Game Theoretic and Coordinated Interference-based Channel Allocation Schemes for Packet Mobile Communication Systems

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I- INTRODUCTION

The steady increase in demand for traditional voice services, the increasingly important user requirements and expectations in terms of Quality of Service (QoS), and the introduction of new bandwidth-demanding multimedia services is creating new challenges to mobile operators that need to develop and implement appropriate Radio Resource Management (RRM) techniques to ensure an efficient use of the scarce available radio resources.

The channel assignment policy is a crucial RRM technique on which the capacity of mobile communication systems depends. Channel allocation algorithms are in charge of allocating, managing and distributing the available channels among users and services according to some QoS or system constraints. Two main channel assignment categories can be defined: Fixed Channel Allocation (FCA) and Dynamic Channel Allocation (DCA) [1]. Current cellular systems use FCA where the available channels are divided into as many disjoint sets as there are cells in a particular cluster and each set of channels is permanently assigned to a cell. To overcome the inefficiency of FCA schemes under high spatial traffic variations, DCA schemes do not permanently allocate channels to a cell but assign them dynamically, as new calls arrive in the system, based on a predefined cost function. DCA algorithms can be identified as Traffic Adaptation (TA) DCA schemes or Interference Adaptation (IA) DCA schemes. While TA-DCA mechanisms adapt to traffic distribution fluctuations in order to cope with 'hot-spot' situations, IA-DCA algorithms use real-time interference measurements to assign an incoming call the most suitable available channel [2]. It is considered that IA-DCA schemes can achieve higher system performance than TA-DCA mechanisms [3]. Despite the acclaimed superior performance of DCA over FCA [1], the implementation of DCA in cellular systems has not been considered yet due to its computational cost and implementation difficulties. As a result, this work is concerned with the optimisation of FCA schemes through the design of novel channel allocation algorithms.

Game theory is a collection of mathematical models formulated to study situations of conflict and cooperation. It is concerned with finding the best actions for individual decision makers in these situations, and with recognizing stable outcomes. Since the objective of RRM techniques is to manage the scarce radio resources among a set of competing users, in a scenario where the actions of a particular user might affect the reminder users, radio resource management is a clear example of a potential application field for game theory [4]. This potential was first recognised by Goodman in [5] where game theory was applied to improve the operation of power control algorithms in wireless communication systems. As shown by Wong et al. [6], the channel allocation dilemma is another promising field for the application of game theory. While Wong proposed a game theoretic formulation of the distributed dynamic channel allocation problem, this research applies game theory to define suitable channel allocation algorithms in FCA scenarios.

Current FCA cellular systems traditionally assign an incoming call a randomly selected available channel. This random assignment simplifies the allocation problem and ensures that all channels, and therefore RF equipment, are uniformly used over time. However, it is not able to cope with the specific and distinctive QoS needs of new wireless multimedia applications [7] and results in a non-optimal system performance [8]. To improve such performance, the work reported in [8] evaluated a set of allocation mechanisms that assign incoming calls the available channel that experienced the best channel quality conditions during previous transmissions. These algorithms were shown to outperform the random one due to an implicit coordination among co-channel interfering cells during the channel allocation process. Such coordination resulted in lower interference levels since interfering cells avoided transmitting using the same channels. Based on these observations, this paper proposes and evaluates a set of game-theoretic channel assignment schemes designed to explicitly increase the coordination among co-channel interfering cells by basing their allocation decision on the interference that is experienced on each one of the available channels at the time of the allocation.

II- COORDINATED CHANNEL ASSIGNMENT SCHEMES

The proposed schemes follow the philosophy of IA-DCA schemes such as those presented in [9] and [10] but with important differences, apart from the fact that this work focuses on FCA schemes. The algorithm described in [10] predicts the experienced interference level on each channel based on signal level measurements of the serving cell and the neighbouring cells. Although this procedure seeks to ease the implementation cost of interference-based channel assignment schemes, this work directly estimates the interference by exchanging channel occupation information among co-channel interfering BSs (Base Stations). This assumption is realistic and can be justified as follows. First of all, it is important to note that the availability of sufficient bandwidth on the core network to transfer all the signalling information is not a problem compared to the radio access network. The operation of the proposed algorithms could be unmanageable if an important number of co-channel interfering BSs required to exchange channel occupancy information. However, this work will show that this is not actually the case since only information from a reduced set of neighbouring cells is required. The potential implementation cost is further reduced if we consider that in current cellular systems the channel assignment decisions are controlled by the BSC (Base Station Controller) and that a single BSC can handle the communications of a considerable number of BSs. As a result, the BSC that controls a set of neighbouring cells directly knows their channel occupancy situation and our proposed solutions can be implemented at the BSC without incurring in an additional relevant implementation cost.

Some interference-based allocation algorithms, e.g. the one proposed in [10], claim that to maximize the performance, the allocation scheme should solely consider the interference received. On the other hand, this work will demonstrate that, under certain operating conditions, the system performance is improved by not only considering the interference received if a given channel is allocated to an incoming call but also the interference produced to other users by this channel assignment.

Taking into account the nature of the posed channel allocation dilemma, the following sections formulate the proposed scheme from a game-theoretical perspective to demonstrate it corresponds to a quasi-optimal solution.

A- Theoretical framework

The problem of channel allocation in wireless systems can be analyzed from a game theoretical point of view by defining a suitable set of games. Let's define a scenario as a possible succession of calls generated in a system. Since the traffic and user loads in a system are not constant, different scenarios can be defined, with S denoting the set of all possible scenarios. In order to illustrate what a scenario is, we consider a simple system with only two BSs, called A and B. If we denote by begin-, end- or reject-call when a call begins, ends or it is rejected in the system, a possible scenario is the following succession of events: begin-call 1 in A, begin call 2 in A, begin-call 3 in B, reject-call 4 in A, end-call 2, end-call 1, begin-call 5 in A, end-call 3 and so on. If only two channels are available per cell then the following decision tree can be constructed:

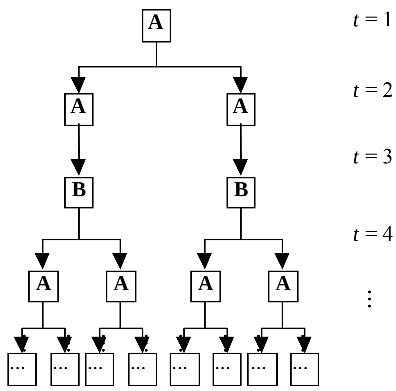

Figure 1. Tree representation of a scenario

In each node the name of the BS which has to make the channel allocation decision appears. The number of branches arising from each node depends on the number of available channels in it. So at $t = 1$ the BS A has two available channels, but at t = 2 the

BS A has only one channel available because the other one is occupied at that moment. Each level of the decision tree corresponds to a time in which one channel allocation decision has to be made, and only the BS where the new call is generated, makes a decision at that time.

For each $s \in S$, a non-cooperative game in extensive-form, G_s, can be associated as follows:

- The players are the BSs which have to make the channel allocation decision and we denote the set of all BSs by $B = \{b_1, b_2, ..., b_n\}$.
- The decision nodes are the events (new calls) for which a BS has to make a channel allocation decision taking into account all previous channel assignments. All these nodes form a decision tree as illustrated in Figure 1. We denote by T_s the tree associated to the scenario s and by $T_s(b_i)$ the set of all nodes of the T_s tree, in which $b_i \in B$ has to make a channel decision considering that $T_s = \bigcup T_s(b_i)$ and $T_s(b_i) \cap T_s(b_j) = \varnothing$ for each b_i, $b_j \in B$. We define $T_s^m(b_i)$ as the set of all nodes in $T_s(b_i)$ for which a decision has to be made before the instant m.
- Let C be the set of all available channels. The set of possible alternatives at each decision node is the number of available channels for the corresponding BS. Hence, given $b_i \in B$ and $j \in T_s(b_i)$, the set of all alternatives for b_i in the node j is denoted by $C_s(b_i, j)$.
- A history for a node t, h_t, is the sequence of decisions (channel assignments) of the players leading to it. A history of the game, h, is a complete sequence of decisions until the game ends with H_s denoting the set of all possible histories in the game.
- The payoffs for the players are defined by an appropriate utility function that will depend on the channel assigned and the game's history until that moment, i.e., for

every player $b_i \in B$ and for every node $j \in T_s(b_i)$, the payoff or utility function is $u_i : C_s(b_i, j) \to \mathbf{R}$. For every finite history $h \in H_s$ we can define the average payoff function for every player $b_i \in B$ as follows:

$$U_i(h) = \frac{1}{\left|T_s(b_i) \cap h\right|} \sum_{j \in T_s(b_i) \cap h} u_i(c(h_j), h_j),$$

where $c(h_j) \in C_s(b_i, j)$ is the decision made by b_i in node j according to the history h, h_j is the history for node j according to h, $T_s(b_i) \cap h$ is the set of nodes along the history h in which b_i has to make a decision, and $\left|T_s(b_i) \cap h\right|$ is the number of different elements of the set $T_s(b_i) \cap h$. If the history is infinite, we can define the average payoff or utility function for every player $b_i \in B$ as follows,

$$U_i(h) = \lim_{m \to +\infty} \frac{1}{\left|T_s^m(b_i) \cap h\right|} \sum_{j \in T_s^m(b_i) \cap h} u_i(c(h_j), h_j),$$

$U_i(h)$ is finite when all the terms $u_i(c(h_j), h_j)$ are bounded above.

The game G_s can then defined by the 5-tuple

$$G_s = \left(B, T_s, (T_s(b_i))_{b_i \in B}, (C_s(b_i, j))_{b_i \in B}^{j \in T_s(b_i)}, (u_i(\cdot,\cdot))_{b_i \in B}\right),$$

In the proposed channel allocation game, the information available to the players regarding previous channel allocations is very important since the payoff or utility functions depend on the history. When the BSs know exactly the previous channel assignments performed in the whole system, then the game is with perfect information. If this information is not available, then each game is with imperfect information and the player doesn't know exactly in which decision node he is, i.e. he is not aware of the history leading to that decision node. As previously mentioned, assuming BSs can exchange channel assignment information is realistic.

It is important to note that not all information in a history h_t is relevant to the player when it has to make an allocation decision. In fact, a BS is only interested in the assigned channels at each BS at the moment of making the decision. Let's term r_t the relevant information from h_t in node t consisting of just the assigned channels at that node. In this environment, different histories could have the same relevant information and so, perhaps, the channel allocation decision in all these cases should be equal. Hence, it seems reasonable to think that the strategy function should be defined in terms of this relevant information.

Let R be the set of all possible relevant information. For each node j we have a history h_j and this history has associated a relevant information $r \in R$. This relevant information consists of the assigned-channels in each BS at the moment of making the allocation decision. If we denote by r^c the set of non-assigned channels in each BS and by $r^c(b_i)$ the set of non-assigned channels in the BS b_i, then a strategy for a player b_i is a function σ_i from R to C such that $\sigma_i(r) \in r^c(b_i) \subset C$. If we consider that the players can choose by random, not necessarily uniformly, their strategies (channels available) then we should introduce the concept of "behavioral" strategy for a player as a probability distribution on the set of his "pure" strategies (channels available). Consequently, a strategy for a player b_i is a function σ_i from R to ΔC such that $\sigma_i(r) \in \Delta r^c(b_i) \subset \Delta C$, where ΔC is the set of all possible probability distributions defined on the set C and $\Delta r^c(b_i)$ is the set of all possible probability distributions defined on the set $r^c(b_i)$. For every player $b_i \in B$ and for every $r \in R$, the payoff or utility function is $u_i : C \times R \to \mathbf{R}$ and the utility for a given strategy $\sigma_i(r)$ is defined as follows:

$$u_i(\sigma_i(r), r) = \sum_{c \in r^c(b_i)} p_c u_i(c, r),$$

where p_c is the probability assigned to the channel c and $\sum_{c \in r^c(b_i)} p_c = 1$.

A priori, one is not able to know which succession of begin-calls, reject-calls and end-calls are going to occur so, in this context, our objective is to define a strategy (a channel allocation algorithm in our case) which is a equilibrium for all possible games (scenarios) and maximises system performance. In this paper, we consider that BSs can communicate among them sharing channel occupancy information. We then obtain a set of games with perfect information, one for each scenario. However, if we take all scenarios together then we can construct a game in which the 'nature' moves first choosing a scenario by random, following a probability distribution defined over all scenarios. However, since 'nature' does not declare its choice, the players are not aware of the scenario chosen. In this case, when a player has to make a decision in a node, he knows the history that took place before, but there are many scenarios with the same history until that moment. As a result, the player doesn't know exactly in which node he is, and the whole game (i.e. considering all scenarios together) can be defined as with imperfect information. In other words, we can consider that the player perfectly knows the past and the present but not the future. This reason makes extremely difficult to find the best channel allocation procedure. The whole game can then be described by the 4-tuple $(B \cup \{0\}, S, G_S, (p_s)_{s \in S})$ where 0 represents the 'nature', G_S is the set of all games G_s, and $(p_s)_{s \in S}$ is the probability vector defined over the set of scenarios S.

In order to define a strategy, we introduce the concept of optimum argument of a function as the set of points which optimize that function. In our particular case, it is formally defined as follows:

$$\arg opt_{c \in r^c(b_i)}\{u_i(c,r)\} = \{c \in r^c(b_i) : u_i(c,r) = opt_{c \in r^c(b_i)}\{u_i(c,r)\}\}$$

Now we are able to define the following strategy for each player b_i in terms of the arg*opt* as follows:

$$\sigma_i(r) = (p_c)_{c \in r^c(b_i)} : p_c = \begin{cases} 0 & \text{if } c \notin \arg opt_{c \in r^c(b_i)} \{u_i(c,r)\} \\ \frac{1}{k} & \text{if } c \in \arg opt_{c \in r^c(b_i)} \{u_i(c,r)\} \end{cases},$$

where $k = \left| \arg opt_{c \in r^c(b_i)} \{u_i(c,r)\} \right|$, i.e., the number of channels with the best payoff value.

The idea behind this strategy is that the players always choose the best channel available in each node taking into account the relevant information at this point. If several channels are equally optimal, then the player chooses randomly one of them. As we can observe in this strategy, the players do not make any inference on the future, for this reason we can call it 'myopic strategy'. In this sense, the players make channel assignment decisions optimally in each node with regards to the relevant information available at this stage, but they do not take into account the possible future histories. Therefore this strategy is constructed under a forward induction principle while the Subgame-Perfect Nash Equilibria (SPNE) are supported under a backward induction principle [11]. As a result, this strategy is not SPNE of the whole game in general, but will be a SPNE for many of the single scenarios. Nevertheless, this strategy provides sensitive improvements with respect to others strategies (channel allocation algorithms) as it will be shown in the simulation results.

On the other hand, for each particular scenario we know that the corresponding game is with perfect information and so there exists at least one SPNE for it [11] when the scenario consists of finite histories, but this is not true in general in the case of scenarios with infinite histories or with a non-determined horizon. Therefore, even in the case of single scenarios, it is not always easy or possible to find the best channel assignment procedure in the sense of Nash Equilibria. For this reason, a common alternative is to look for reasonably good strategies (quasi-optimal) but not optimal in general, as it is the case for our 'myopic strategy'. In the context of this work, further research will consist of defining a strategy taking into account the forward induction principle and a probabilistic forecast on the likely future histories.

B. Payoff or utility function

This paper proposes a game-theoretic channel assignment scheme based on the occupied channels in co-channel cells. At this point, it is important to consider the differences between an omnidirectional cellular scenario and a sectorized one. In the first case, two co-channel cells produce and receive from each other the same interference level. As a result, there is no difference in between considering in the channel assignment process just the interference received, or the interference produced and received by a new channel allocation; this statement will be demonstrated with some simulations results. In the case of a sectorized cellular network, a cell (in this case representing a sector) receives interference from a set of co-channel cells but produces interference to a different set of co-channel cells; this property results from the use of directive antennas. As a result, an important parameter during a channel assignment is how much weight is given in the decision process to the interference received in a channel being allocated and to the interference produced to other cells by this channel allocation. To generalise the following reasoning the interference caused and received are considered.

The objective of the proposed schemes is to minimise the interference caused and received by a new channel assignment. For that purpose, a BS that receives a new channel request, evaluates for each one of its available channels the number of interfering and interfered BSs that would result from assigning each channel to the new user. After all available channels have been evaluated, the BS assigns the channel resulting in the lower interference level (both received and created). This process is equivalent to minimizing, for each channel assignment, the following payoff function:

$$u_i(c,r) = w\big(IR_1(c,r) + \xi IR_2(c,r)\big) + (1-w)\big(IC_1(c,r) + \xi IC_2(c,r)\big),$$

where $c \in C_S(b_i, j)$ is the available channel under evaluation in node j, r is the relevant information in node j and w ($0 \le w \le 1$) is a weight parameter defining the relative importance, during the evaluation, of the interference caused and received. If w is equal to 0, the channel assignment scheme only considers the interference caused by a potential new assignment to the rest of BSs (generous behaviour). On the other hand, if w is equal to 1, the scheme behaves selfishly and only considers the interference received by other BSs if the channel assignment is performed. If w is set to 0.5, the BS equally considers the interference received and caused by each potential new channel assignment. This parameter w could also be used to define different utility functions depending on the type of service since their QoS requirement varies. In this case, the payoff or utility function would depend not only on the channel and its relevant information but also on the type of service required. So the utility or payoff function has the following expression:

$$u_i(c,r,t) = w(t)\big(IR_1(c,r) + \xi IR_2(c,r)\big) + (1-w(t))\big(IC_1(c,r) + \xi IC_2(c,r)\big),$$

where t is the type of service required and $w(t)$ is the weight corresponding to that type of service.

In the interference evaluation, the channel allocation process can consider co-channel interferers from the first and second tiers. $IR_1(c, r)$ and $IR_2(c, r)$ correspond, respectively, to the interference received from interferers of the first tiers and second tiers. On the other hand, $IC_1(c, r)$ and $IC_2(c, r)$ represent the interference caused to BSs in the first and second tiers. The interference caused and received can either be exactly computed (using the transmitting power, the Okumura-Hata pathloss model and the distance between receiver and interferers) or estimated. For the latest option, the interference is incremented by 1 whenever the channel under consideration is occupied in an interfering or interfered BSs. When estimating the interference, the parameter ξ has been used to define the ratio between the interference from the first and second tiers. For the simulations here reported, ξ has been set to 0.15.

III- SIMULATION ENVIRONMENT

The performance of the proposed schemes has been evaluated using a system level simulator that emulates, at the burst level, packet-data transmissions in a GPRS-like system. The event-driven simulator models the RLC/MAC (Radio Link Control/Medium Access Control) and physical layers and has been implemented in C++ using the CNCL-Communication Networks Class Library developed by ComNets at Aachen University of Technology.

The simulator implements two types of cellular networks, one considering omnidirectional macrocells and the second one modelling equally sized 3-sector macrocells. The study, concentrating on the downlink performance, has considered a load of eight users per sector, with each user operating for the complete duration of the simulation. Users are assigned channels in a first-come-first-served basis and the channel is kept until all its data has been correctly transmitted. In this study, only single slot transmissions have been considered. Users can move at a speed of 50km/h within each sector, but no handover between sectors has been considered. As a result, mobile stations are connected to the closest base station and not to the best serving base station. Three different traffic sources have been modelled: real-time H.263 video, email and WWW browsing. No channel partition has been applied between the different services. The H.263 video traffic model considered employs three different frame types, namely I, P and PB, and targets a bit rate of 16 kbit/s.

The effects at the physical layer have been included by means of an advanced link-to-system level interface working at the burst level and capable of including the effect of fast fading at the system level. The GPRS standard defines four different coding schemes, CS1 to CS4, that have been designed to provide different resilience to propagation errors under unfavourable radio conditions. As a result, these different transport modes offer a trade-off between data rate and coding protection, paving the way for the application of Link Adaptation (LA) to GPRS. LA is an adaptive radio link technique that selects its transport mode based on the experienced channel quality conditions. This work implements a LA algorithm that selects the coding scheme maximizing the throughput. Table 1 summarises the main simulation parameters with a full description of the simulator provided in [12].

Parameter	Value
Cluster size	4
Cell radius	1km
Sectorisation (if aplicable)	120º
Modelled interference	1st and 2nd co-channel interfering tiers
Channels per sector	16
Users per sector	8
Traffic type	H.263 video: 2 users/sector WWW: 3 users/sector Email: 3 users/sector
Pathloss model	Okumura-Hata
Shadowing	Log-normal distribution. 6dB standard deviation and a 20m decorrelation distance
Fast Fading	Included through Look-Up Tables
ARQ protocol	Only for WWW and email users. Ack/Nack reports sent each 16 RLC blocks
LA updating period	100ms

Table 1. Simulation settings

IV- SYSTEM LEVEL PERFORMANCE

This section compares the performance of the proposed game-theoretic FCA channel assignment scheme against that obtained used the random mechanism and the minBLER proposal [8]. The minBLER algorithm assigns an incoming call the available channel that experienced the lower Block Error Rate (BLER) during previous transmissions. The performance of the three channel assignment schemes is compared within omnidirectional and sectorised cellular networks. This comparison is highly relevant to define the optimum configuration of the proposed channel assignment scheme under different operating conditions. For example, while the number of first tiers co-channel interfering cells is equal to six in an omnidirectional environment, this value is reduced to two in 3-sectorised cellular networks. This difference can be very relevant to define the number and distance of co-channel interfering BSs that need to exchange channel occupancy information, and therefore to evaluate the implementation cost of the proposed solution. Also, another key difference between both deployment options is the fact that in a sectorised scenario, a sector receives interference from a set of co-channel sectors but produces interference to a different set of co-channel sectors. As a result, how the channel allocation process weights the interference received and produced could result in significant performance differences and has to be thoroughly investigated.

A. Sectorised cellular network

Figure 2 compares the system throughput performance of the proposed channel assignment scheme, according to the 'myopic strategy' described in Section II, against that achieved with the random and minBLER mechanisms. While the A2T (Approximated 2 Tiers) option estimates the interference produced by the first and second tiers of co-channel interfering cells, the A1T (Approximated 1 Tiers) mechanism only considers the first tiers. The E2T (Exact 2 Tiers) algorithm also considers the first and second tiers of co-channel interfering cells but instead of just estimating the interference it exactly calculates it, which assumes that the transmitting power and the position of mobile stations is perfectly known at each BS. The plotted A2T, A1T and E2T schemes consider a weight w equal to 0.5, while the A2T selfish proposal considers a weight w equal to 1. Figure 2 shows that all different configurations of the proposed scheme improve the system performance compared the random and minBLER algorithms. The A2T configuration provides the highest system throughput which proves that for sectorised cellular networks the proposed scheme needs to consider the channel occupancy in co-channel cells of the first and second tiers. Since the A2T and E2T options achieve nearly identical system performance, the obtained results also suggest that, under the considered operating conditions, estimating the interference not only reduces the implementation cost but is also enough to guarantee the highest performance levels. Contrary to the indications provided in [10] for DCA schemes, Figure 2 clearly shows that considering the interference received and produced in a new channel assignment improves the system performance compared to only considering the interference received (selfish behaviour).

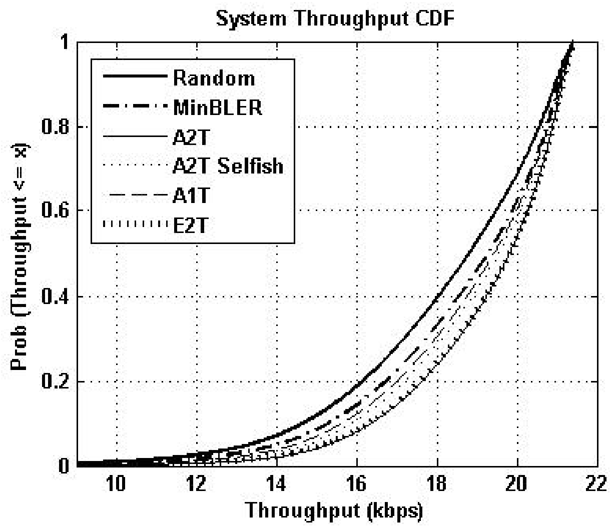

Figure 2. System throughput cumulative distribution function (cdf) for a sectorised cellular network

Table 2 compares the performance of the evaluated channel assignment schemes for different relevant system parameters. First of all, it is important to highlight that the proposed channel assignment scheme not only improves the mean performance (throughput and normalized delay) but also the most restrictive QoS parameter, i.e. the minimum performance guaranteed for 95% of the samples. This observation is highly relevant since it indicates that the proposed game-theoretic channel assignment scheme increases the system fairness by improving the performance of the more poorly served users. The improved performance is due to the lower experienced BLER as a result of inducing co-channel cells to avoid using simultaneously the same channels. The resulting better experienced channel quality conditions promotes the use of the less robust coding scheme (CS4) and reduces the use of the most robust coding schemes (CS1); using the least robust coding schemes enables to transmit a higher user payload per RLC block. The combined higher use of CS4 and lower experienced BLER conditions result in the previously described higher system throughput of our proposed schemes. The proposed scheme induces a higher mode error for the more robust CS; the mode error represents the percentage of time that a given coding scheme was being used and it was not the optimal one. However, the more robust coding schemes are so marginally used that their mode error is not relevant to the system performance. On the other hand, the proposed channel assignment scheme reduces the mode error of the more highly used coding scheme (CS4).

Parameter	Random	A2T, w=0.5	A1T, w=0.5	E2T, w=0.5	A2T Selfish
Mean throughput (kbps)	18,23	19,2	18,93	19,19	18,81
Minimum throughput guaranteed for 95% of the samples (kbps)	13,33	15,3	14,76	15,22	14,44
Mean normalized delay (ms/kbit)	61,65	58,66	59,47	58,66	59,84
Max normalized delay guaranteed for 95% of the samples (ms/kbit)	90,17	81,46	82,78	81,7	83,76
Mean BLER (%)	6,45	4,52	5,02	4,54	5,29
Maximum BLER guaranteed for 95% of the samples (%)	15,34	10,98	12,02	11,09	12,81
Mean number of CS changes per sec	2,25	1,83	1,96	1,82	2,03
Proportion of RLC blocks transmitted with the optimal CS (%)	72,20	79,19	76,96	78,75	76,19
Usage percentage of CS1 (%)	2,09	0,53	0,81	0,56	1,06
Usage percentage of CS2 (%)	3,51	1,51	2,01	1,56	2,29
Usage percentage of CS3 (%)	24,85	19,06	21,11	19,14	21,67
Usage percentage of CS4 (%)	69,55	78,90	76,07	78,75	74,98
Mode error of CS1 (%)	48,26	54,58	52,97	54,41	53,02
Mode error of CS2 (%)	83,87	84,47	84,19	84,40	84,58
Mode error of CS3 (%)	77,91	81,03	79,93	80,87	79,59
Mode error of CS4 (%)	6,46	4,82	5,31	4,82	5,42

Table 2. System performance comparison for sectorised networks

Table 2 also highlights that the proposed channel assignment scheme improves the operation and performance of adaptive radio link techniques such as LA. In fact, the proposed scheme increases the percentage of RLC blocks transmitted with the optimal coding scheme, according to the experienced channel quality conditions, and therefore reduces the mean number of coding scheme changes per second request by LA. Such reduction results in a lower signalling load associated with the use of LA.

Table 3 compares, for each traffic type, the A2T throughput performance (weight equal to 0.5) against that obtained using the random or minBLER mechanisms. The most important observation is that real-time H.263 video transmissions are the service that mostly beneficiates from the A2T proposal. This is highly relevant if we consider that this service, which does not employ ARQ protocols to guarantee the correct transmission of information, is the one imposing the most restrictive QoS constraints. In the implemented real-time video transmission model, a video frame is discarded if it is not completely transmitted by the time the next video frame is generated; in this case, the user maintains the same channel to transmit the new video frame. To increase the system capacity, a channel is released whenever a video frame is transmitted before the next one is generated. Since the implemented simulator only considered single slot transmissions, a considerable number of video frames had to be discarded and the user maintained the same channel for a longer period of time compared to more bursty services such as web or email transmissions. In this case, a non-optimal channel assignment results in a prolonged poorer performance, which explains why the real-time H.263 video service shows the most noticeable improvements with the proposed channel assignment scheme. Such improvements are particularly important when observing final user-perceived QoS parameters such as the percentage of video frames transmitted without delay (i.e. that their transmission is finished before the next video frame is generated) and the percentage of video frames transmitted without delay and with a BLER below 5% (see Table 4). According to [13], a BLER below 5% would not produce a noticeable video degradation for H.263 transmissions.

Throughput		Random	MinBLER		A2T, w=0.5		
		Perf. (kbps)	Perf. (kbps)	Impr. Random (%)	Perf. (kbps)	Impr. Random (%)	Impr. MinBLER (%)
System	Mean	18,23	18,64	2,19	19,2	5,05	2,91
	95%	13,33	14,02	4,92	15,3	12,87	8,36
WWW	Mean	18,57	18,89	1,69	19,39	4,22	2,57
	95%	13,78	14,34	3,9	15,43	10,69	7,06
Email	Mean	18.60	18,82	1,18	19,37	4,14	2,92
	95%	13.85	14,15	2,17	15,39	11,12	8,76
H263	Mean	17,53	18,2	3,68	18,84	6,95	3,39
	95%	12,37	13,59	8,97	15,08	17,97	9,88

Table 3. Throughput performance per services

Parameter	Random	A2T, w=0.5	A1T, w=0.5	E2T, w=0.5	A2T Selfish
% of H.263 video frames transmitted without delay	72.86	77.31	76.22	77.16	76.18
% of H.263 video frames without delay and BLER <= 5%	51.38	58.98	56.74	58.82	56.98

Table 4. H.263 video quality

Figure 3 shows that the highest A2T system performance is obtained when the interference received and produced is equally considered during the channel allocation process (weight equal to 0.5). Only considering the interference received or produced can significantly decrease the system performance in sectorised cellular deployments. This is the case because if all users act selfishly (the same pattern would be observed if the users only act ‘altruistly’) and only take into account the received interference, they don’t consider their impact on other users. Consequently users that will request a channel in the future will also not consider the damage that a new channel assignment can produce in previous channel allocation decisions. As a result, this behaviour prevents from obtaining an optimal result from the system level perspective.

While the same conclusions have been obtained for best-effort services (web and email), the achieved results suggest that real-time H.263 video transmissions would benefit from a slightly selfish behaviour during the channel assignment process. Such behaviour results from the increased sensitivity of this type of services to transmission errors, and from the fact that with the considered implementation, real-time H.263 video transmissions resulted in longer periods of time using the same channel[1]. In this case, a non-optimal channel selection could significantly reduce the performance, whereas selecting slightly selfishly the channel could improve the performance compared to very bursty data services. The obtained results seem then to suggest that varying the weight parameter according to the transmitting service might be a good system design approach.

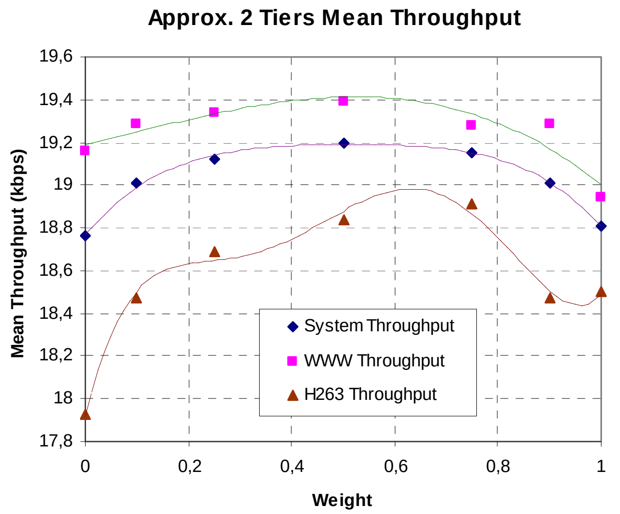

Figure 3. Effect of the weight parameter on the mean throughput performance

B. *Omnidirectional cellular network*

Figure 4 compares, for an omnidirectional cellular deployment, the system throughput performance of the proposed channel assignment scheme, considering the 'myopic

[1] In a sense, the implemented real-time video model emulates circuit-switched voice communications where channels are maintained during the complete call.

strategy' defined in Section II, against that achieved with the random and minBLER mechanisms. As previously explained, the weight parameter has not an influence on the system performance for omnidirectional cellular networks and the same results are obtained for the selfish scheme and the one setting the weight to 0.5. Figure 4 also proves that the proposed schemes considerably improve the system performance. The main difference with the sectorised environment lies on whether to consider just the first tiers of co-channel cells or the first and second tiers. The results shown in Figure 4 clearly indicate that in the case of an omnidirectional cellular network considering the two first tiers of co-channel cells not only increases the implementation cost of the proposed schemes (the information of 18 BSs needs to be exchanged to perform a channel assignment compared to just 6 if only the first tiers of co-channel cells is considered) but also slightly degrades the system performance. In this case, the highest performance is achieved when only considering the first tiers of co-channel cells, which highlights their dominant effect. It can also be observed from Figure 4 that when only considering the first tiers of co-channel cells in the proposed schemes, the algorithm that exactly computes the interference levels (E1T) outperforms the one estimating them (A1T). However, the difference obtained between both algorithms does not seem enough to justify the higher implementation cost of E1T compared to A1T.

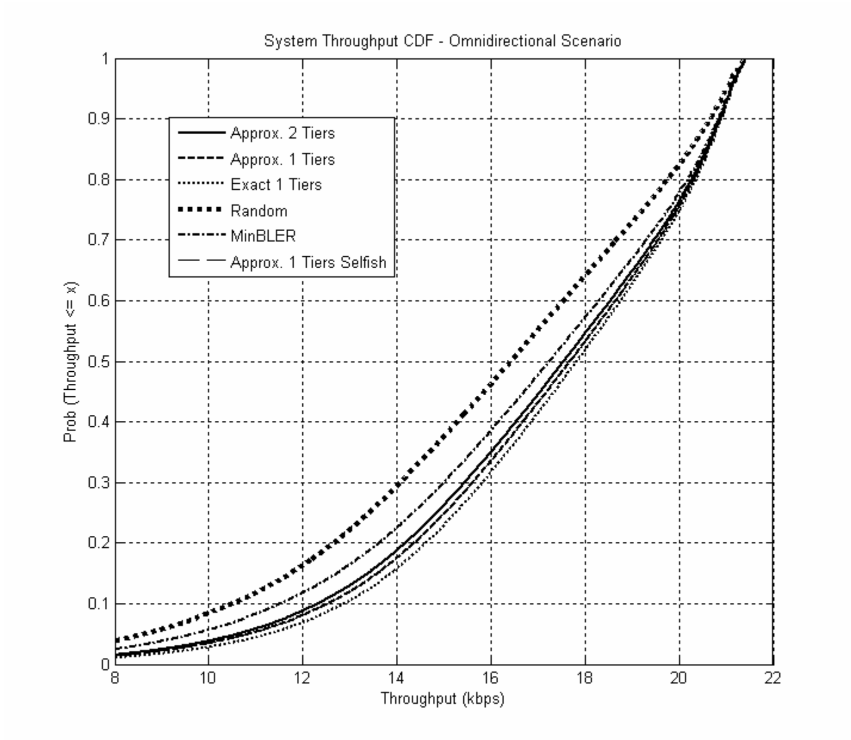

Figure 4. System throughput cdf for an omnidirectional cellular network

Table 5 compares the system performance of the evaluated channel assignment schemes. Apart from the observations extracted from Figure 4, very similar conclusions to those reported from Table 2 can be reached in omnidirectional cellular deployments.

Parameter	Random	minBLER	A1T	E1T	A2T
Mean throughput (kbps)	15,94	16,64	17,11	17,27	
Minimum throughput guaranteed for 95% of the samples (kbps)	8,63	9,66	10,82	11,26	
Mean normalized delay (ms/kbit)	70,75	68,05	66,04	65,26	
Max normalized delay guaranteed for 95% of the samples (ms/kbit)	119,79	114,55	105,93	100,85	
Mean BLER (%)	11,65	9,86	8,71	8,28	
Maximum BLER guaranteed for 95% of the samples (%)	31,71	26,74	22,26	20,71	
Mean number of CS changes per sec	2,75	2,61	2,54	2,51	
Proportion of RLC blocks transmitted with the optimal CS (%)	61,89	64,70	66,26	66,69	
Usage percentage of CS1 (%)	9,55	6,69	4,89	4,25	
Usage percentage of CS2 (%)	8,77	7,20	6,16	5,85	
Usage percentage of CS3 (%)	31,37	30,20	29,47	29,45	
Usage percentage of CS4 (%)	50,32	55,91	59,48	60,45	
Mode error of CS1 (%)	37,86	40,00	42,87	44,21	
Mode error of CS2 (%)	82,00	82,19	82,58	82,67	
Mode error of CS3 (%)	72,84	73,79	74,68	74,82	
Mode error of CS4 (%)	8,86	7,91	7,64	7,55	

Table 5. System performance comparison for sectorised networks

C. *Channel occupancy*

Random channel assignment schemes are characterised by a long-term uniform use of all physical channels. This property avoids surcharging particular channels and radio equipments. Figure 5 plots the average channel occupancy for all channels per cell and the complete simulation time, considering the random and the proposed channel assignment scheme that achieved the highest performance in the case of omnidirectional and sectorized cellular networks. The obtained results show that the proposed mechanisms exhibit the same long-term uniform use of all channels, and therefore RF equipment, as the random allocation scheme. Their improved performance is then not due to the long-term channel use pattern but to the short-term one.

The first plot of Figure 6 shows, for a 300 seconds observation period, the channel occupancy in a given cell (central) and its first tiers co-channel interfering and interfered cells for the A2T scheme and in just the central cell for the random assignment mechanism. This sub-plot clearly shows that, while the random mechanism maintains its uniform use of all channels, the A2T scheme promotes the fact that the central cell and its interfering or interfered cells avoid using the same channels simultaneously. As a result, the proposed scheme guarantees lower instantaneous interference levels, compared to the random allocation mechanism, that result in higher system performance. The second sub-plot of Figure 6 shows that as we increase the observation time, the proposed scheme tends to exhibit a uniform use of all channels (Figure 5 corresponds to the long-term limit of the second sub-plot in Figure 6).

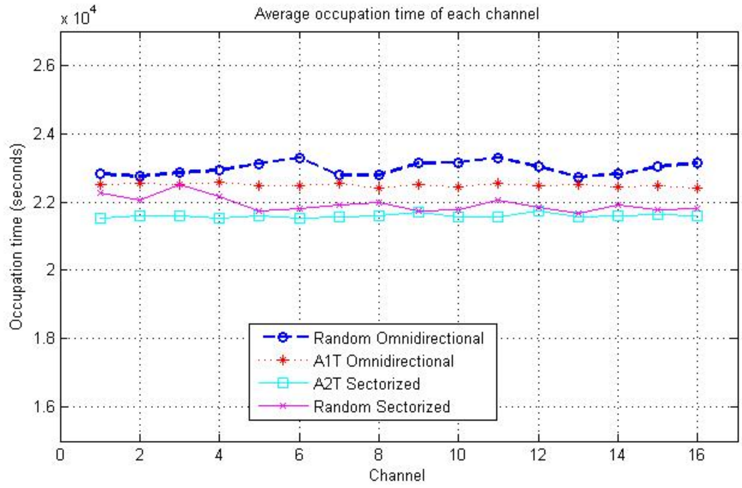

Figure 5. Average channel occupancy over the whole simulation time

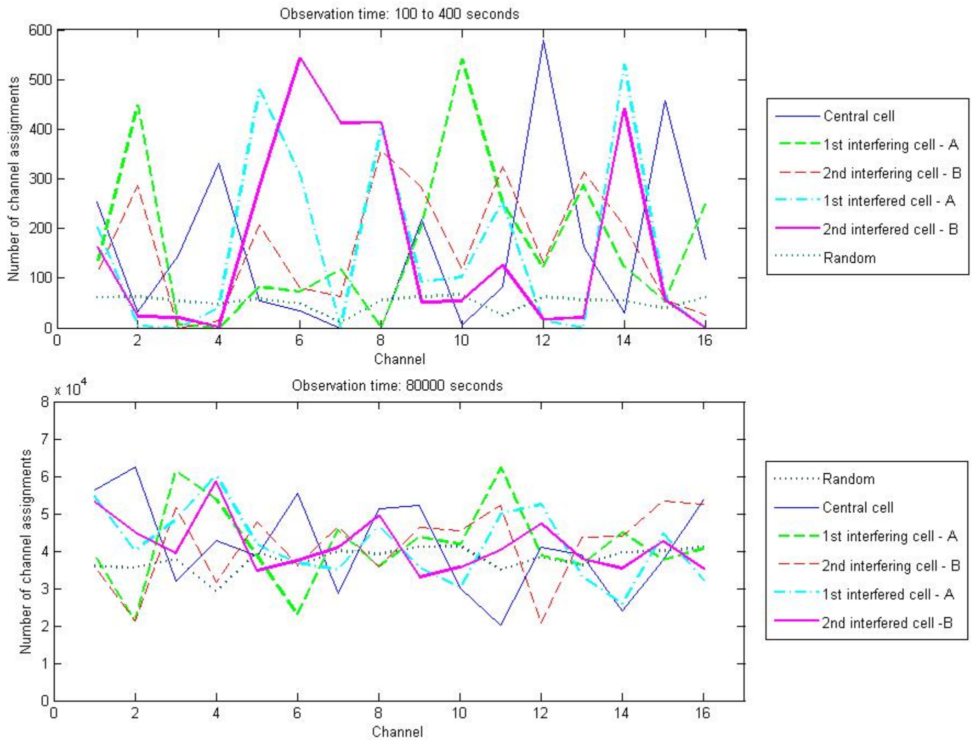

Figure 6. Instantaneous and mid-term channel occupancy for the A2T and random schemes (sectorised environment)

V- CONCLUSIONS

This paper has proposed and evaluated a game-theoretic channel assignment scheme for FCA networks that bases its allocation decision on the instantaneous received and produced interference levels. The obtained results demonstrate that the proposed scheme improves the system performance compared to the commonly used random allocation mechanism while also exhibiting a long-term uniform use of all RF channels. The results have shown that computing the interference rather than just estimating does not produce significant improvements whereas it significantly increases the implementation cost. The conducted study has also highlighted the need to modify the algorithm's configuration based on the cellular deployment scenario and the type of service that has requested the channel allocation.

The proposed channel assignment scheme requires neighbouring BSs to exchange channel occupancy information. The research conducted has shown that only a reduced set of BSs need to exchange this information, significantly reducing the implementation cost. The implementation of the proposed scheme is also highly realistic since the BSC is the network entity in charge of making the channel allocation decisions and that a single BSC controls various neighbouring BSs.

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