Decentralized Spectrum and Radio Resource Management Enabled by an On-demand Cognitive Pilot Channel

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Abstract

This paper presents a framework to achieve an efficient dynamic and decentralized spectrum and radio resource usage in heterogeneous wireless network scenarios. The envisaged technical solution follows a layered approach, where Joint Radio Resource Management (JRRM) and Advanced Spectrum Management (ASM) mechanisms are identified at both intra and inter-operator level. The importance of cognitive network functionalities is highlighted. An on-demand Cognitive Pilot Channel (CPC) is proposed as radio enabler solution for decentralized operation with decision making processes executed at the mobile terminal side. The suitability of the proposed solution is shown by comparison with a broadcast CPC approach. Finally, the paper presents and evaluates decentralized JRRM algorithms both at intra and inter-operator level using the proposed framework.

Keywords: Advanced Spectrum Management, Joint Radio Resource Management, Decentralized algorithms, Cognitive Pilot Channel, Cognitive Networks.

I. Introduction

It is widely acknowledged that technological innovation has a relevant impact on economic growth. In turn, wireless communications are a key driver for the stimulation of economies, building social networks and facilitating sustainable development, to the point that wireless communications are nowadays an integral part of modern living. Not surprisingly, wireless technologies are rapidly evolving in order to allow operators delivering more advanced multimedia services to their customers. For example, HSDPA (High Speed Downlink Packet Access) and HSUPA (High Speed Uplink Packet Access) are seen as intermediate evolutionary steps since the first wave of WCDMA-based (Wideband Code Division Multiple Access) networks rollout, E-UTRAN (Evolved UMTS Terrestrial Radio Access Network) being the long term perspective for 3GPP (Third Generation Partnership Project) technology family both in terms of new architecture and radio access technologies. Similar paths are drawn from 3GPP2 around the evolution of CDMA2000. On the other hand, IEEE 802 is producing an evolving family of standards, such as 802.11 local, 802.15 personal, 802.16 and 802.20 metropolitan and 802.22 regional area networks.

Furthermore, the regulatory perspective on how the spectrum should be allocated and utilized in such a complex and heterogeneous technology scenario is evolving as well. The evolution is towards a cautious introduction of more flexibility in spectrum management together with economic considerations on spectrum trading. This new spectrum management paradigm is driven by the growing competition for spectrum and the requirement that spectrum is used more efficiently [1]. For this purpose, a narrow view would be to look to technology as a mean to provide more robust communications systems with increased efficiency. Instead, a broader view is to examine spectrum utilization from a time/location/band/power perspective as suggested in the Federal Communications Commission Spectrum Policy Task Force Report [2].

Indeed, numerous studies support the observation that the usage of radio resource spectrum experiences significant fluctuations. Usually, heavy spectrum utilization takes place in unlicensed bands while some licensed bands often experience low (e.g. TV bands) or medium utilization. Based on these considerations, the TV band Notice of Proposed Rule Making (NPRM) [3] was the natural next step taken by the FCC. The proposition of the NPRM allows unlicensed radios to operate in the TV broadcast bands if no harmful interference is caused to incumbent services (e.g. TV receivers). These events culminated in the formation of the IEEE 802.22, developing an air interface for unlicensed operation in the TV broadcast bands [4].

Several works in the literature have recently dealt with flexible spectrum management strategies. In [5] the DIMSUMNet architecture is presented for coordinated, real-time dynamic spectrum access based on a centralized entity called Spectrum Broker as opposite to other opportunistic, uncoordinated methods. The concepts of coordinated access band and statistically multiplexed access to spectrum are introduced. Further work on this topic is presented in [6], where different formulations for solving the spectrum allocation problem based on linear programming are presented. In [7] a spectrum etiquette protocol for efficient coordination of radio communication devices in unlicensed frequency bands using different radio technologies is proposed. It uses a common protocol for the announcement of radio and service parameters.

The framework envisaged above, characterized by a multiplicity of Radio Access Technologies (RATs) empowered by flexible spectrum capabilities, can only be fully accomplished by further enhancing the Radio Access Networks (RANs) towards Cognitive Networks complemented with Cognitive Radio-based technologies. On the one hand, a cognitive network exploits a process that can perceive current network conditions, and then plan, decide and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals [8]. On the other hand, Cognitive Radio technology is built upon software defined radio (SDR) technology and allows individual radios or groups of radios to make choices about their frequency and RAT use based upon their location and the radio use environment [9]. Thus, cognitive radios have the potential to utilize the large amount of unused spectrum in an intelligent way while not interfering with other incumbent devices in frequency bands already licensed for specific uses. Cognitive radios are enabled by the rapid and significant advancements in radio technologies and can be characterized by the utilization of disruptive techniques such as wide-band spectrum sensing, real-time spectrum allocation and acquisition, and real-time measurement dissemination [4].

In this context, this paper firstly presents an integrated layered approach to achieve an efficient dynamic spectrum and radio resource usage in heterogeneous wireless network scenarios, as described in Section II. Then, Section III discusses the suitability that those management strategies include a decentralized operation component with decision making processes executed at the mobile terminal side. Section IV proposes an on-demand CPC as a radio enabler for the decentralized functionalities. Section V shows that the proposed solution outperforms the broadcast CPC approach. Section VI presents a case study to illustrate the benefits of the decentralized operation component in the proposed layered approach. Finally, conclusions close the paper in Section VII.

II. An Integrated Layered Approach

A number of techniques have been identified, proposed and analyzed in the recent years to cope with heterogeneous wireless networks with flexible spectrum management capabilities as it will be further detailed within this section. However, the different resource optimization techniques have to be integrated into a coherent framework, given that the use cases (ranging e.g. from the dynamic allocation of spectrum between the different RATs of one operator to the more complex allocation and management of radio resources between the access networks of different operators) pose individual problems of resource utilization; each requiring a different approach to achieve the optimal resource allocation.

Let assume that a reference operator faces traffic variations on the planned conditions at the short-term, long-term as well as spatially. Traffic variations may respond to the total aggregated offered traffic but also to the offered traffic service mix. Other operators in the same area are characterized in a similar way.

In order to achieve an efficient usage of the spectrum and radio resources, the proposed solution is a layered approach, as depicted in Figure 1, which intends to cope with actual traffic conditions through the most suitable mechanism. To this end, four different layers are identified together with supporting Cognitive Network concepts:

II.1. Intra-operator JRRM

At this layer, current traffic demand is managed by means of algorithms applied over the pool of resources of each operator. Joint Radio Resource Management (JRRM) is the process that enables the allocation and de-allocation of radio resources from different radio access systems to the users. In that respect, the intra-operator JRRM layer operates over a fixed spectrum band allocated to each of these systems.

Intra-operator JRRM acts at the shortest time scale (in the order of one second or below). With the current cellular deployment and spectrum allocation to cells, intra-operator JRRM is able to provide a significant gain derived from the joint consideration of radio resources available for the different RATs. It has been identified as an important issue by 3GPP, which defines some recommendations and architectures for JRRM operation [10][11], as well as by the research community [12][13].

Assuming that a good JRRM algorithm is implemented, if key performance indicators (KPIs) point out degradation in QoS (Quality of Service) levels, this may indicate that intra-operator JRRM has reached its limits with the current allocation of spectrum in the scenario facing the current traffic conditions. In such case, the operator may question whether the RAT/spectrum mapping to cells is suitable in the actual radio network state. This will be targeted by intra-operator Advanced Spectrum Management (ASM) mechanisms at the next layer of the architecture, which will look for a suitable spectrum/RAT allocation fitting the current conditions as detailed in the next subsection. The outcome of the intra-operator ASM algorithm will be to get a more suitable system operation point.

II.2. Intra-operator ASM

At this layer, current traffic demand is managed by means of dynamic spectrum management algorithms, which come up with suitable spectrum re-allocation to cells and RATs. Intra-operator ASM re-arranges the spectrum bands allocated to that particular operator, enabling the dynamic management (allocation, de-allocation, sharing) of spectrum blocks within a single or between different radio access systems. Here, spectrum bands allocated to each RAT and cell are not fixed but flexible. In this context, dynamic spectrum allocation refers to the partitioning of the spectrum that dynamically changes to adapt to the current or future demand of radio resources resulting in certain gain in spectrum allocation.

In case the synergised operation between intra-operator JRRM and ASM is exhausted, which again could be observed by QoS degradation, it can be concluded that the amount of available resources for the operator is not enough to cope with the offered traffic. In such case, inter-operator mechanisms are envisaged, as a source of getting additional resources coming from complementary operators. This corresponds to the two upper-layers in Figure 1.

II.3. Inter-operator JRRM

At this layer, current traffic demand of a given operator is managed with the operator's infrastructure deployment together with the use of other operators' infrastructure when needed. In this way, the potentially dissatisfied users can be given access to the service through another network operator. A trading agent implemented as a "metaoperator" may be the actor that provides the bridge among different operators by making transactions for offering and demanding radio resources. Both operators participating in the trading process are benefited by the establishment of inter-operator agreements. In particular, the operator "renting" radio resources takes advantage of this exchange in the short term, in terms of revenue coming from the service provision for the user. On the other hand, the operator "borrowing" radio resources is benefited in the long term since its user, instead of being blocked, is provided with service in a transparent manner and, consequently, is not motivated to churn.

II.4. Inter-operator ASM

At this layer, current traffic demand is managed with the help of additional resources that the operator rents/buys to other operators. Inter-operator ASM applies to substantial pieces of radio spectrum (e.g. renting 5 MHz band to deploy an additional UMTS carrier). Inter-operator JRRM and inter-operator ASM are mainly distinguished by the granularity in the amount of resources traded: in the former, the inter-operator exchange is at a user level, while in the later it is at system level. Both parties may benefit from this deal. The ultimate objective would be to achieve an automatic, self-adaptive operation, where suitable mechanisms/layers are activated.

Finally, the Cognitive Network element monitors and captures the network status at different levels, which are of interest for the different strategies in each layer. It is worth noting that the triggering events may advice to skip some of the layers depending on the actual traffic conditions (e.g. intra-operator JRRM triggers intra-operator ASM, which readily realizes that the current intra-operator spectrum is suitably allocated and the required additional capacity has to be reached through inter-operator JRRM and/or ASM mechanisms).

III. Decentralized JRRM/ASM

Traditionally, (J)RRM functions in a wireless cellular network are mainly centralized, i.e. the functions are implemented in a central network node such as RNC (Radio Network Controller) in UTRAN (UMTS Terrestrial Radio Access Network). This can be justified because a central network node may have a more complete picture of the radio access status than a particular node, so that (J)RRM decisions can be made with more inputs. However, a centralized (J)RRM implementation has some drawbacks in terms of increased signaling load or transfer delay of the (J)RRM algorithm's inputs to the central node. This prevents an efficient implementation of short-term (J)RRM functions such as packet scheduling and explains why wireless cellular technology evolution (e.g. HSDPA) exhibits the trend towards implementing (J)RRM functions on the radio access network edge nodes (e.g. base stations).

Additionally, the terminal also keeps relevant information that could be of great interest for making smarter (J)RRM/ASM decisions. This is why some (J)RRM/ASM functions, although typically implemented in the network side (either on central or edge nodes), are assisted by mobile terminal measurement reports. Handover algorithm is a clear example, since the knowledge of the propagation conditions from the terminal to the different surrounding cells is key for making the proper decision on what cell(s) the terminal should be connected to.

Indeed, there is a clear trend towards decentralized (J)RRM/ASM functions in the mobile terminals. This approach has claimed to be inefficient in the past because of the limited information available at the terminal side (e.g. the terminal does not know what is the cell load). Nevertheless, this can be overcome if the network is able to provide some information or guidelines to the terminal assisting its decisions. In this way, while a mobile-assisted centralized decision making process requires the inputs from many terminals to a single node, the network-assisted decentralized decision making process requires the input from a single node to the terminals, which can be significantly more efficient from a signaling point of view. In this respect, on-going IEEE P1900.4 standardization effort would provide the necessary support to this network-assisted mechanism [17].

The objective of the IEEE P1900.4 is to define standardized protocols and corresponding reconfiguration management system architecture for the optimization of resource management, in order to provide improved capacity, efficiency and utility within a heterogeneous wireless network wherein devices support multiple air interfaces, with multi-homing and dynamic spectrum access capabilities in licensed and unlicensed bands. In some more detail, the scope of IEEE P1900.4 includes (1) providing protocols carrying information between network resource managers and device resource managers supporting wireless terminal and network reconfiguration management, including the context of heterogeneous networks, (2) providing corresponding reconfiguration management functionalities of the wireless system for the support of efficient optimization of resource usage, and (3) providing corresponding management functions and standardized rules to allow the multimode and/or dynamic spectrum access capable devices making decisions in a distributed fashion whilst providing operators with fair and effective exploitation of network resources thanks to an exhaustive set of rules to be followed by user equipments.

In this framework, Figure 2 depicts how the network-centric layered approach presented in Section II would be applicable to a decentralized decision making context thanks to the availability of communication means between the network and the terminal implemented as a Cognitive Pilot Channel (CPC). Cognitive network functionalities would be readily exploited in the layered JRRM/ASM. The knowledge acquired in the network side and properly processed would be transmitted to the terminal through the CPC upon request. With this information available together with information locally acquired at the terminal side (e.g. spectrum measurements, interference conditions, etc.), the mobile terminal could make intelligent choices in various radio-related dimensions: frequency band of operation, RAT and cell site to get connected to, transmitted power level, etc. Certainly, the radio-related information could be properly combined with business-related aspects representing operator and/or user preferences.

IV. Radio Enabler: Cognitive Pilot Channel

Following a similar approach as the Spectrum Information Channel in [4] and the Common Spectrum Coordination Channel in [7], the Cognitive Pilot Channel

(CPC) concept was recently conceived as a solution to assist the mobile reconfigurable and cognitive terminal in procedures like RAT selection in heterogeneous scenarios with different access networks available and varying spectrum allocations [14]-[16]. The CPC basically consists in a channel that carries relevant information for the mobile terminal. Then, terminals can make use of this information in order to carry out several procedures, like decentralized RAT selection, optional download of software modules for reconfigurability purposes or identification of temporary unused frequency bands to enable a secondary usage of the spectrum for different types of applications (e.g. establishment of an ad-hoc network, communication of devices in personal area networks, etc.).

Under this framework, the CPC channel can be regarded as a radio enabler of reconfiguration management in cognitive networks, and it is expected that it can provide benefits for the different players involved in the wireless communications arena, as summarised in the following:

a) CPC helps the mobile terminal to select the proper network depending on the specific conditions (e.g. desired services, RAT availability, interference conditions, etc.). This provides *support to JRRM*, enabling a more efficient use of the radio resources.

b) It provides *support to Reconfigurability* by allowing the terminal to identify the most convenient RAT to operate with and to download in case the necessary software modules to reconfigure the terminal capabilities.

c) It provides *support to Context Awareness* by helping the terminal in identifying the specific frequencies, operators and access technologies in a given region without the need to perform long time and battery consuming spectrum scanning procedures.

d) It helps the network provider to facilitate dynamic changes in the network deployment by informing the terminals of the availability of new RATs/frequencies, thus providing *support to Dynamic Network Planning (DNP) and ASM* strategies.

e) It helps the spectrum regulator to *improve the spectrum utilisation* thanks to enabling a secondary use of the temporary unused frequency bands in a specific region.

The different papers existing in the literature concerning CPC mainly focus on the CPC concept as enabler for reconfiguration management as well as on how it should be mapped onto physical resources. Particularly, in [14] an out-band architecture is presented where the CPC is transmitted in a global harmonized frequency over a certain area, subdivided into smaller portions, denoted as meshes. The information in the CPC included the operators and technologies available in each mesh and was intended to help the mobile terminal in the RAT and operator selection procedure. In [15][16] another approach including a hierarchical CPC organised into three levels (country, operator and network level) was proposed in order to reduce the amount of information that is sent at each level. Combining in-band CPC (i.e. using some channels of the existing RATs) and out-band CPC architecture is another possibility.

IV.1. CPC Operation Procedure

The CPC operates in a geographical area subdivided into meshes. A *mesh* is defined as a region where certain radio electrical commonalities can be identified (e.g. a certain frequency that is detected with a power above a certain level in all the points of the mesh, etc.). The mesh is univocally defined by its geographic coordinates, and its adequate size would be related to the spatial distribution of RATs and frequencies deployed in a given scenario. For example, in scenarios involving cellular 2G/3G technologies mesh sizes of several hundreds of meters could be expected, while for shorter range RATs, such as WLANs, mesh sizes of some tenths of meters would be envisaged. As a result, the definition of the suitable mesh size depends on the considered environments and scenarios, and results from the trade-off between keeping a reduced number of meshes for practical operation and ensuring the homogeneity in the frequencies/RATs that can be measured in a mesh area, so that spatial resource usage can be correctly captured. For the sake of simplicity, and in order to better illustrate the CPC procedure, square meshes of identical dimension will be considered in this paper. Nevertheless, concepts presented here could be extended to other approaches based on e.g. dynamic definition of meshes, irregular mesh size for different environments, etc.

The steps of the overall CPC operation procedure are described in the following. After switching on, the terminal determines its geographical information making use of some positioning system and afterwards it detects and synchronises with the CPC. Such CPC detection will depend on whether an out-band CPC (i.e. transmitted in a global harmonised frequency) or an in-band CPC (i.e. transmitted using channels in the existing RATs) is used [14]-[16]. Afterwards, the terminal retrieves the CPC information corresponding to the mesh where it is located, which completes the procedure. Notice that these steps can also be performed periodically to detect changes in the environment due to either variations in the mobile position or network reconfigurations.

IV.2. On-demand CPC

In this sub-section, an on-demand CPC implementation defining how the CPC information is delivered to the terminals is analysed, as opposite to the other possible broadcast CPC approach in which the information for all the meshes is continuously broadcast through a downlink channel. The rationale of the proposed on-demand CPC approach is that, if all the CPC information should be continuously broadcast for all meshes, this would require either a long time or a wideband channel, particularly, if mesh size is small. However, depending on the number of terminals that are located in each mesh, this information will be in practice most of the time unused. Consequently, it may become more efficient from both power and bandwidth consumption point of view, to transmit the information only when needed and requested by a terminal [18].

In the proposed approach, the on-demand CPC makes use of both uplink and downlink components and it consists in the following logical channels:

- Random Access CPC (RACPC): It consists of an uplink slotted channel where the mobiles operating with CPC send requests to retrieve the CPC information corresponding to their meshes. Each request basically contains an indicator of the geographical coordinates of the mobile terminal. Operation according to a simple protocol such as S-ALOHA can be envisaged for this channel.
- Acquisition Indicator CPC (AICPC): This downlink channel follows the same slotted structure of the uplink RACPC and is devoted to indicate that

a request has been successfully received. The channel consists in Acquisition Indicators (AI) each one indicating the identifier of the terminal whose request has been received or the value *Null* if no request has been received.

- Downlink On-Demand CPC (DODCPC): This downlink logical channel is used to transmit the CPC information corresponding to the mesh of each received request from a Mobile Terminal (MT).

The operation of these channels is illustrated in Figure 3. The uplink and the downlink channels are organised in slots of duration T_S. The AICPC and the DODCPC are multiplexed on the same time slots by making use of different fields of a certain burst structure. In Figure 3, terminal MT1 sends a request in slot #1. This request simply contains the geographical coordinates of the terminal and a short random identifier. Since there is no collision in the transmission, slot #2 in the AICPC indicates that MT1 request has been successfully received by means of the Acquisition Indicator (AI) including the random identifier sent by MT1. Then, transmission of the CPC information corresponding to the mesh of MT1 starts in the DODCPC during a total of $T_{m,OD}=N_s \cdot T_s$ being N_s an integer number of slots depending on the bit rate of the downlink channel. Similarly, mobile terminal MT2 sends its request in slot #2 and receives the corresponding AI in the downlink of slot #3. However, since the DODCPC in this slot is transmitting the information of MT1, MT2 should wait until slot #k to start receiving the information of its mesh. In slot #3 a collision occurs between MT3 and MT4, and therefore the AI in the subsequent slots indicate a Null value, reflecting that no request has been received. Then, the terminals will wait a random retransmission time. In the example, MT3 retransmits the request in slot #k+1.

The proposed implementation of the on-demand CPC including both an uplink and a downlink channel enables a wider range of CPC-based applications in addition to the retrieval of the information about operators, RATs and frequency lists. For example, the CPC could eventually be used by the terminals to retrieve other terminal-dependent information, such as initial software downloads to enhance the reconfigurable terminal capabilities. Furthermore, the uplink channel can also be used to ensure that the information has been delivered correctly thus improving the integrity and the security in the transmitted information.

On the other hand, notice that the interaction with the mobiles in the on-demand CPC allows the network operator and the spectrum regulator having eventually a higher control of the terminals accessing CPC than if the broadcast approach was used. In that sense, it is easier to fit the CPC operation within specific business models and exploitation plans e.g. for a controlled secondary use of the spectrum.

V. Performance of the On-Demand CPC

This section presents some illustrative results of the CPC operation. Let assume a scenario in which each CPC transmitter sends the information corresponding to N_m meshes of the same size. The area covered by a CPC transmitter is assumed to be circular with a radius R km. A number of wireless devices or terminals require getting the CPC information corresponding to the mesh where they are located. A scenario with a homogeneous user density of η users/km^2 is considered. The arrival ratio of requests corresponding to these devices in the whole area of one CPC transmitter is assumed to follow a Poisson distribution with average λ requests/s. Each user or wireless device generates a total of λ_u=0.0003 requests/s to access the CPC (i.e. around 1 request per hour).

Let I_m be the total number of information bits to be transmitted for a single mesh. For illustration purposes, results have been obtained considering that the amount of information corresponding to a mesh is I_m=4253 bits [18]. On the other hand, it is assumed a time slot duration T_S=10 ms and a downlink net bit rate of the CPC channel initially set to R_b=10 kb/s (notice that this is the net bit rate of information bits, without including redundancy bits for channel encoding, synchronisation bits, etc.) for both the broadcast and the on-demand CPC.

Figure 4 plots the performance in terms of delay in retrieving the CPC information as a function of the CPC transmitter range R for the broadcast and the on-demand CPC. Mesh size is assumed to be fixed and equal to 100m×100m, so the larger the CPC transmitter range the higher the number of meshes. Similarly, user density is equal to η=2000 users/km^2, and therefore the total load also increases with the range. Figure 4 shows that the increase in the range turns into an increase in the delay for the two approaches, but the delay experienced by the broadcast CPC is in general much higher than that of the on-demand CPC. In the broadcast CPC, the delay increase is due to the higher number of meshes included in the CPC transmitter area when increasing the range. On the contrary, in the on-demand CPC the delay increases with the range due to the larger number of requests, which require a longer queuing waiting time to be served. In that sense, there is a fixed limit in the access phase because it should be fulfilled the condition $\lambda\cdot T_{m,OD}<1$ in order for the system to be stable. This is reflected in the figure by the steep delay increase for ranges above 1.05 km.

From Figure 4, and assuming a performance requirement to retrieve the CPC information with an average delay below e.g. 5 s, it can be observed that, for these conditions, the maximum range for CPC operation with the on-demand approach is around 1.08 km. On the contrary, for the broadcast CPC the maximum range would be only about 260m. This observation reflects also that, for a given range, the broadcast CPC would require a higher bit rate than the on-demand CPC in order to achieve comparable performances. Notice that the difference could even be higher if a lower maximum average delay bound below 5s was set. This is reflected in Table I, which indicates the maximum CPC range for different values of the maximum delay requirement with the two approaches. It can be observed that the range of the on-demand CPC is much larger than that of the broadcast CPC. Furthermore, the behaviour of the on-demand CPC is less sensitive to the maximum delay bound than the broadcast CPC.

The behaviour of the CPC depending on the value of the bit rate R_b is further analysed in Figure 5, which plots the required downlink CPC bit rate R_b for the two approaches as a function of the CPC transmitter range if a maximum average delay of 5s in retrieving the CPC information was set. The same conditions in terms of user density as in Figure 4 are considered. Furthermore, the results are presented for three different mesh sizes, namely 50m×50m, 100m×100m and 200m×200m. It is worth mentioning that the bit rate required for the on-demand CPC does not depend on the number of meshes (or equivalently on the mesh size), because only the information of the requested meshes is transmitted. On the contrary, the bit rate required for the broadcast CPC increases very significantly when reducing the mesh size. For a mesh size of 100m and below it can be observed that the broadcast CPC requires a bit rate higher than the on-demand CPC in more than one order of magnitude for comparable delay performance (e.g. the required bit rate of the on-demand CPC is around tenths of kb/s while that of the broadcast CPC is around hundreds of kb/s or even Mb/s if the mesh size is 50m). Consequently, a more efficient CPC implementation with the on-demand CPC follows.

From Figure 5 it is also observed that when increasing the mesh size the bit rate requirement for the broadcast CPC becomes closer to that of the on-demand CPC. The reason is the reduction in the number of meshes and the consequent reduction in the total broadcast period. In that sense, Figure 6 plots the value of the minimum mesh size so that the broadcast CPC requires a lower bit rate than the on-demand CPC for different desired performances in terms of the maximum average delay bound *Dmax*. It can be observed that the more stringent the delay bound, the larger the meshes should be in order that the broadcast CPC becomes a more efficient solution than the on-demand CPC. Particularly, for maximum delay bounds of 1s the mesh size should be as big as 1km×1km.

VI. Performance Evaluation of the Decentralized intra-operator and inter-operator JRRM Layers

This section presents an example of application of CPC as a support to a decentralized JRRM framework according to the layered architecture discussed in section II. The JRRM problem has traditionally been faced from a centralized perspective [19]-[22], considering that in a decentralized implementation the mobiles would lack of the necessary information to make a comprehensive decision. However, as discussed in Section III, nowadays there is a clear trend to decentralize RRM functions towards edge nodes and eventually mobile terminals, which can become more efficient from a signalling point of view. In that respect, the introduction of the CPC as a radio enabler allows providing the necessary information at the terminal side to take the adequate JRRM decisions.

As a result of these considerations, we propose to study a decentralized implementation of a JRRM strategy which has already been presented by authors in [19][20] as a centralized approach. The proposed JRRM scheme is based on fuzzy neural methodology, where a reinforcement learning algorithm operates over a fuzzy logic controller, as it is briefly outlined in sub-section VI.1. The advantage of this choice is two-fold. On the one hand, by means of fuzzy logic, it allows capturing in the JRRM decision making process the vagueness and dissimilarity typical of a heterogeneous composite network. On the other hand, by means of the reinforcement learning capabilities of neural networks, the JRRM scheme is capable of interacting with the surrounding environment and accordingly self-tuning and acting. Besides, the proposed JRRM algorithm is economic-driven, in the sense that micro-economic considerations are included in the radio interface decision. In particular, the user satisfaction is considered to be dependent not only on technical aspects such as the bit rate assignment, but also on economic aspects such as the price the user is paying for the service. As a result the concept of the user satisfaction is identified with the so called user acceptance (A), defined as an increasing function of the user utility (u) and a decreasing function of the price (p) the user pays for the service, given by [20]:

$$A(u,p) = 1 - \exp\left(-Cu^{\mu} p^{-\varepsilon}\right) \qquad (1)$$

where C, μ and ε are constants representing the different user sensitivity to utility and price, also defined in [20]. In this context it is also interesting to define the satisfaction from the network operator point of view. The identified metric is the operator revenue (R), defined as [20]:

$$R = \sum_{i=1}^{N_u} p_i A(u_i, p_i) \qquad (2)$$

where N_u is the number of users and u_i, p_i are, respectively, the utility observed by the *i*-th user and the corresponding price paid by this user.

The rest of this section is organized in five parts. Subsection VI.1 provides a brief description of the fuzzy-neural JRRM algorithm. Then, subsection VI.2 develops the role that CPC plays in support of decentralized intra/inter operator JRRM/ASM. Subsection VI.3 presents the simulation scenario where the decentralized algorithm is evaluated. Then, within the layered framework identified in Section II, the described decentralized fuzzy neural JRRM algorithm is evaluated in a single operator scenario in subsection VI.4 (i.e. decentralized intra-operator JRRM layer), and in a multi-operator context in subsection VI.5 (i.e. decentralized inter-operator JRRM layer).

VI.1. Brief description of the fuzzy-neural JRRM algorithm

The fuzzy neural JRRM algorithm selects the RAT that the mobile should be connected to and the corresponding transmission bit rate, based on both technical inputs and techno-economical measurements. The algorithm consists in two main blocks, as indicated in the following (for all the details and formulation of the algorithm the reader is referred to [19]):

- Fuzzy logic controller: This procedure consists in the fuzzification, inference engine and defuzzification steps and converts the technical inputs (i.e. signal strength, resource availability in each RAT and mobile speed) into two outputs for each RAT: (1) a number between 0 and 1, denoted as FSD (Fuzzy Selected Decision), reflecting the suitability of selecting each RAT, and (2) the corresponding bit rate in each RAT. Finally, the selected RAT will be the one with the highest FSD. Other possibilities could include, as in the general framework in [19], the combination of the FSD outputs with other subjective inputs through a multiple objective decision making.
- Reinforcement learning algorithm: This procedure basically adjusts the different membership functions and parameters of the fuzzification and defuzzification steps in the fuzzy logic controller, with the objective of ensuring a certain target of a reinforcement signal reflecting some QoS guarantees. In the considered algorithm, we define as reinforcement signal the overall average user acceptance in the scenario as defined in (1), so that the proposed framework is able to maintain this metric at a target desired rate. The operation of the reinforcement learning algorithm is based on considering the steps of the fuzzy logic controller as a layered neural network and backpropagating the reinforcement signal to adjust dynamically the parameters of each layer. Details can be found in [19].

VI.2. Role of the CPC

In order to execute at the terminal side the fuzzy neural JRRM algorithm, it is needed to identify the information that has to be provided through the CPC to the mobile terminal, in addition to the information for ASM purposes that was detailed in [18], in order to be able to execute autonomously the fuzzy logic controller and the reinforcement learning algorithm. Specifically, the following inputs are required:

- Signal strength of the different available RATs. This measurement can be carried out at the terminal receiver, using the information in terms of currently allocated frequencies to the different RATs that is transmitted in the CPC.
- Mobile speed. This information is assumed to be estimated at the mobile terminal, so it is not necessary to be transmitted through the CPC.
- Resource availability in the different RATs: This information has to be provided to the user from the network side by means of the CPC. It should be taken into account that the resource availability information is received by the mobile terminal with a certain signalling delay, consequently this information does not represent the exact current value of resources available in the different cells.
- Maximum allowed bit rates in the different RATs: By fixing a limit on the allowed bit rate, the network is able to limit the user's behaviour, which could tend to act selfishly and occupy many radio resources, so that the base station would experience overload and the mobiles connected to it would be dissatisfied (i.e. the user utility u and consequently the user acceptance A would tend to zero). Then, in order to keep the overload probability at a reduced rate, the maximum bit rate that a user can occupy will be fixed and communicated through the CPC. Particularly, this maximum bit rate should be reduced as the number of users attached to a given cell increases.
- Average acceptance probability in the scenario: This input corresponds to the reinforcement signal to be used by the reinforcement learning algorithm, and it has to be provided to the terminal by means of the CPC, together with the corresponding desired target value. In this way, using as input the information from the CPC, the terminal can execute autonomously the reinforcement learning algorithm and adjust the different parameters of the fuzzy-based decision process, so that the acceptance probability is kept equal to the target value.

On the other hand, in order to enable inter-operator JRRM strategies, it is possible to include, for each operator in the CPC, the list of the other operators with whom inter-operator agreements have been established. In this way, in case the operator that a mobile is subscribed to (i.e. the Home operator, denoted here as H-operator) is not able to provide service, the terminal could select the most appropriate Serving operator (i.e. S-operator, that is, the operator which actually provides service to the user) among those included in the list and according to a given criteria. It is worth mentioning that, in the multi-operator case the fuzzy-neural JRRM is executed separately for each operator.

Based on the above considerations, Table II summarises the information that should be transmitted through the CPC, on a mesh basis, in order for the decentralized fuzzy neural JRRM algorithm to be implemented, supporting both intra and inter-operator levels. Furthermore, notice that the information in Table II includes the frequency carriers that are currently allocated to each RAT, so that ASM strategies in which the frequencies are changed can also be implemented.

VI.3. Simulation Model

The proposed decentralized fuzzy neural JRRM is evaluated in a multi-cell, multi-RAT scenario where each operator is characterized by a seven cell deployment, including 4 UMTS base stations, 2 GERAN base stations and one WLAN access point, as it is shown in Figure 7. The considered scenario consists of circular cells, with radii 210m for WLAN, 650m for UMTS and 1km for GERAN.
A mobility model with users moving according to a random walk model inside the coverage area is adopted with a randomly assigned mobile speed in the interval [0,50] km/h and a randomly chosen direction.

The propagation model considered for UMTS and GERAN is given by L=128.1+37.6 log d (km), which assumes that the frequency band is similar for both systems [23]. For WLAN the propagation losses inside the hotspot are modelled by L= 20 log d(m)+40 [24]. The beginning and the end of the user's activity periods are defined according to a Poisson scheme with an average of 6 calls per hour and user and average call duration of 180 seconds.

The set of available bit rates in UMTS are {32 kb/s, 48 kb/s, 64 kb/s, 80 kb/s, 96 kb/s, 112 kb/s, 128 kb/s, 192 kb/s, 256 kb/s, 320 kb/s, 384 kb/s}, considering a single UTRAN FDD carrier with maximum allowed uplink load factor 0.75. For GERAN, the set of bit rates is {32 kb/s, 48 kb/s, 64 kb/s, 80 kb/s, 96 kb/s}, assuming a total of four carriers available and coding scheme CS-4. For WLAN it is considered that the total bandwidth available (11 Mb/s) is equally distributed among the WLAN users. It is also assumed that no more WLAN users are accepted when the bandwidth per user is less or equal than 384 kb/s. A single access point is considered.

A static pricing strategy is considered in which the price the user pays for the service provided is proportional to its allocated bandwidth B (i.e. p=0.01·B).

The performance results are evaluated based on the following metrics:

- Blocking probability: A user is blocked if at session start the bit rate selected by the fuzzy neural algorithm is zero.
- Overload probability: It is the probability that one base station in the scenario is overloaded, which occurs whenever in the decentralised allocation process the users select more bandwidth than the available one, so that in practice all of them will be unsatisfied.

Simulation results have been obtained considering that the target user acceptance probability is retained to A*=0.8 as in [20].

The information about the resource availability in the different cells of the scenario which has to be conveyed in the CPC is considered to be available to the user with a delay of 100 ms and the resource availability value which is inputted in the fuzzy neural machine is averaged over a 2 s window.

VI.4. Decentralized Intra-operator JRRM

We compare simulation results obtained considering two different algorithms. Alg. #1 is a decentralized Fuzzy Neural JRRM algorithm in which the maximum allowed bit rate is not transmitted through CPC, so that users can autonomously select any bit rate supported by the selected RAT. In turn, Alg. #2 is a decentralized Fuzzy Neural JRRM algorithm in which the CPC provides indications on the maximum allowed bit rate for UMTS and GERAN depending on the existing load. Specifically, in Alg. #2 it is assumed that if the number of users in UMTS is less or equal than 3, then the maximum bit rate is set to 384 kb/s, in turn, if there are 4 users it is reduced to 320 kb/s, while for more than 4 users it is further reduced to 256 kb/s. As for GERAN, if the number of users is less or equal than 5 the maximum bandwidth is limited to 96 kb/s, if the number is between 6 and 7 the maximum bit rate is 80 kb/s, and if there are more than 7 users the maximum bit rate is 64 kb/s.

The results for the two algorithms are plot in Figure 8, which shows that both the blocking probability and the overload probability can be kept at lower rates with Alg. #2, in which the CPC is used to convey also information about maximum allowed bit rates in order to improve the network performances and the radio resource usage. Notice that for the considered loads the blocking rate increases very slowly with values between 1% and 2% in case of Alg. #1 and between 0% and 1% in case of Alg. #2.

VI.5. Decentralized Inter-operator JRRM

In a multi-operator context, inter-operator agreements can be established in order to exploit the complementary characteristics existing spatially and temporally in terms of traffic distribution in different operators' domains. In particular, when a user can not be admitted in the H-operator's domain at session initiation, an inter-operator JRRM algorithm can be applied to select another appropriate serving operator with whom inter-operator agreements have been established. This procedure should be carried out in a transparent way to the user, which should perceive a similar quality and pay the same price as if it was connected to the H-operator. Furthermore, the revenue coming from this user can be shared between the H and the S-operator according to different principles, as it was discussed in [25], where a centralized inter-operator JRRM algorithm was presented.

In the following, we extend the decentralized intra-operator JRRM algorithm analysed above to include the inter-operator JRRM component. Particularly, whenever a user is blocked by the decentralized intra-operator JRRM algorithm, the alternative operator is selected from the list of operators with inter-operator agreements based on the execution of the fuzzy-neural JRRM algorithm for the rest of operators following the principles of [25], specifically selecting the operator with the highest output of the fuzzy logic controller (i.e. with the highest FSD for the selected RAT).

The considered simulation scenario takes into account two operators that deploy their infrastructure in the same area. The two operators deploy the same infrastructure, which is the one shown in Figure 7, and are characterized by the same market share. Simulation results show that this approach allows an improvement in terms of operator profit, defined as the difference between the operator revenue computed as in (2) and the cost of infrastructure invested by the operator [25][26]. Figure 9 plots the percentage of operator profit increment when inter-operator agreements (IOA) have been established with respect to the case that no inter-operator agreements (NIOA) have been established, as a function of the number of users per operator in the scenario. Significant gains up to 68 % can be observed thanks to the use of the inter-operator JRRM. Notice that as the number of users demanding service increases the percentage of profit increment in case of IOA with respect to NIOA decreases. The reason is that both the operators are so loaded that it is not possible to exploit the complementary characteristics of traffic distribution in the scenario.

VII. Conclusions

This paper has presented an integrated framework where JRRM and ASM mechanisms operate synergistically towards an optimized dynamic spectrum and radio resource usage in multi-operator heterogeneous wireless networks scenarios. Given the complexity of the problem, the proposed solution follows a layered approach, where both intra and inter-operator levels are considered. The solution is sustained on cognitive network functionalities.

The interest of decentralized JRRM/ASM functionalities has been identified and the role of the Cognitive Pilot Channel (CPC) as radio enabler has been stressed. In this respect, this paper has proposed an on-demand CPC as opposite to the broadcast mechanism. It has been obtained that the on-demand approach is able to achieve the same performance in terms of delay to retrieve the information as the broadcast approach but requiring a significantly lower bit rate of the CPC channel, particularly when a high granularity in the mesh sizes is desired. Differences in more than one order of magnitude have been observed in the required bit rate for the two approaches.

Besides, the role of the CPC as support to JRRM in a heterogeneous network context has been developed. In particular, the CPC enables the implementation of a fuzzy neural JRRM at the mobile terminal so that, by means of adequate information sent through CPC, mobile terminals are able to take JRRM decisions in a decentralized manner. Simulation results have shown that the decentralized implementation of JRRM allows keeping both blocking and overload probabilities at reduced levels, mainly when CPC provides the terminals with the maximum bit rates that they are allowed to use. The same framework has also been considered in a multi-operator scenario through inter-operator JRRM algorithms in which the user can receive service through an alternative operator in case the home network is blocked. Simulation results have shown that this approach improves the operators' profit and the radio resource usage.

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Figure legends

Figure 1 Layered intra/inter-operator and JRRM/ASM approach

Figure 2 Decentralized JRRM/ASM enabled by an on-demand CPC

Figure 3 Operation of the on-demand CPC

Figure 4 Total average delay as a function of the CPC range for a mesh size of 100m×100m

Figure 5 Required CPC net bit rate to ensure a maximum average delay of 5s.

Figure 6 Minimum mesh size so that the required bit rate with the broadcast CPC is below that of the on-demand CPC

Figure 7 Simulation scenario

Figure 8 Blocking and Overload probability versus number of users in the scenario

Figure 9 Operator profit versus number of users in the scenario subscribed to each operator

Tables

Table I Maximum CPC range for different maximum delay requirements

Average delay bound	On-demand CPC	Broadcast CPC
1s	0.91 km	0.08 km
2s	1.00 km	0.14 km
5s	1.08 km	0.26 km
10s	1.08 km	0.37 km
20s	1.08 km	0.53 km

Table II Information to be transmitted through the CPC for JRRM and ASM operation

<table>
<tr><td>Positioning info</td><td colspan="2">Mesh coordinates</td></tr>
<tr><td>List of operators</td><td colspan="2">Information per operator:</td></tr>
<tr><td rowspan="7"></td><td>List of RATs</td><td>Information per RAT:</td></tr>
<tr><td rowspan="3"></td><td>Frequency carriers</td></tr>
<tr><td>Resource availability</td></tr>
<tr><td>Maximum allowed bit rate</td></tr>
<tr><td colspan="2">Average measured user acceptance</td></tr>
<tr><td colspan="2">Target user acceptance</td></tr>
<tr><td colspan="2">List of operators with inter-operator agreements</td></tr>
</table>

Figures

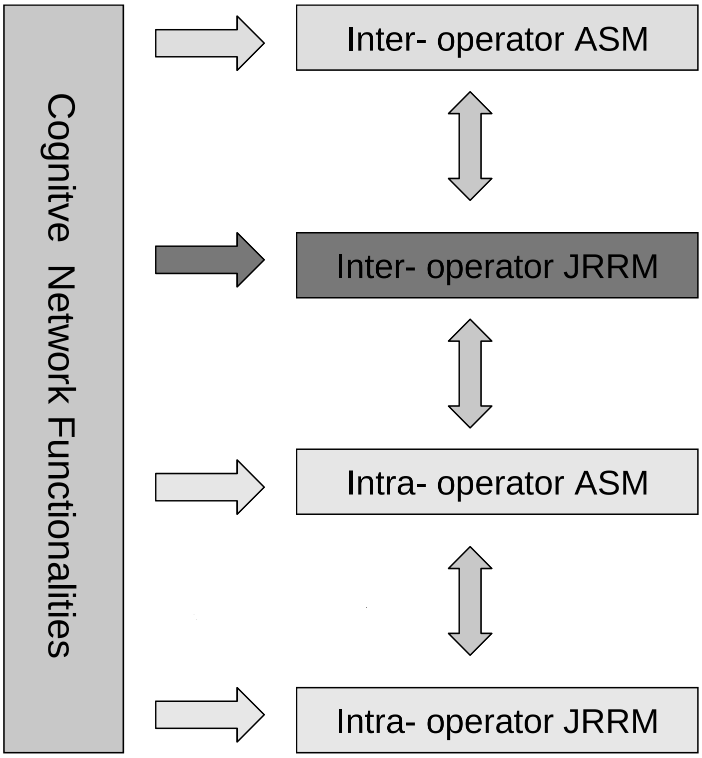
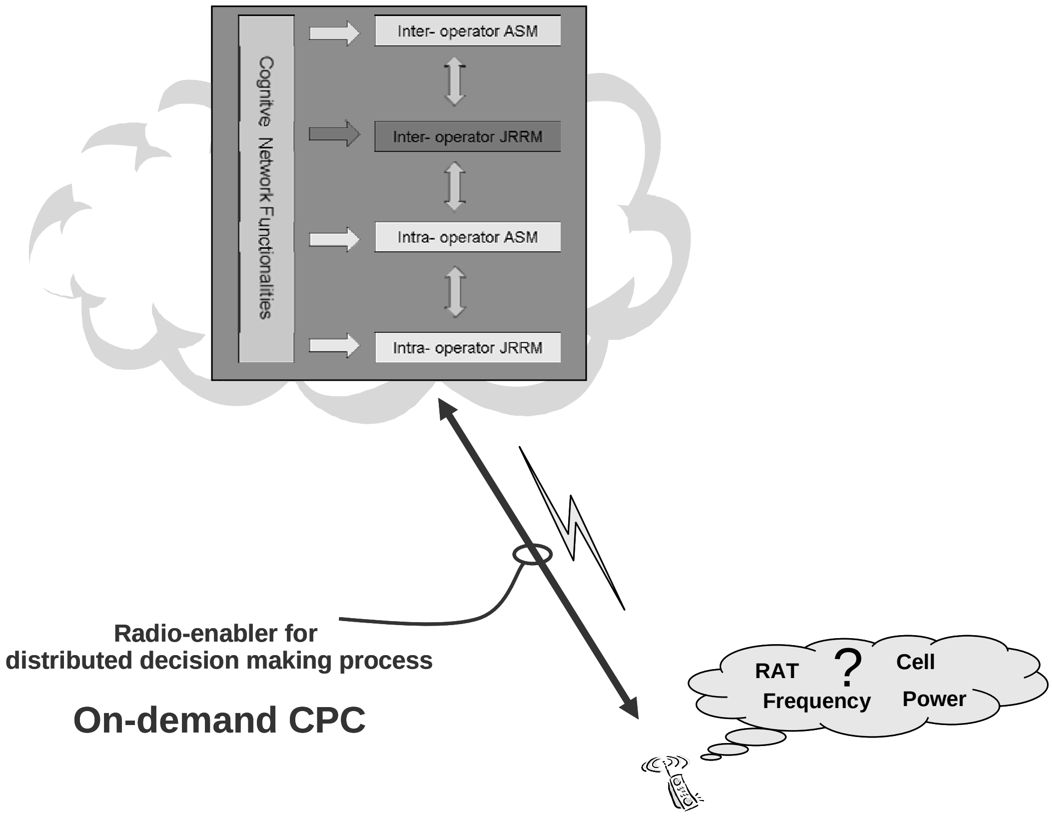


Figure 1 Layered intra/inter-operator and JRRM/ASM approach



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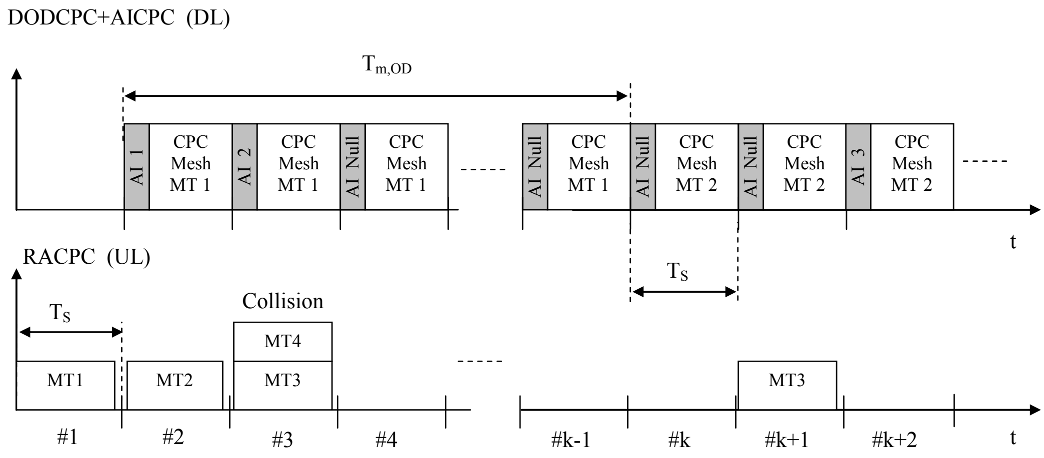

Figure 3 Operation of the on-demand CPC

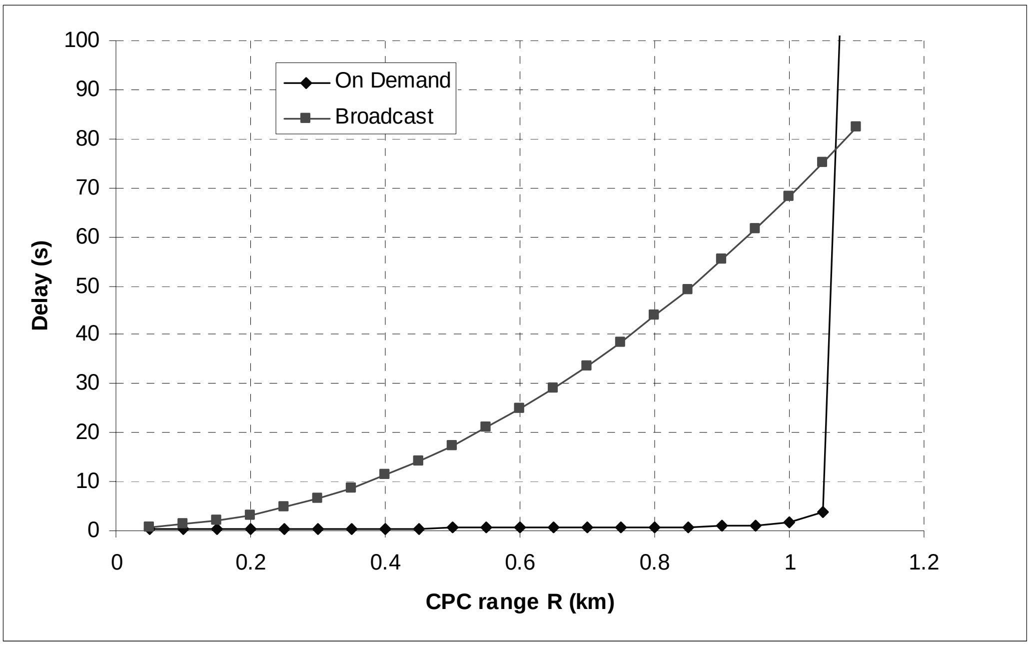

Figure 4 Total average delay as a function of the CPC range for a mesh size of 100m×100m

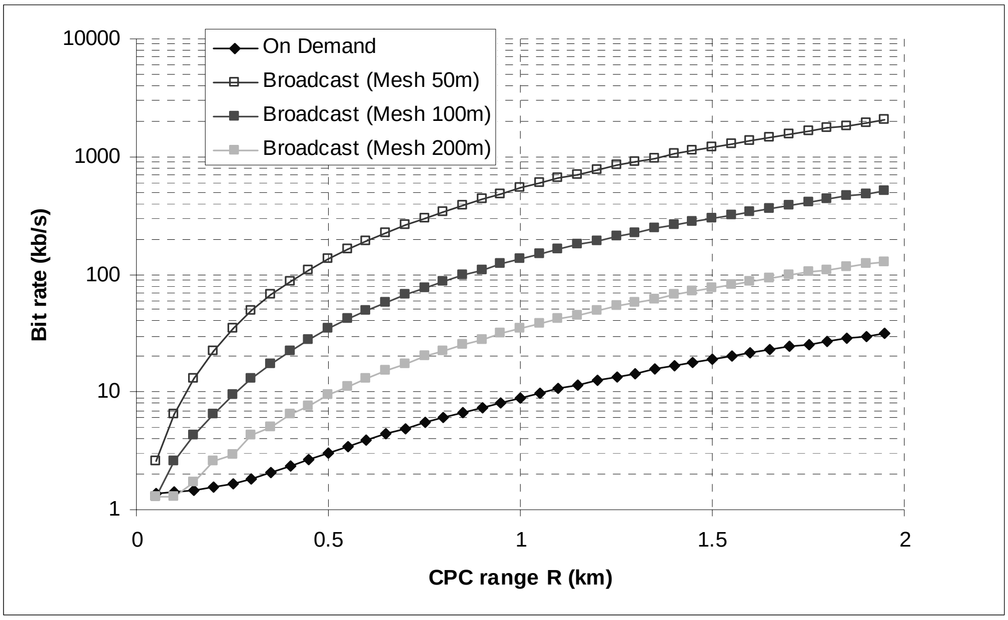

Figure 5 Required CPC net bit rate to ensure a maximum average delay of 5s.

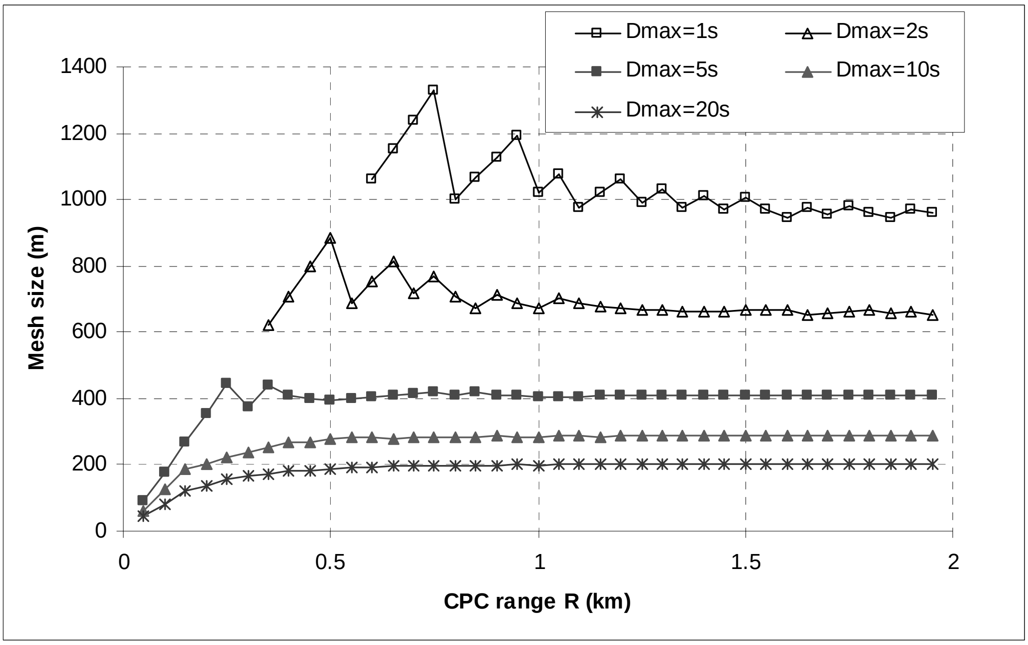

Figure 6 Minimum mesh size so that the required bit rate with the broadcast CPC is below that of the on-demand CPC

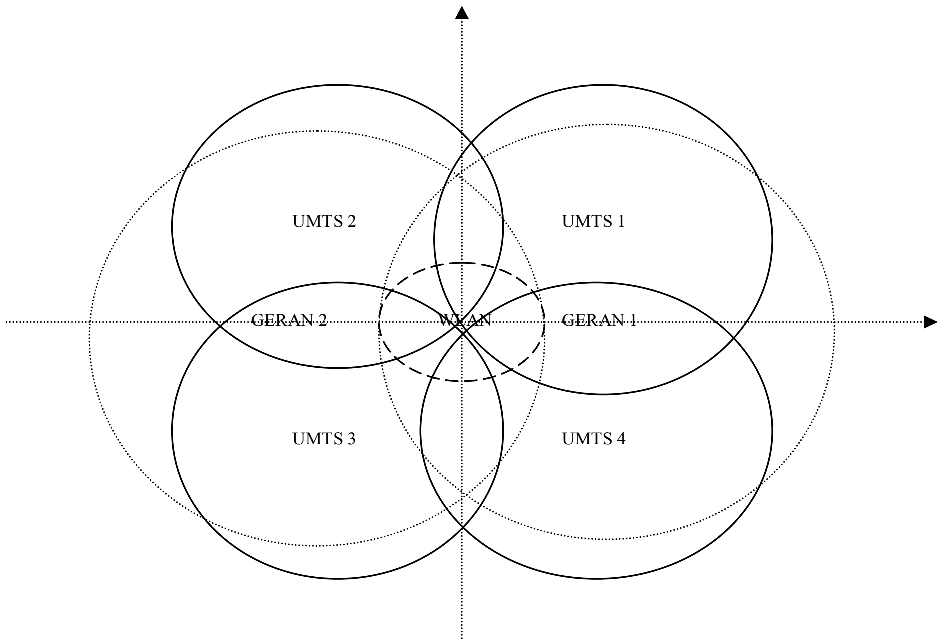

Figure 7 Simulation scenario

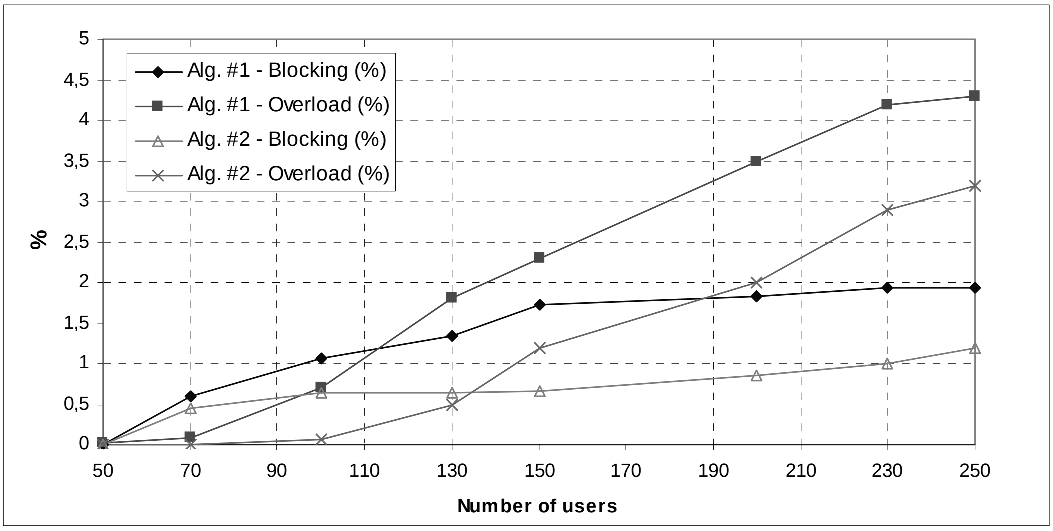

Figure 8 Blocking and Overload probability versus number of users in the scenario

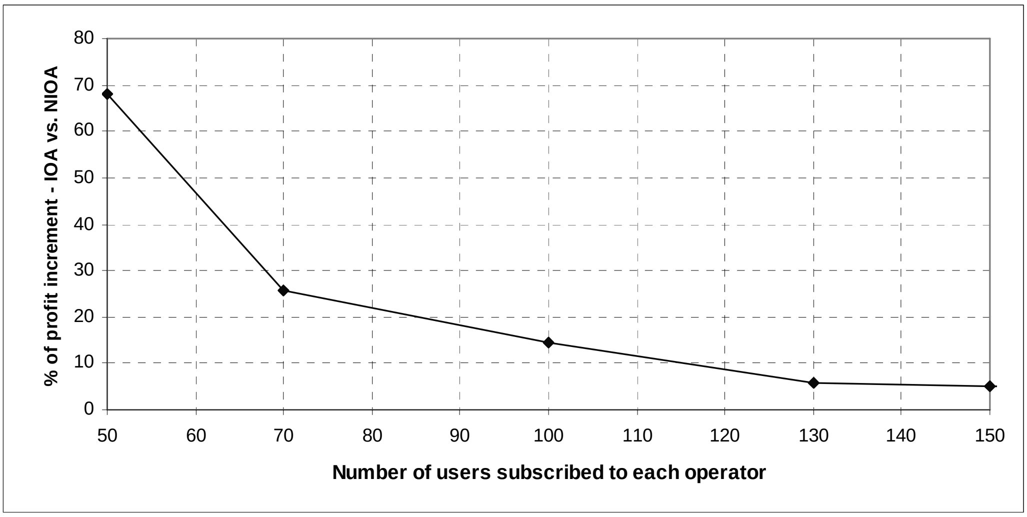

Figure 9 Operator profit versus number of users in the scenario subscribed to each operator