A DYNAMIC RADIO SIMULATION PLATFORM FOR THE STUDY OF RADIO RESOURCE MANAGEMENT TECHNIQUES IN HETEROGENEOUS WIRELESS SYSTEMS*

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Abstract Beyond 3G mobile communication systems are being defined as the integration of diverse radio access technologies into what is generally known as heterogeneous wireless systems. These systems present important challenges in terms of the management of the available radio resources for each radio access technology. Given the complexity of mobile communication systems, the use of simulation tools to analyse their performance is common within the research and industrial communities. The

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development of such simulation platforms to accurately investigate radio resource management techniques in heterogeneous wireless systems is a challenging task. In this context, this paper presents SPHERE, a Simulation Platform for HEterogeneous wiREless systems developed at the University Miguel Hernández. The system level simulation platform is currently capable of simultaneously emulating the transmission of GPRS, EDGE and HSDPA at the packet level. Given the modularity of the SPHERE platform and its detailed modelling of each radio access technology, the platform can also be used to investigate the optimisation of radio resource management techniques within each modelled system. This paper not only presents and validates the SPHERE platform, but it also introduces radio resource management investigations currently being conducted using the advanced simulation platform.

Keywords: Simulation platform, heterogeneous wireless systems, common radio resource management, radio resource management.

Introduction

While cellular operators are currently directing their efforts towards the development and exploitation of third generation (3G) systems, research activities are focused on the definition of beyond 3G (B3G) or fourth generation (4G) systems [21]. While some research initiatives consider 4G as a new radio access technology, most of the research community, including research programs within the European Commission, envisage B3G or 4G systems as the integration and joint management of various radio access technologies, including current 2G/3G/3.5G cellular systems, WLAN (Wireless Local Area Network), DVB (Digital Video Broadcasting), DAB (Digital Audio Broadcasting), and any potential new technologies that might appear in the future.

In this context, one of the main challenges that heterogeneous wireless systems must overcome is the ability to guarantee the interoperability and efficient management of the different Radio Access Technologies (RATs) in order to provide the user with a suitable and consistent Quality of Service (QoS) level. To this end, one of the key elements that must be considered by the network provider, and that is currently a hot topic within the 4G research community, is the Common Radio Resource Management (CRRM) of the different radio access technologies.

To accurately evaluate the performance of mobile communication systems before considering a prototype or full-scale deployment, the use of simulation platforms is becoming increasingly common within the research community. To conduct meaningful and appropriate studies, such simulation platforms need to accurately implement the entities 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.

This work presents and describes SPHERE, an advanced Simulation Platform for HEterogeneous wiREless systems developed at the Signal Theory and Communications Division of the University Miguel Hernández. In its current state, the platform integrates three advanced system level simulators, which emulate the radio transmissions at the packet level, enabling an accurate evaluation of the final user perceived QoS. In particular, the SPHERE platform emulates the GPRS (General Packet Radio Service), EDGE (Enhanced Data-rates for GSM/Global Evolution), and HSDPA (High Speed Downlink Packet Access) radio access technologies. The radio interface specifications of these three technologies are faithfully implemented in the SPHERE simulation platform, which works with a high time resolution (in the order of some milliseconds) since it emulates transmissions at the slot or packet level. This modelling approach validates the capability of the SPHERE simulation platform to dynamically and precisely evaluate the performance of RRM/CRRM techniques. It is important to highlight that such techniques try to optimise the radio transmission and therefore developing simulation platforms, such as SPHERE, that model the complete radio transmission effects is of paramount importance. 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 radio access technologies.

The remainder of this paper is organized as follows. First, section 1 briefly revises some previous related work in order to position the SPHERE simulation platform with respect to other simulation tools. Section 2 describes the SPHERE platform, which is then validated in section 3. Two RRM and CRRM investigations that are currently being conducted at the Signal Theory and Communications Division of the University Miguel Hernández using the SPHERE simulation platform are then presented in section 4 to demonstrate the potential of SPHERE. Finally, section 5 summarises and concludes the paper.

1. Related Work

To demonstrate the suitability and need in the research community of a simulation platform such as SPHERE, this section presents some related work and the simulation platforms being employed. It is important to highlight the availability of various simulation platforms with different degrees of detail in their implementation depending on the particular investigation that is being carried out.

For example, while the work reported in [16] and [23] investigate different traffic distribution policies, implemented at the session level, among a variety of RATs, their simulation tools do not model specific radio features of each RAT or even the radio transmission process at the packet level. The implemented tools also do not account for the radio propagation effects, limiting the finally obtained user perceived QoS figures given the strong influence of such effects on the performance of mobile communication systems. Although such modelling approach reduces the complexity of the simulation platform and can be valid for certain objectives, the use of detailed radio simulation platforms would be desirable when investigating advanced CRRM techniques.

The work reported in [18] proposes and evaluates several traffic distribution algorithms in a heterogeneous network composed of GPRS and UMTS. Although to measure the user satisfaction achieved with such algorithms, the implemented simulation tool takes into account propagation models and some specific RAT-features, it does not simulate the complete radio transmission process. As a result, the user perceived QoS is only derived from the experienced Carrier-to-Interference Ratio (CIR). The study carried out in [24] is based on 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.

Some European research projects, such EVEREST and DRiVE, have been devoted to the general study of heterogeneous wireless systems, and in particular of CRRM-related aspects. However, DRiVE references [3–4] point out that the simulation tools "were not designed to model packet level traffic, but only modelled services on a session level. The reason for this was that the simulations needed to model long-term variations in the traffic, and simulated a long time period (i.e. 24 hours). Therefore, the modelling of packet level traffic would lead to unacceptably long computation times". On the other hand, the EVEREST project has developed more sophisticated simulation tools to conduct their investigations [5–6], although such tools do not seem to be integrated into a single simulation platform that would enable the parallel and simultaneous emulation of all interacting aspects on a heterogeneous wireless system.

As it has been discussed, there are a variety of simulation platforms available within the research community to study heterogeneous wireless systems. The previous discussion has highlighted that their level of detail depends on the specific objectives of the conducted investigations.

Although all simulation platforms are valid within their research framework, to the best of the authors' knowledge, there is no simulation platform available that implements at the packet/slot level different RATs and enables their simultaneous and parallel emulation. It is the authors' belief that such platform would be highly desirable to investigate CRRM policies and provide accurate results on the system performance and user perceived QoS.

In this context, the University Miguel Hernández has developed, in the framework of a nationally funded research project (entitled 'Decision making processes for common radio resource management in heterogeneous wireless networks'), the SPHERE simulation platform. This platform integrates three detailed system level simulators emulating the operation of different RATs (GPRS, EDGE and HSDPA) at the packet level, which enables accurate estimations of the system performance and user perceived QoS. The platform is currently being used to investigate advanced RRM and CRRM policies.

2. The SPHERE Platform

Figure 1 shows the logical structure of the SPHERE simulation platform. The components shown in this figure and all related aspects and features will be described in the following sections.

2.1 Cellular Environment

The SPHERE platform is a discrete-event system level simulator currently based on a cell layout of 27 omni-directional cells with a radius of 500m. The cells of the system are distributed following a three-cell cluster structure as shown in Figure 2. This configuration can be rapidly modified, including considering a sectorised cellular network, to match other cellular scenarios. In order to avoid border effects, a wrap-around technique has been applied (see Figure 2). Coverage from all RATs is provided in each cell. However, the existence of some regions without coverage from one or more RATs will also be considered.

The *Cellular Environment* entity in Figure 1 stores the location of each base station in the system and an updated list of all the resources allocated at any given time by any base station. This information will be needed to estimate the experienced interference levels.

2.2 Radio Link

This component models the radio propagation conditions between transmitter and receiver. The *Radio Link* element characterises the long-term variations of the signal, i.e. path loss and shadowing.

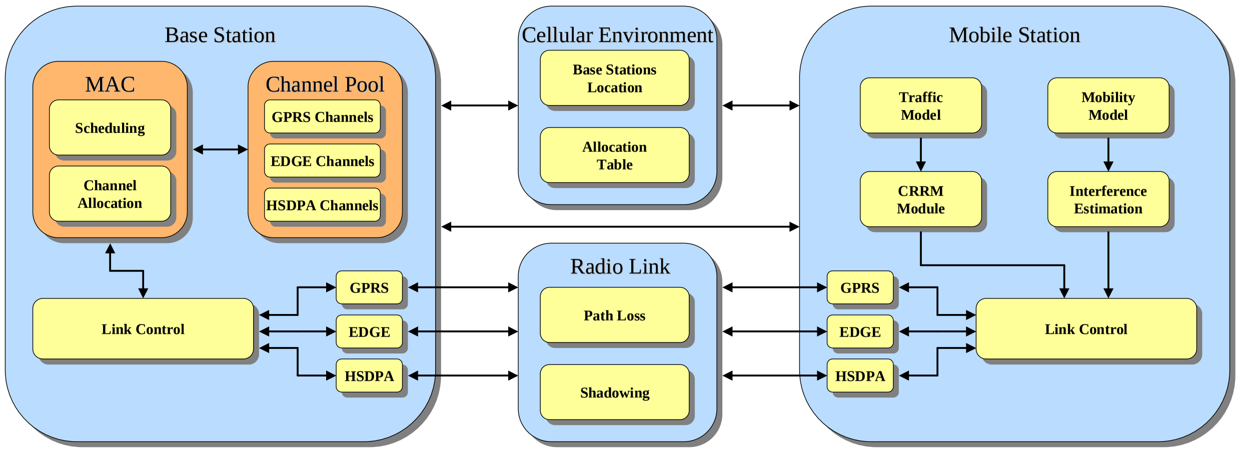


Figure 1. Logical structure of the SPHERE simulation platform.

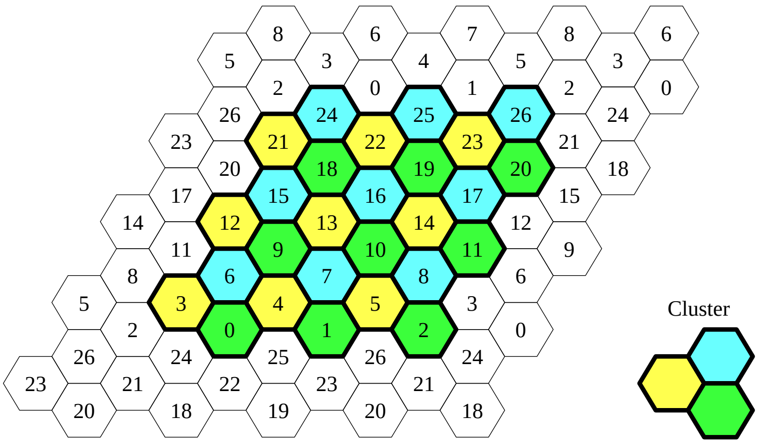


Figure 2. Cell layout of the SPHERE simulation platform.

For path loss estimation, the COST 231 extension of the well-known Okumura-Hata model has been used, which is applicable to frequencies from 1.5 GHz up to 2 GHz. For GPRS and EDGE, a carrier frequency of 1.8 GHz has been assumed. A carrier frequency equal to 2 GHz has been considered for HSDPA. For the rest of parameters of the model, typical values have been used.

The path loss model provides an average measure of the signal attenuation over a given distance. However, for the same distance between transmitter and receiver, different values of instantaneous loss can be obtained due to different surrounding environments. This effect is included by means of the shadowing, which adds additional signal attenuation due to obstacles in the path between transmitter and receiver. Measurements have shown that the shadowing loss can be modelled 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. A shadowing standard deviation of 6 dB has been considered in this work. 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. This spatial correlation has been modelled as detailed in [12] with a de-correlation distance of 20 m.

2.3 Base Station

As the platform currently focuses on downlink transmissions, the *Base Station* component is responsible for the Medium Access Control (MAC) functions, in particular the scheduling and the channel allocation.

When a mobile station requests a channel from a given RAT, the channel pool of the serving base station is examined. If a free channel is available on the requested RAT, the mobile station is assigned the channel, which can be selected in a random manner or according to the quality experienced in previous transmissions [9] or the estimated interference [11]. If a free channel is not available on the requested RAT, several options can be considered: either the mobile station is placed in a queue until a transmitting mobile ends its transmission and releases its channel, or the user is assigned a channel from a different RAT. 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 in a round robin fashion or according to the Max C/I criterion, which selects at any moment the user with better transmission quality.

Multi-channel operation has also been modelled in the platform. In this operation mode, the number of channels that the base station allocates to the mobile is subjected to the multislot or multicode capability of the mobile, the system load, the number of available resources, the requested service and the operator's policy.

2.4 Mobile Station

2.4.1 Mobility Model. The initial position of a mobile station within a cell is set randomly according to a random uniform distribution and the movement within the cell is currently performed at a constant speed. In order to integrate the mobility (continuous character) into the event-driven simulation (discrete character), the mobile's movement is modelled as a set of random steps. The length of each step is constant and equal to the de-correlation distance used for the shadowing model. Therefore, the time required to cover the distance is dependent on the speed. The position of a mobile at a particular time between two random positions is extracted by lineal 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. This modelling procedure has been shown to be consistent with an analysis performed on real data. It also leads to a uniform density of users within the cell area on the long term.

2.4.2 Interference Estimation. Each mobile station is responsible for estimating the CIR level. The carrier level is obtained from the mobile's position, the base station's transmission power, and the base station's position. For FDMA/TDMA systems (i.e. GPRS and EDGE), the interference level is obtained in a similar manner but considering the power transmitted by co-channel interfering base stations, their positions and their active channels. Thus, the GPRS and EDGE CIR levels can be expressed as follows:

$$CIR_{GPRS/EDGE} = \frac{\dfrac{P_i}{L_P^{ii} \cdot L_S^{ii}}}{\displaystyle\sum_{j \in \Omega} \frac{P_j}{L_P^{ij} \cdot L_S^{ij}} + N_0 \cdot W} \qquad (1)$$

where P_i is the transmission power of the desired signal in the reference cell (cell i), 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 transmitters in co-channel interfering cells, P_j is the transmission power of the interfering cells, 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_0W 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.

In CDMA-based systems as HSDPA, channelisation codes for the users of the same cell are perfectly orthogonal. However, due to multipath fading, this orthogonality decreases and some intra-cell interference component is observed. Intra-cell interference on a CDMA system is modelled by an orthogonality factor, which is usually denoted as α. In absence of multi-path fading, the codes are perfectly orthogonal, so $\alpha = 1$. When two different samples of the same signal are received with similar strength, $\alpha \approx 0.5$. 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:

$$CIR_{HSDPA} = \frac{\dfrac{P_i}{L_P^{ii} \cdot L_S^{ii}}}{\displaystyle\sum_{i' \in \Omega'} \frac{P_{i'} \cdot (1-\alpha)}{L_P^{ii'} \cdot L_S^{ii'}} + \sum_{j \in \Omega} \frac{P_j}{L_P^{ij} \cdot L_S^{ij}} + N_0 \cdot W} \qquad (2)$$

where i' is related to users in the reference cell i other than the user of interest. In this expression, the parameters $P_{i'}$ and P_j also include the base station power reserved for other channels different from the HSDPA High Speed Downlink Shared Channel (HS-DSCH).

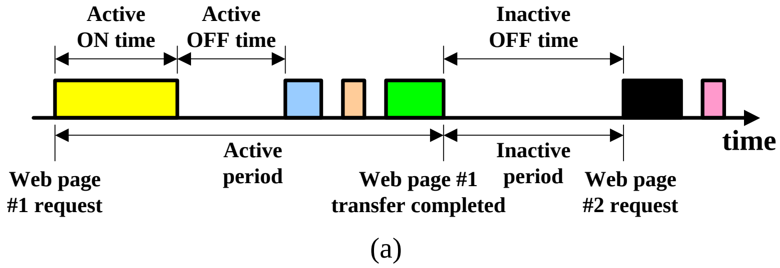
2.4.3 Traffic Model. The transmitted information is generated by the *Traffic Model* component. Although this component should be implemented at the base station given that the tool models the downlink, it has been finally implemented in the *Mobile Station* entity for code optimisation reasons.

The SPHERE platform incorporates three accurate traffic models for web browsing, email, and H.263 video transmission. Future wireless systems will be used as a platform to support a wide range of data applications. Web browsing and email are some of the most popular applications in the fix network traffic. As this trend is expected to continue on the wireless domain, web browsing and e-mail applications have therefore been considered in the context of this work. This scenario has been extended by including a video service in order to enable the evaluation of system performance over a wider set of services (background, interactive, streaming, and conversational).

For web browsing traffic, the model detailed in reference [1] has been implemented. The behaviour of web browsing applications is described in [1] by means of an ON/OFF model. Figure 3a illustrates this model. 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. As [1] is based on HTTP 0.9/1.0, where a different TCP connection is established for the transmission of each object in a web page, a distinction is made between active ON and active OFF times. The active ON time corresponds to the time needed for the transmission of a single object of a web page, while the active OFF time corresponds to the time between closing a TCP connection and opening a new one to transfer the next object.

For email traffic the model detailed in [13] has been implemented. It is also based on an ON/OFF approach (see Figure 3b). The model assumes that incoming messages are stored at a dedicated email server. This server keeps the emails in a mailbox until the user logs onto the network 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 downloads a message (active period), she/he will read it (inactive period) before downloading the next message, and so on.

For real-time H.263 video traffic, the model described in [15] has been implemented. This model takes into account the three different frame types considered in the H.263 standard, namely I, P and PB. Each frame type exhibits different statistical properties, which are accurately cap-



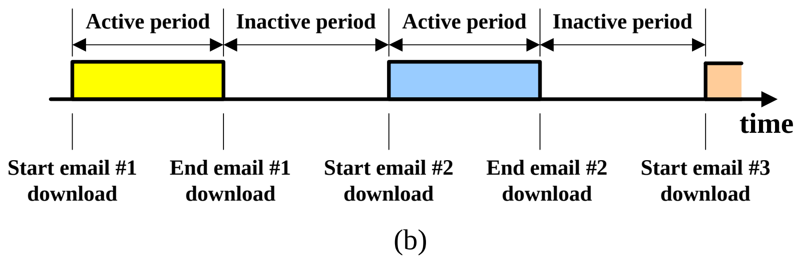


Figure 3. Web browsing (a) and email (b) traffic models.

tured by the model. The parameters defined by the model are the size and the duration of the frames, the correlation between both parameters for each video frame, and the transition probability between different video frame types. The modelling is performed at two levels. On one hand, the first level establishes the frame type to generate. I-frames are periodically created, while a Markov chain drives the transition between P- and PB-frames generation. On the other hand, once the frame type to be generated is decided, the second modelling level determines the size and the duration of the video frame to be transmitted.

Each generated real-time H.263 video frame has an associated deadline. The transmission of the whole video frame must be completed before the deadline is reached. If this is the case, the channel is released so other users can use it. On the other hand, if the transmission of a video frame is not finished by the time the next video frame is generated, the previous video frame is discarded and the channel is using to transmit the new H.263 video frame.

2.4.4 CRRM Module. This component is responsible for several CRRM functions that are currently being developed by the research group at the University Miguel Hernández. The SPHERE simulation platform is currently being used for the study and design of algorithms to decide, based on pre-established criterions and utility functions, the optimum RAT for transmission. The platform has been designed to allow a flexible distribution of traffic across the modelled RATs. A RAT change for a given user can therefore be performed every time a new session begins, periodically, or every time a new packet is generated (this last option has been implemented only for experimentation purposes).

It is important to highlight that when the *CRRM Module* decides to change from one RAT to another one, the change is made dynamically during the simulation and the radio transmission can be immediately resumed by the newly selected RAT at the stage where the radio transmission ended using the previous RAT. Therefore, it is possible for a given user to perform a web session through EDGE, then download several emails through GPRS, and then change to HSDPA in order to receive a video sequence. It is also possible that a user handles an application session using alternatively the various available RATs. All three RATs in the system are simultaneously operated, so one user can be connected to GPRS at the same time another user is connected to EDGE and another one is connected to HSDPA. It is important for a heterogeneous wireless system simulation platform to be capable of modelling this type of situations since in a real system the instantaneous load of each RAT is a key aspect to be taken into account when deciding the optimal transmitting RAT.

Finally, it is worth noting that although the *CRRM Module* appears integrated in the *Mobile Station* entity (for code optimisation reasons), it is possible to evaluate CRRM techniques whose criterion is based not only on user-related aspects but also on network provider interests.

2.5 Link Control

The Link Control entity accurately implements the specifications of the different RATs available in the simulation platform and reproduces with a high degree of detail the transmission process through their radio interfaces. In particular, the platform considers the GPRS, EDGE and HSDPA interfaces that are described in the following sections.

2.5.1 GPRS. GPRS is based on a combined FDMA/TDMA multiple access technique that has been implemented as detailed in specifications ETSI GSM 05.01 and ETSI GSM 05.02. FDD is employed as the duplexing methodology with two 25 MHz bands being used, respectively for the uplink and downlink transmissions. Each 25 MHz band is divided into 125 carriers with a bandwidth of 200 kHz. In the TDMA dimension, each carrier is further divided into time-slots of 0.577 ms. By grouping 8 time-slots, a 4.615 ms TDMA frame is obtained. The temporal hierarchy considers higher order structures such as super-frames and hyper-frames (see specifications above) that have not been implemented given that the SPHERE platform has been devised to optimise radio transmissions.

The simulation platform implements the different available GPRS transmission modes (see Table 1), and models its adaptive operation resulting from the use of Link Adaptation (LA) technique. LA 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 maximises the throughput is selected. For H.263 video service, the algorithm proposed in [10] has been used since it outperforms the former in several key aspects affecting real-time operation.

Transmission mode	Modulation scheme	Code rate	Bits per radio block	Bit-rate (kbps)
CS-1	GMSK	1/2	181	9.05
CS-2	GMSK	$\approx 2/3$	268	13.4
CS-3	GMSK	$\approx 3/4$	312	15.6
CS-4	GMSK	1	428	21.4

Table 1. GPRS transmission modes.

In GPRS, the information is segmented into radio blocks in order to be transmitted through the radio interface. The number of data bits within a radio block varies according to the transmission mode used (see Table 1), but the time required to complete the transmission of a single radio block is always equal to 20 ms. A radio block is further divided into four normal bursts, which are interleaved over four consecutive TDMA frames.

In order to decide whether a radio block is received in error, the experienced CIR is computed each time a normal burst is transmitted (every 5 ms). After completing the transmission of a whole radio block, the four associated CIR values are averaged and a single CIR_{avg} value is obtained, which is representative of the quality experienced by the radio block. This CIR_{avg} value is then mapped to a BLock Error Rate (BLER) value ($BLER_0$) by means of a Look-Up Table (LUT) as shown in Figure 4. LUTs are used as a means of interfacing link and system level investigations using the link level analysis as a source of informa-

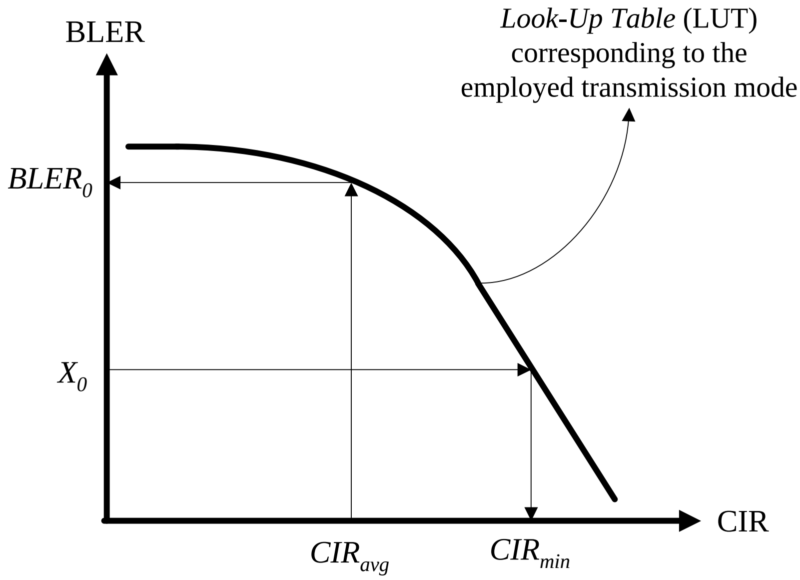


Figure 4. Use of look-up tables.

tion 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). GPRS LUTs for the different transmission modes and various mobile speeds under a typical urban scenario have been produced by means of extensive link level simulations modelling the radio link at the bit level [8].

Once a $BLER_0$ value is obtained from the LUT corresponding to the transmission mode that has been used, a random number X_0 between zero and one is drawn from a uniform distribution. If $X_0 > BLER_0$, the radio block is assumed to be successfully received. However, if $X_0 \leq BLER_0$, the radio block is then assumed to be received in error.

For retransmission of erroneous blocks, a detailed implementation of the Automatic Repeat reQuest (ARQ) protocol described in specification 3GPP TS 04.60 has been performed. This ARQ protocol is based on the numbering of the blocks and a sliding window principle, where two windows, one in the transmitting side and other in the receiving side, are used. The transmitter sends blocks and the receiver sends acknowledgment messages when requested. These messages acknowledge all correctly received blocks and request the retransmission of erroneously received blocks. The transmitter and the receiver require buffers to store the radio blocks until they are correctly received and acknowledged. The size of these buffers limits the maximum number of blocks that can be pending of a positive confirmation. The size of the windows has been set to 64 blocks according to 3GPP TS 04.60. 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 been considered.

2.5.2 EDGE. The EDGE radio interface is based on the same multiple access scheme and format as GPRS. On the other hand, EDGE considers different transmission modes (see Table 2), generally referred to as Modulation and Coding Schemes (MCS), that have also been incorporated into the SPHERE platform; it is worth noting the introduction of a new modulation scheme, 8-PSK, compared to GPRS.

Transmission mode	Modulation scheme	Code rate	Transmission 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

Table 2. EDGE transmission modes.

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, as shown in Figure 5. 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.

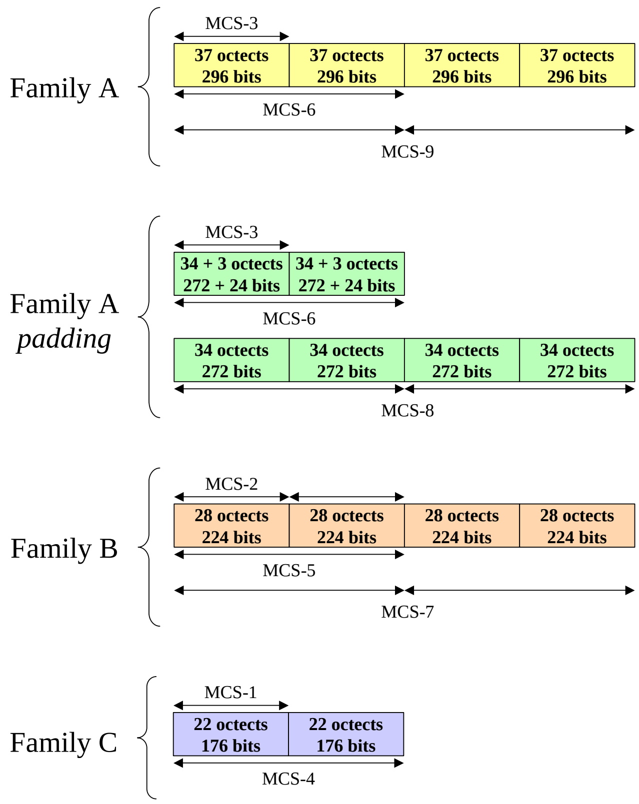


Figure 5. EDGE transmission mode families.

A block received in error can be resegmented and retransmitted using a more robust transmission mode within the same transmission family. The adaptive nature of the EDGE radio interface has also been considered in the SPHERE platform by implementing LA algorithms based on the same selection criterion as those employed for GPRS. For multislot operation, the channel quality conditions, expressed in terms of CIR, are estimated over all the slots being simultaneously allocated to a single user. Their average value is then used to estimate the optimum transmission mode according to the established selection criterion.

The GPRS and EDGE transmission procedures are very similar, although some differences for high order modes need to be highlighted. When 4 payload units are transmitted (MCS-7, MCS-8 and MCS-9), these are splitted 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. As for GPRS, the transmission of a whole radio block in EDGE requires 20 ms.

The same procedure as for GPRS is used to model the channel quality and to decide when a radio block is received in error. The retransmission of erroneous radio blocks is also performed by a sliding window ARQ protocol (3GPP TS 04.60). The EDGE window size is set according to the number of channels that are simultaneously allocated to the user terminal, ranging from 64 to 1024 radio blocks. For instance, the maximum window size is equal to 192 blocks for single slot operation. The reporting period has been established to 32 radio blocks.

2.5.3 HSDPA. The HSDPA multiple access scheme is based on CDMA and distinguishes between a FDD component and a TDD component. In this work, the FDD component has been implemented. In FDD, two 60 MHz bands are used, one for the uplink and one for the downlink. 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) equal to 2 ms is defined. A TTI is divided into three 667 μs slots. In the code domain, channelisation codes at a fixed spreading factor of 16 are used. Multi-code transmission is allowed, which translates to a single mobile station being assigned multiple channelisation codes in the same TTI.

The SPHERE platform implements the different HSDPA transmission modes (see Table 3), and models its adaptive operation by means of an Adaptive Modulation and Coding (AMC) technique, which is equivalent to the LA technique. Again, the same configuration as for the GPRS and EDGE LA algorithms has been employed for the HSPDA AMC scheme.

Transmission mode	Modulation scheme	Code rate	Bits per radio block	Bit-rate (kbps)
MCS-1	QPSK	0.25	240	120
MCS-2	QPSK	0.50	480	240
MCS-3	QPSK	0.75	720	360
MCS-4	16-QAM	0.50	960	480
MCS-5	16-QAM	0.75	1440	720

Table 3. HSDPA transmission modes.

In HSDPA, the information is segmented into transport blocks in order to be transmitted through the radio interface. The number of information bits within a transport block varies according to the transmission mode that is going to be used (see Table 3), but the time required to complete the transmission of a single transport block is always equal to 2 ms, i.e. one TTI.

In order to decide whether a transport block is received in error, 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.

When a transport block is received in error, it is not discarded but stored in the receiver buffer and combined with subsequent retransmissions of the same transport block according to different methods. One possibility is to use the same coding for each retransmission. Retransmitted blocks are therefore identical to that of the first transmission. The different transmissions of the same transport block are weighted by their respective experienced CIR values according to the Chase Combining (CC) method. When employing Incremental Redundancy (IR), retransmissions are typically not identical to the original transmission. Retransmitted blocks carry additional redundancy for error correction purposes. This additional redundancy is combined with the previously received data and the resulting code word, that exhibits a higher coding gain, is then decoded. The CC and IR schemes have been implemented in the SPHERE simulation platform following the model proposed in [7].

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 combining several transmissions of a transport block. 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 a LUT as shown in Figure 4 (the LUT employed in this process will depend on the transmission mode that is going to be used). 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} value 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 and a retransmission is requested.

Retransmission of erroneous transport blocks is performed by a N-channel stop-and-wait (SAW) ARQ protocol. In stop-and-wait, the transmitter operates on the current block until the block has been successfully received. The receiving side sends an acknowledgment message for every transmitted transport block. Based on this message, the transmitting side will retransmit the previous transport block or will transmit a new one. A major drawback of the SAW protocol is that acknowledgements are not instantaneously transmitted and therefore after every transmission, the transmitter must wait to receive the acknowledgement prior to transmitting the next block; this is a well-known problem with SAW protocol. In the interim, the channel remains idle and system capacity goes wasted. In a slotted system, the feedback delay will waste at least half the system capacity while the transmitter is waiting for acknowledgments. As a result, at least every other timeslot must go idle even on an error free channel. N-channel SAW ARQ offers a solution by running a separate instantiation of the SAW ARQ protocol when the channel is idle. No transport block losses or errors on the transmission of the acknowledgement messages have been considered.

3. Validation Results and Potentials

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 expectable range. Of course, the results might vary within this range based on the operating conditions and parameters. Table 4 summarises the configuration of the simulation platform.

Figure 6 shows the Cumulative Distribution Function (CDF) of the throughput for the different RATs implemented in SPHERE. EDGE has been simulated considering different multislot configurations. These curves 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).

As it can be observed from Figure 6, the performance per RAT does not overpass their maximum theoretical value, which validates the cur-

Parameter	GPRS	EDGE	HSDPA
Environment	Urban macro cellular		
No. of cells	27		
Reuse factor	3	3	1
Cell radius	500 m		
Channels/cell	8	8	8
Ch. allocation	Random		
Scheduling	FCFS	FCFS	Round Robin
Power/channel	30 dBm	30 dBm	30 dBm
Path loss model	Okumura-Hata COST 231 f_c = 1.8 GHz	f_c = 1.8 GHz	f_c = 2.0 GHz
Shadowing model	Log-normal, with standard deviation of 6 dB and decorrelation distance of 20 m		
Thermal noise	-121 dBm	-121 dBm	-107 dBm
ARQ protocol configuration	Window size of 64 blocks. Reporting period of 16 blocks.	Window size according to multislot class. Reporting period of 32 blocks.	4 SAW processes. Maximum 4 transmissions.
LA/AMC upd. period	60 ms	60 ms	2 ms

Table 4. Configuration of the simulation platform.

rent 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 increases the experienced BLER, decreases the throughput performance and promotes, in adaptive radio interfaces such as those modelled in SPHERE, the use of transmission modes with high error protection and lower bit rate. Figure 6 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, as reported in [7].

Figure 6 clearly shows that the SPHERE platform offers a considerably wide range of transmission capabilities, highlighting its suitability for analysing CRRM policies in a heterogeneous wireless framework. From such perspective, and given that EDGE under multislot operation increases the transmission bit rate 'variety', each EDGE multislot configuration could be considered as a different RAT for the CRRM policies implemented in heterogeneous systems. This results in a heterogeneous

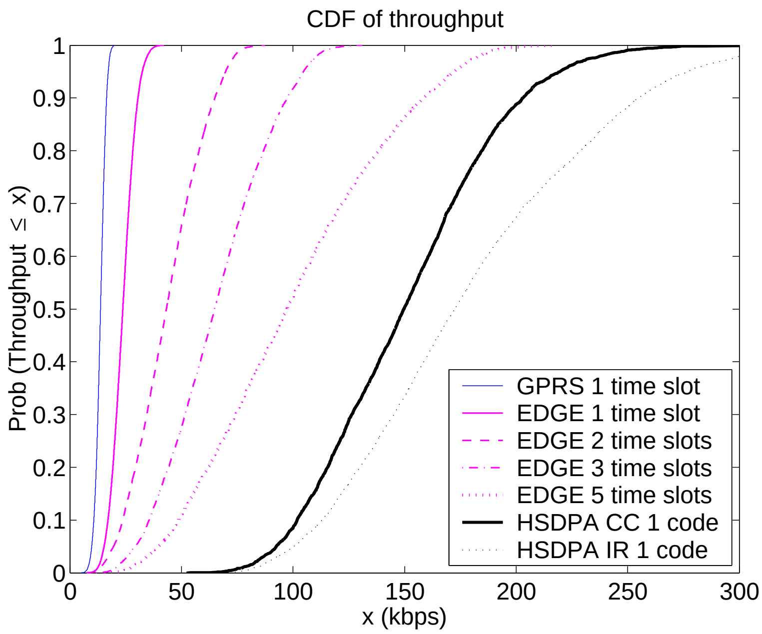


Figure 6. CDF of throughput.

wireless framework with a larger set of radio access alternatives that offer a wider set of transmission capabilities.

While Figure 6 illustrated the system throughput performance (i.e., considering all services together), Table 5 shows the mean throughput performance per RAT and modelled traffic service. Although it can be observed that the performance for each service is similar for a given RAT, it is important to remember that the configuration of LA and AMC differ for real-time video, and web and email services. Despite similar performance, user satisfaction is not similarly maintained for each RAT since each service has different QoS expectations. We have then defined user satisfaction parameters per traffic service. 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 6 shows the obtained results.

In general, for a given service, the user satisfaction increases as the selected RAT offers better capabilities. However, we can observe that for

	Web	Email	H.263 32 kbps	H.263 64 kbps	H.263 256 kbps
GPRS	12.20	12.31	14.23	13.71	13.72
EDGE 1 slot	22.25	21.61	22.66	21.58	26.68
EDGE 2 slots	31.40	31.17	39.70	38.67	40.04
EDGE 3 slots	70.20	69.45	60.85	64.57	64.03
EDGE 5 slots	82.52	78.59	105.20	105.60	124.14
HSDPA CC	164.40	174.33	126.95	133.32	153.94
HSDPA IR	216.36	188.25	162.60	143.16	188.66

Table 5. Mean throughput performance (kbps).

	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 1 slot	53.8	53.9	87.9	43.0	0.0
EDGE 2 slots	64.1	55.7	99.9	85.9	0.2
EDGE 3 slots	74.4	59.7	100.0	98.9	0.6
EDGE 5 slots	84.7	71.9	100.0	100.0	15.9
HSDPA CC	95.1	90.4	98.0	82.7	33.8
HSDPA IR	97.1	91.3	98.5	87.7	39.5

Table 6. User satisfaction (%).

some H.263 users, EDGE using 5 slots obtains better user satisfaction than HSDPA despite its lower throughput performance (Table 5). 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 transmissions have been allowed for HSDPA to take profit of the IR and CC capabilities (see Table 4). 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.

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 is 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 fulfil the user expectations. Given such observations, next section will show a case study in which simple traffic distribution algorithms that assign users to a given RAT, according to their QoS requirements, have been studied.

4. Case Studies

This section presents two investigations that are currently being conducted using SPHERE. In particular, the first one illustrates the design and evaluation of CRRM techniques in heterogeneous wireless systems. Due to its modularity, the platform can also be used, which is illustrated by the second investigation, to study and optimise concrete RRM aspects of a particular RAT.

4.1 Case Study I: CRRM Traffic Distribution

The traffic distribution function is responsible for deciding in a heterogeneous wireless system what RAT will be used by each user. The decision may be made considering parameters such as the actual load of each RAT, the user QoS requirements, etc. To validate the SPHERE platform and show its potential in heterogeneous wireless investigation, this section defines a simple traffic distribution algorithm where each traffic type is always assigned the same RAT. Based on the results from Table 6, real-time 64 and 256 kbps H.263 video users transmit using HSDPA since this is the only RAT that can offer acceptable QoS levels (in this section, only single slot and two slot EDGE transmissions are being considered). Web-browsing and 32 kbps real-time H.263 video users are assigned to EDGE since they are acceptably satisfied with this RAT. Finally, given its best-effort nature, email service is provided through GPRS.

The performance of the traffic distribution algorithm is evaluated considering three different scenarios. In the first one, every cell is loaded with 15 users, following the same traffic distribution as in section 3, and all RATs are operated in single slot and single code mode. The mean throughput performance for each traffic service is illustrated in Figure 7. As it can be observed by comparing the results from Table 5 (where all load was transmitted using a single RAT) and Figure 7, traffic distribution enables better throughput performance. For instance, when the 15 users were simultaneously connected to GPRS, the throughput experienced by email users was equal to 12.31 kbps (see Table 5). However, if only email users are assigned to GPRS, this parameter improves to 18.75 kbps (see Figure 7, scenario I), which represents an improvement of 52.3%. For web-browsing and 32 kbps H.263 video users (assigned to EDGE), the throughput improves from 22.25 to 26.58 kbps (19.5%) and from 22.66 to 29.25 kbps (29.1%) respectively. On the other hand, 64 kbps and 256 kbps H.263 video users experience a lower throughput compared to when all users were handled by HSDPA. This was actually due to a higher use of higher order HSDPA transmission modes in Scenario I. Although these modes exhibit a higher theoretical performance, they can also increase the error probability, and therefore reduce the throughput as it has been observed in the results obtained for Scenario I. In any case, the AMC HSDPA algorithm could be improved to optimise its performance and avoid the effects observed in scenario I.

The simple traffic distribution algorithm defined in this section can perform in an acceptable way in certain situations where the traffic is distributed across the RATs of the system in such a way that the load remains approximately balanced, as in the scenario I. However, this static approach might not be suitable to scenarios where the load per traffic service dynamically varies. To illustrate this possibility, a second scenario is simulated. In scenario II, the number of GPRS and HSDPA users remains constant whereas the number of EDGE users is doubled. As a result, six web-browsing and six 32 kbps H.263 video users compete for the eight channels available in the cell. The results illustrated in Figure 7 show that in this case the EDGE users performance is deteriorated due to this excessive load while free unused resources are available in the others RATs.

To try to improve this situation, it has also been analysed the possibility of allocating multiple slots, in particular two, per EDGE user. This option corresponds, in Figure 7, to the third simulation scenario. This case considers the same traffic load as in scenario II, but EDGE users are assigned two slots. The results shown in Figure 7 clearly show that this strategy improves 32 kbps H.263 video user's performance but

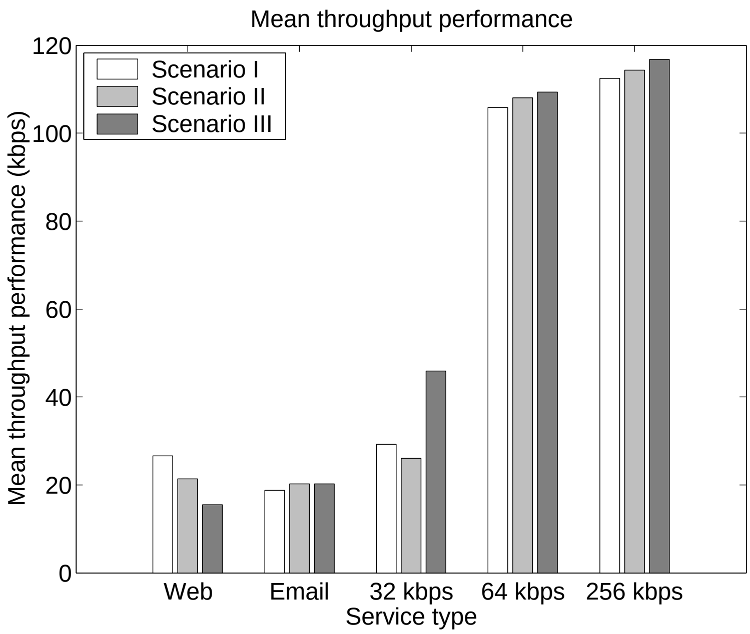


Figure 7. Mean throughput for different scenarios.

degrades the web user's performance. This varying behaviour is due to the fact that there is a limited number of resources and that not all two slot requests can be served. Since H.263 video transmissions exhibit a less bursty traffic pattern and longer transmission times, H.263 video users tend to monopolise EDGE resources.

The conducted simulations have not only shown the potential of the SPHERE simulation platform for dynamically and accurately evaluating the performance of CRRM algorithms, but also the need to define more elaborated CRRM algorithms that are currently being investigated by the authors. In reference [17], new CRRM policies developed by the authors are proposed, and evaluated with the SPHERE platform.

4.2 Case Study II: EDGE Multislot Operation

In order to facilitate their interoperability in heterogeneous wireless systems, the EDGE standard defines the same QoS classes as UMTS (3GPP TS 23.107). Each class has different QoS requirements that shall be provided to the end user (3GPP TS 22.105). They range from the conversational class, which imposes very stringent delay requirements, to the background class which imposes relatively loose delay requirements.

The EDGE multislot capability offers the chance to simultaneously allocate various channels to a single user (the allocation can be dynamically varied based on the system load or other user's request). This capability can therefore be used to respond and guarantee each user's QoS requirements while optimizing the usage of the available radio resources based on the current system loads. The work reported in [2] demonstrated the possibility to increase throughput performance using multislot operation but also highlighted that this operation mode might produce higher queuing delays. In this context, appropriate RRM schemes to dynamically distribute the radio resources under multislot operation need to be defined. The work reported in [20] provides a first study comparing the performance of fixed and adaptive multi-channel assignment policies. The investigations carried out in [14] and [22] are based on the use of different queues per traffic type. With this approach, certain traffic types can be priorized as shown in [14] where the importance of modifying the weight parameters based on the system load is highlighted. Although the resource allocation scheme reported in [19] is based on continuous resource usage and not slotted operation, it presents techniques based on resource usage fairness. In this context, this section presents initial investigations on suitable and simple resource allocation policies for EDGE multislot operation. The discussed policies will base their resource assignment on the traffic type QoS requirements. The study is again being conducted using the SPHERE platform. Its detailed modeling of each implemented RAT allows not only for CRRM investigations but also for particular studies directed at optimizing the resource usage within each RAT.

To define the multislot allocation policies, we have established a user utility based on the traffic type being transmitted (see Table 7). The utility value establishes the number of needed slots to reach minimum, mean and maximum user satisfaction considering the traffic type and the maximum theoretical throughput that could be achieved with the allocated slots. Given that email is considered a background service, its requirements has been kept low. However, to model different QoS requirements, the number of assigned slots is increased with the satisfaction level. This has not been the case for the real-time video H.263 service since its target bit rate is 16kbps. As a result, no QoS difference was found between allocating two or more slots to a H.263 video user; this explains why the same number of time slots is considered for mean and maximum satisfaction levels. Web service has been established as the most demanding service with target bit rates of 32 kbps, 64 kbps and 128 kbps for minimum, mean and maximum user satisfaction, respectively. For establishing the throughput value, we have considered that MCS5 has been used for the radio transmissions. However, it is important to note that since EDGE employs the adaptive RRM technique Link Adaptation, the used MCS will vary according to the channel quality conditions. As a result, the achieved throughput performance using the SPHERE simulation platform can finally differ from that obtained if only MCS5 was used throughout the whole radio transmission process.

	Minimum satisfaction	Mean satisfaction	Maximum satisfaction
Web	2 slots	3 slots	6 slots
Email	1 slot	2 slots	3 slots
H.263	1 slot	2 slots	2 slots

Table 7. User utility values per traffic service.

The evaluated allocation techniques are based on guaranteeing different satisfaction level per user and on potential network operator's policy. These techniques are just initial trials and are being used to demonstrate the capability of the SPHERE simulation platform to investigate RRM techniques seeking to optimize the individual performance of each RAT. However, the authors are currently working on more advanced algorithms that prioritize certain traffic types and that introduce pricing schemes to decide which users should be served with higher QoS.

Figure 8 shows the throughput performance for the alwaysMin, alwaysMean and alwaysMax schemes. These schemes always assign for each traffic type the required slots to guarantee minimum, mean and maximum user satisfaction based on the utility values reported in Table 7. The simulated scenario considers a load of 18 users, uniformly distributed per traffic type, and the availability of just one frequency carrier per cell (or 8 time slots). It is interesting to note the higher throughput performance achieved with EDGE compared to the results shown in Section 3. This is the case because in this section, higher cell radius and cluster sizes are considered in an sectorised cellular environment, therefore reducing the interference levels. As it was expected, the throughput performance increases with the number of allocated slots. However, as the number of allocated slots per user increases so does the percentage of transmissions being queued (see Tables 8 and 9), with the worst delay QoS achieved for the most demanding traffic type, i.e. web. Tables 8 and 9 also show that the mean time a user is queued increases importantly with the most demanding multislot allocation policies (for 16 kbps H.263 video users only small difference in delay QoS performance was observed between the different allocation policies).

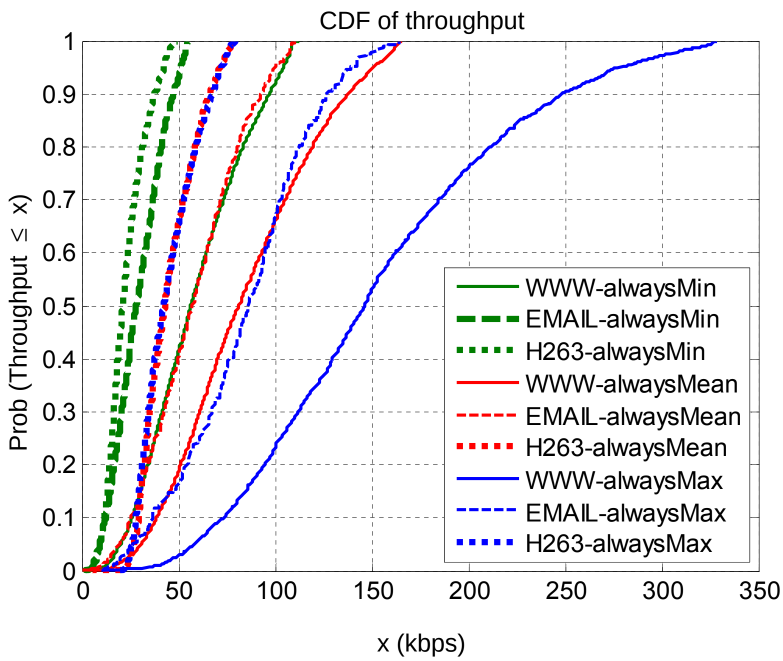


Figure 8. Throughput for various multislot policies.

	alwaysMin	alwaysMean	alwaysMax
Queued transmissions	86.9 %	86.2 %	93.8 %
Mean queue time	1.17 sec	1.39 sec	2.29 sec
Var. queue time	7.90 sec	38.70 sec	65.76 sec
Max. queue time	66.73 sec	213.94 sec	330.87 sec

Table 8. Delay performance for web browsing users.

	alwaysMin	alwaysMean	alwaysMax
Queued transmissions	83.1 %	80.6 %	87.1 %
Mean queue time	0.46 sec	2.53 sec	8.81 sec
Var. queue time	1.04 sec	142.38 sec	828.38 sec
Max. queue time	10.97 sec	105.24 sec	277.80 sec

Table 9. Delay performance for email users.

As it has been previously mentioned, the discussed policies and results are just initial proposals used to dimension the multi-channel resource allocation problem and the authors are working on more advanced and dynamic schemes.

5. Conclusions

This work has presented SPHERE, a radio simulation platform for heterogeneous wireless systems developed at the University Miguel Hernández. The platform, currently modelling GPRS, EDGE and HSDPA, has been designed to investigate advanced RRM and CRRM techniques seeking to optimise the radio resource usage, across RATs and for individual RATs, under dynamically varying channel quality conditions. As a result, SPHERE models in detail the radio transmission effects and all specific radio features for the three considered RATs. 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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