contracted QoS and the service type requested. In particular, the authors are working on bankruptcy theory and utility-based schemes in a multi-service scenario. The techniques under evaluation include Discrete Constraint Equal Award (DCEA), Discrete Constraint Equal Loss (DCEL), maximum utility (MaxUtil) scheme and Required Data Rate (ReqDataRate).

In DCEA, resources are allocated first to the users experiencing lower satisfaction levels until all users reach the same user satisfaction (the same user satisfaction for different services might not require the same number of channels). In case an equal user satisfaction cannot be reached, priorized users (e.g. real-time H.263) receive the remaining channels. DCEL follows a similar assignment except that users get initially all necessary resources to guarantee maximum user satisfaction, and resources are sequentially reduced to try to guarantee at the end of the channel distribution the same user satisfaction levels. As for DCEA, if such aim is not possible, real-time services are priorized. In the MaxUtil scheme, channels are assigned to the users that will see a higher increase in user satisfaction if a channel is being assigned to them. The ReqDataRate mechanism calculates the required data rate to transmit pending data in time to maintain user satisfaction and allocates the channels necessary to reach such data rate, again based on service type priority.

An example of the performance of the four multi-channel allocation schemes currently being assessed using the SPHERE simulation platform is shown in Table VII.

TABLE VII. USER SATISFACTION (%) FOR MULTI-CHANNEL ASSIGNMENT SCHEMES IN EDGE

Service	**DCEA**	**DCEL**	**MaxUtil**	**ReqDataRate**
Web	48.94	57.48	45.52	46.38
Email	11.31	15.09	91.60	10.09
16 kbps	86.52	63.71	99.93	89.91
32 kbps	87.54	79.64	82.58	88.54
64 kbps	87.18	83.65	86.34	85.15

C. *Effect of Channel-Quality Indicator Delay on HSDPA*

The authors have also assessed the intrinsic delay of the Channel Quality Indicator (CQI) reporting process and its effect on the HSDPA system performance. As the authors are currently investigating, this delay has a severe impact in the efficiency of the link adaptation process and also affects the scheduling process since the upper limit of the resources allocated to each user depends on this report.

D. *Hybrid HCF Scheduling Mechanism for WLAN*

The classical HCF scheduling mechanism, where real time traffic is delivered through HCCA and best effort users mutually contend to get the channel control, presents a clear bottleneck for the downlink best effort users since the access point competes in the same manner with the rest of uplink users. In order to overcome this limitation, authors are also currently working using the SPHERE platform to develop a new hybrid scheme. The authors have proved that an adequate allocation of the downlink and uplink best effort traffic between EDCA and HCCA can increase the system's performance compared to the traditional scheme.

E. *CRRM mechanisms for RAT selection*

In terms of CRRM research, initial investigations from the authors have proposed a selection RAT algorithm, named UBReQoS algorithm [20], that intelligently distribute users among the RATs of a heterogeneous system according to the load of each RAT, the required QoS level, and the effect of a RAT selection on users already employing such RAT. In particular, the UBReQoS scheme considers three different utility functions. The first one aims at selecting the RAT that achieves the user required QoS level. A distinctive feature of this utility function is that users are not always assigned to the RAT achieving the highest transmission rate but to the RAT that ensures its QoS even if there are other available RATs with higher data rates; this procedure will enable a load balancing policy among RATs. The second utility function considers the RAT's load to avoid assigning RATs that are already overcharged which will increase transmission times and therefore reduce user perceived QoS. The third utility function considers the effect of interfering users per RAT in order to favor the selection of RATs with lower interference levels.

Table VIII shows the performance improvements that can be achieved with the UBReQoS proposal in a multi-service scenario compared to a reference algorithm in which each service type is permanently allocated to the same RAT; the reference schemes assigns web and email users GPRS, H.263 video users with a bit rate of 32 kbps to EDGE, and H.263 video users with bit rates of 64 and 256 kbps to HSDPA (no multi-channel operation is considered here). The simulation results have been obtained using the SPHERE simulation platform.

TABLE VIII. USER SATISFACTION (%) FOR UBREQOS AND REFERENCE ALGORITHMS (SCENARIO I, SINGLE-CHANNEL OPERATION)

Service	Reference	UBReQoS	Improvement
Web	49.79	59.70	+ 9.9 %
Email	54.32	58.78	+ 4.5 %
32 kbps	88.23	91.41	+ 3.2 %
64 kbps	92.90	90.45	– 2.5 %
256 kbps	51.86	55.92	+ 4.1 %
Global	85.15	86.20	+ 1.1 %

V. CONCLUSIONS

This work has presented SPHERE, a radio simulation platform for heterogeneous wireless systems jointly developed by the University Miguel Hernández and the Polytechnic University of Valencia.

In this paper the main features of the implemented simulation tool have been briefly described. Starting from an overview of all the considered RATs, this paper has given a full account of the logical structure of SPHERE and all its modules, especially describing those related with the radio resource management strategies, which are the main concern of the research project under which the SPHERE platform is being built.

The platform has been validated through system level simulations and some initial investigations that are being conducted using SPHERE have been explained to illustrate the potential of the implemented software platform.

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REFERENCES

[1] EVEREST Project IST-2002-001858. Available at http://www.everest-ist.upc.es/.

[2] A. Tolli, P., Hakalin, and H. Holma, “Performance evaluation of common radio resource management (CRRM)”. IEEE International Conference Communications (ICC’02),pp. 3429-3433, 28 April-2 May, 2002.

[3] F. Malavasi, M. Breveglieri, L. Vignali, P. Leaves and J. Huschke, “Traffic control algorithms for a multi access network scenario comprising GPRS and UMTS”, 57th IEEE Vehicular Technology Conference, vol. 1, pp. 145-149, April 2003.

[4] R. Veronesi, “Multiuser scheduling with multi radio access selection”, 2nd International Symposium on Wireless Communication Systems, pp. 455-459, September 2005.

[5] R. Ferrus et al., “EVEREST testbed: QoS management evaluation in B3G networks”, IEEE International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities, March 2006.

[6] M. Takai et al., “Scalable Testbed for Next-Generation Wireless Networking Technologies”, IEEE International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities, pp. 162-171, February 2005.

[7] 3GPP, Physical layer procedures (FDD), 3GPP TS25.214 V7.1.0.

[8] ETSI, “Universal Mobile Telecommunications System (UMTS); Selection procedures for the choice of radio transmission technologies of the UMTS”, TR 101.112, Apr. 1998.

[9] Y. Wang and L. Cuthbert; “Agent-based load balancing of WLAN in indoor usage“, IASTED International Conference on Wireless and Optical Communications , June 2003.

[10] J.F. Monserrat, J. Gozalvez, R. Fraile and N. Cardona, “Effect of Shadowing Correlation Modeling on the System Level Performance of Adaptive Radio Resource Management Techniques”, IEEE International Symposium on Wireless Communications Systems, September 2005.

[11] M. Gudmundson, “Correlation model for shadow fading in mobile radio systems”, IEE Electronics Letters, pp. 2145–2146, November 1991.

[12] J. Gozalvez y J. Dunlop, “Link Level Modelling Techniques for Analysing the Configuration of Link Adaptation Algorithms in Mobile Radio Networks”, Proceedings of European Wireless, pp 325-330, February 2004.

[13] J. Gozálvez and J.J González-Delicado, “Channel allocation mechanisms for improving QoS in packet mobile radio networks”, IEE Electronics Letters, pp. 21-22, January 2005).

[14] J. Gozálvez, M. López-Benítez and O. Lázaro, “Link adaptation algorithm for improved wireless transmission of delay-sensitive packet data services”, IEE Electronic Letters, pp. 813-815, July 2005.

[15] P. Barford and M. Crovella, “Generating representative web workloads for network and server performance evaluation”, Joint International Conference on Measurement and Modeling of Computer Systems, June 1998.

[16] J. Ho, Y. Zhu and S. Madhavapeddy, “Throughput and buffer analysis for GSM general packet radio service (GPRS)”, IEEE Wireless Communications and Networking Conference, pp. 1427-1431, September 1999.

[17] O. Lázaro, D. Girma and J. Dunlop, “H.263 video traffic modelling for low bit rate wireless communications”, IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications, pp. 2124-2128, September 2004.

[18] J. Laiho, A. Wacker and T. Novosad, “Radio network planning and optimisation for UMTS”, Wiley, 2002.

[19] B. Wang, K.I. Pedersen and P.E. Mogensen, “Performance of VoIP on HSDPA”, IEEE Vehicular Technology Conference, pp. 2335-2339, May 2005.

[20] M. López-Benítez y J. Gozalvez, “QoS provisioning in beyond 3G heterogeneous wireless systems through common radio resource management algorithms” Proceedings of the Second ACM Workshop on QoS and Security for Wireless and Mobile Networks (Q2SWinet 2006), pp 59-66, October 2006.