Improving the Capacity in Wireless Networks Through Integrated Channel Base Station and Power Assignment

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Abstract

The limited availability of radio frequency spectrum will require the future wireless systems to use more efficient and sophisticated resource allocation methods to increase network capacity. In this work we propose a Joint Resource Allocation Algorithm (JRAA) that makes the channel base station and power assignment in a wireless network with arbitrary number of base stations and mobiles attempting to minimize the number of channels needed to provide each user in the system an acceptable radio connection. We compare the performance of the JRAA for both the forward (downstream) and reverse (upstream) directions, in terms of the achievable traffic capacity, with some bounds on the performance of the maximum packing, clique packing and reuse partitioning techniques, that are usually used as benchmarks on the capacity that can be achieved by any traffic-adaptive dynamic channel assignment strategy where the quality is guaranteed by the reuse distance. Those performance results verify the improvement that can be achieved by the integration of the channel base station and power assignment. Finally several versions of the two-way channel assignment problem are studied and evaluated.

1 Introduction

With the current trend towards digital systems, that are flexible and have increased processing capability in mobiles and base stations, sophisticated resource allocation methods are an attractive way to improve network capacity and performance. The goal of an efficient resource allocation method is to guarantee the quality of service of the ongoing connections, while at the same time the available radio spectrum is used efficiently. The radio connection comprises three dimensions: the allocated channel (channel assignment procedure), the allocated power (power assignment procedure) and the allocated location (base station assignment procedure).

In the existing analog system the frequency channels of each cell are fixed and preallocated off-line during the frequency planning phase. A call can be served only if the cell where it arises has a free channel, otherwise it is lost. In the digital system of the near future, there will be increased flexibility in radio network control. All the channels will be potentially available to all base stations, to be allocated in a dynamic fashion. Usually many users share a common channel and one user's transmission causes interference to the others. As a result transmitted powers should be controlled both to provide each user an acceptable connection and to limit the interference seen by the other users sharing the same channel. Moreover the potential flexibility on the way that mobiles are assigned to base stations to communicate with, is another factor that helps towards the alleviation of frequency congestion.

The problem of joint channel base station and power assignment is illustrated in figure 1. Clearly the three problems are interrelated. For certain channel allocations and base station assignments there may be power vectors that satisfy the interference constraints while for others may be not. Therefore these problems need to be considered jointly. In this paper we provide an algorithm that makes the joint resource allocation in a wireless network (in the following we refer to that algorithm as JRAA). Specifically for every available channel in the system the algorithm tries to allocate as many mobiles as possible, according to some rule, making simultaneously the base station assignment and the power selection.

The channel assignment problem in cellular networks (when the powers and base stations are preassigned and fixed) has been shown to be equivalent to a generalized graph coloring problem [10, 22], which is known to be NP-hard. If we have only cochannel interference then the graph is obtained by representing each cell by a vertex with an edge connecting

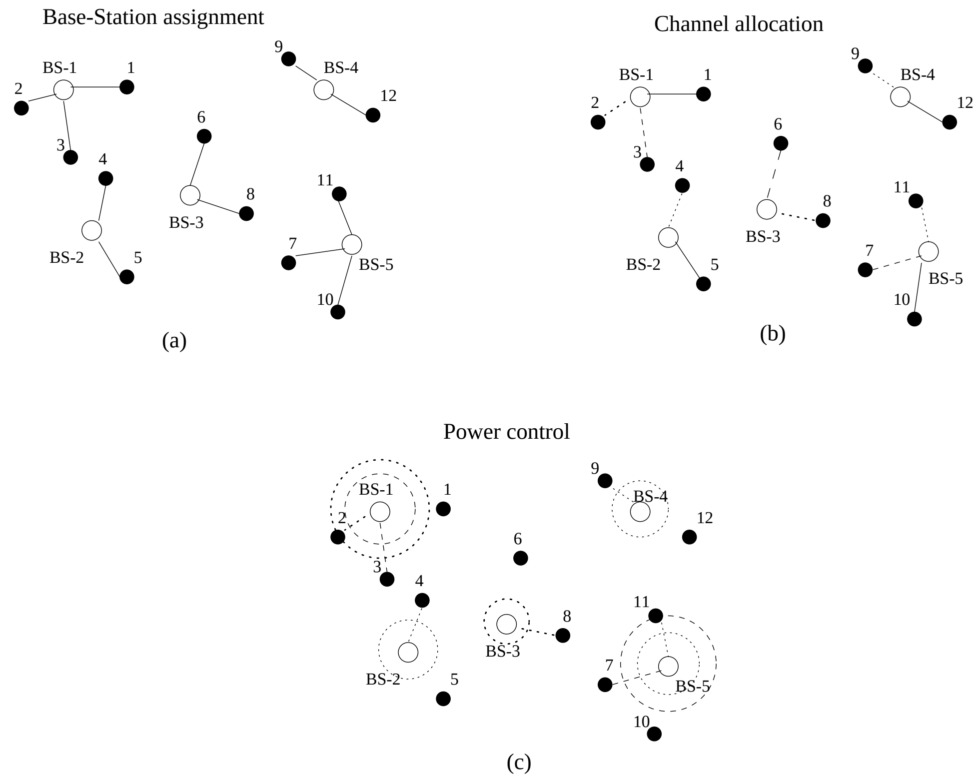

Figure 1: (a) A base station is selected by each mobile for its forward and its reverse links. The two base stations need not be the same. (b) A channel is selected by each link. The cochannel links are represented by the same type of line. (c) The transmission powers of the cochannel links should be selected such that the interference constraints at each mobile are satisfied.

two vertices if the involved cells are forbidden from using common channels. The problem is to assign channels (or colors) to the vertices of this graph such that adjacent vertices are assigned disjoint sets of color. The assignment should use as few channels (colors) as possible. Since no efficient algorithm that solves this problem exists, many heuristic channel assignment algorithms with varying complexities have been suggested and evaluated in the literature. In fixed channel assignment strategy [4, 6, 13] a set of nominal channels is permanently allocated to each cell and an arriving call can only be served by the nominally allocated channels. In dynamic channel assignment [3, 7, 22, 26] all the channels are kept in a central pool, and any channel can be used by any user and base station. However a channel in one cell can only be reassigned simultaneously to another cell in the system if the separation distance between the two cells is greater than a prespecified minimum distance to avoid cochannel interference. Moreover, different channel borrowing strategies and hybrid channel assignment methods which try to combine the advantages of the fixed and dynamic channel assignment have been proposed and simulated [12, 22].

In [25] the optimum transmitter power control problem for the case of preassigned base stations and considering only one channel is studied. A power control scheme that is optimum in the sense that it maximizes the number of simultaneous connections in the system is discussed. The algorithm removes combinations of cells and computes the eigenvalues of each reduced system until the (C/I) requirement is fulfilled. Such a submatrix problem is computationally hard and at the present it is not known if an algorithm exists to solve the problem in polynomial time. The above procedure was found to be impractical, since the computational complexity of the optimum procedure proposed is exponentially increasing with the size of the cochannel set. However the satisfiability problem is solvable [25]. That is, for a given set of cochannel links, whether there exist feasible power vector that guarantees (C/I) ratios at all mobiles above a prespecified threshold. If not then the previous step by step removal algorithm needs to be applied. It has been shown that the largest achievable (C/I) level in such systems is reached by balancing the (C/I)s of all users. Similar results of applying power balancing to both the forward and reverse links of a spread spectrum cellular mobile radio system have been reported in [15]. Zander [24] and Grandhi,Vijayan & Goodman [8] proposed synchronous distributed power control algorithms that converge to the optimal solutions with varying convergence rates. Foschini & Miljanic [5] presented a distributed power control algorithm that avoids some of the difficulties that may occur in the afore mentioned distributed algorithms due to the absolute power settings problem, by the inclusion of the receiver noise in the definition of the interference. In [14] Mitra extended Foschini's synchronous algorithm in allowing asynchrony between the various mobiles and base stations reducing the need for coordination. All those distributed power control schemes that follow the (C/I) balancing approach have the nice property of fast, geometric convergence if a feasible power vector exists, satisfying the (C/I) requirements of all users. However if no such power vector exists, they produce fluctuations of the powers, diverging to infinity. Moreover during the updating the (C/I)s of operational links may drop below their lower thresholds rendering the links unreliable and "killing" on-going transmissions. In [1] a distributed power control algorithm that protects the operational links and prevents the dropping of on-going calls at the expense of some reduction in the system capacity and slower convergence, is presented.

In [23] and [11] the combined problem of regulating transmitter powers and assigning users to base stations, assuming that all users share one channel, is considered. Specifically Hanly [11] proposed a spread spectrum cellular system in which cells are allowed to expand and contract enabling a user to transmit to the optimal base station based on current interference levels and on the user's particular location with respect to the cell sites. In [23] an algorithm that represents an implementation of Hanly's concept of expanding and contracting cells and always finds a power vector and base station assignment that provides acceptable connections for all users, as long as such a feasible solution exists, is provided. When a feasible solution does not exist, the primary issue becomes how to maximize the number of acceptable connections and in that case the algorithm does not provide good results since it is possible even for all users to end up with unacceptable (C/I)s. In [2] several algorithms for joint power control and channel assignment with varying complexities, assuming that the assignment of users to base stations is fixed or prespecified by outside means, are proposed and compared.

In [18, 19] the joint otimal resource allocation problem has been defined and formulated, and an algorithm that solves it for two base stations and arbitrary number of mobiles has been proposed. The algorithm identifies all the possible pairs of mobiles that can share a channel and therefore the problem is reduced to the solution of a maximum matching on the appropriate compatibility graph. In the general case of arbitrary number of base stations the same steps could be followed but instead of identifying pairs of mobiles that can share a channel we should identify all the possible subsets of mobiles that can make use of the same channel. Then we have to select those subsets that correspond to the use of the minimum number of channels in the system, as well as to assign base stations and select powers. As the number of base stations and mobiles increases such a procedure becomes intractable. Therefore some heuristic algorithms that approximate the optimal assignment should be devised as they could provide useful bounds on the performance of the system.

In this work we propose a heuristic algorithm (JRAA) that makes the channel, base station and power assignment in a wireless network with arbitrary number of base stations and mobiles, trying to minimize the number of channels needed to accommodate all the calls. The only quality of service criterion used here, in regard with the acceptance or rejection of a new incoming call, is to satisfy the carrier to interference ratio requirements at all the active mobiles and base stations in the system, by maintaining the possible co-channel interference at acceptable level. By minimizing the number of channels in use at the current state, the system is better prepared to accept new incoming calls in the future and therefore adapts itself better to the new traffic requirements. We compare the performance results of the algorithm we propose with the corresponding results of different traffic-adaptive channel allocation strategies, based on the techniques of maximum packing, clique packing [21] and reuse partitioning [17]. The performance evaluation of the different resource allocation strategies is done in terms of the achievable traffic capacities appropriately defined. Let $C_N^f(C_N^r)$ be the minimum number of channels needed to establish a forward (reverse) connection to N mobiles, randomly and uniformly distributed. The traffic capacity T_N^f in the forward direction is defined as

$$T_N^f = \frac{N}{E[C_N^f]}, \tag{1}$$

and similarly for the reverse direction. We obtain the traffic capacities in the forward and reverse directions, under the application of JRAA algorithm, by simulation for both the cases of fixed powers and controllable powers and we study the effect of power control on the system capacity. Moreover we observe a considerable improvement on the traffic capacity that is achieved by our algorithm over what can be achieved by many different fixed and dynamic channel assignment strategies, due to the joint consideration of the channel, base station and power assignment problem. The problem of two-way channel assignment is also studied and similar results are obtained. It should be noted that the JRAA is a centralized algorithm and therefore the amount of data that would have to be managed by the central controller would be enormous, especially in a large network. The JRAA mainly aims to quantify the limits on the gains that can be achieved through joint channel base station and power assignment. Future research efforts should be devoted to developing other heuristic algorithms that could be operated in a more distributed fashion and therefore could be more easily implemented in real time.

The paper is organized as follows. In section 2 we provide the model as well as the main assumptions that we are going to use in our simulations. In subsection 3.1 we describe the joint resource allocation algorithm (JRAA) we propose. Subsection 3.2 contains the power assignment procedure that we use in our algorithm, in subsection 3.3 we discuss the complexity of the proposed algorithm, while in subsection 3.4 we describe how the resource allocation algorithm can be applied in the different versions of the two-way channel assignment problem. In section 4 we compare the performance of the JRAA with the performance of different traffic-adaptive dynamic channel assignment strategies. Specifically in subsection 4.1 we provide some bounds on the performance of the Maximum Packing (MP), Clique Packing (CP) and Reuse Partitioning (RP) techniques, that are used in the literature as traditional benchmarks on the traffic capacity achieved by any traffic-adaptive dynamic channel assignment strategy in cellular networks, where the quality is guaranteed by the reuse distance. In subsection 4.2 we present some simulation results that indicate the improvement on traffic capacity achieved by the joint channel base station and power assignment.

2 System Model

The formulation of the resource allocation problem is similar to the one described in detail in [18], but for the sake of completeness we present it briefly here, too. There are M base stations and N mobiles at arbitrary locations with respect to the base stations. The path loss coefficients G_{ij} between any base station i and mobile j are provided. They characterize completely the propagation properties of the system in the sense that when i transmits power P_i, j receives power $G_{ij}P_i$. Throughout our simulations we assume that the signal strength decreases inversely proportional to d_{ij}^4, where by d_{ij} we denote the distance between transmitter i and receiver j. Moreover we prohibit the reuse of the same channel at the same base station. The channels may be either frequency bands in a FDMA system or carrier and a time slot in a TDMA system or different codes in a CDMA system. We denote by P_{il}^f the transmitted power from base station i in forward channel l. Similarly P_{jl}^r denotes the transmitted power from mobile j in the reverse channel l. Cochannel interference is the prevailing interference type; this is equal to $\sum_{k\neq i} G_{kj}P_{kl}^f$ in mobile j receiving from base station i at channel l. The carrier to interference ratio $(C/I)_{jl}^f$ at mobile j in channel l is equal to

$$(C/I)_{jl}^f = \frac{G_{ij}P_{il}^f}{\sum_{k\neq i} G_{kj}P_{kl}^f}. \tag{2}$$

The interference constraint at mobile j that receives on channel l is satisfied if

$$(C/I)_{jl}^f \geq T, \tag{3}$$

where T is a threshold imposed by physical layer's constraints. Similarly the carrier to interference ratio $(C/I)^r_{il}$ at base station i in channel l is equal to

$$(C/I)^r_{il} = \frac{G_{ij}P^r_{jl}}{\sum_{n\neq j} G_{in}P^r_{nl}}. \quad (4)$$

The reverse radio link from mobile j to base station i at channel l satisfies the interference constraints if

$$(C/I)^r_{il} \geq T. \quad (5)$$

In this paper we consider a snapshot during the dynamic operation of the system. The same problem should be solved continuously as the system state and parameters change with the evolution of the system (call arrivals, departures, mobility, hand-offs, fading etc.). The static problem considered here may be related to the dynamic situation as follows: consider these resource allocation algorithms that permit reassignment of all calls at every change in the configuration of users. The solution of the static problem gives the "best" assignment at each step. Certainly such algorithms yield higher capacity than algorithms that do not reassign existing users or do limited reassignments. The study of the static problem aims to quantify the limits of the gains achievable through joint power control, channel and base station assignment.

3 Joint Resource Allocation Algorithm (JRAA)

In the following we describe an algorithm (JRAA) for the joint channel, base station and power assignment in a general network with N mobiles and M base stations, trying to minimize the number of channels needed to accommodate all the calls. The main idea of the algorithm is the following: for every available channel in the system allocate as many mobiles as possible making simultaneously the base station assignment and the power selection, if the latter is allowed (when the powers are controllable parameters). First we consider the case of unidirectional channels, that is each channel can be used in only one direction (either as forward or as reverse channel) and we describe the application of the resource allocation algorithm in one direction (forward or reverse). Later on we will consider several versions of the two-way channel assignment problem including the possibility of using bidirectional channels.

3.1 Description of the Algorithm

Before proceeding with the presentation of the various steps of the algorithm we describe in detail the major parameters and the heuristic rules that are involved in the JRAA implementation.

Each mobile is usually associated with its closest base station but the algorithm gives the flexibility to a mobile to get connected to another neighboring base station instead, if this is preferable. Such a flexibility on the choice of base stations helps the base stations with many mobiles close to them to get uncongested by assigning some mobiles to neighboring base stations with lower traffic density in their coverage area. This is achieved by keeping a list of base station preference, L_j, for every mobile j, for the channel under consideration, that dictates the order of the base stations that a mobile should get associated with. Actually L_j is an ordered list where the ordering is on the path gain between mobile j and each one of the available base stations for the channel under consideration. With such an ordering, initially the first element in the list of mobile j is the base station i_j for which $G_{i_j j}$ is the maximum among all $G_{kj},\ k \in \{1, \ldots, M\}$, that is, the base station closest to mobile j.

At each step of the algorithm for every unassigned mobile j we construct a trade-off t_j for connecting mobile j with the "nearest" available (first element in list L_j) base station (call it i_j). In this trade-off we take into consideration a measure of the interference caused to the receiver of this tentative connection by the other transmitters already using the same channel, as well as a measure of the interference that this candidate connection (mobile j with base station i_j) would cause to the other already active links. Therefore we consider:

$$t_j = \frac{G_{i_j j}}{F_j},$$

where

$$F_j = \max\left\{ \sum_{k \in B^l} G_{kj}, \sum_{u \in A^l} G_{i_j u} \right\},$$

where by B^l we denote the set of base stations already transmitting on channel l and A^l denotes the set of mobiles already using channel l. Among all the unassigned mobiles we want to choose as the next candidate connection that one which will cause the smallest interference in the system. That connection is indicated by the maximum among all the available t_j's.

Then we check if the new configuration, old active links plus the new proposed connection, satisfies the threshold constraints. If we assume that all base stations and mobiles use the same transmission powers, equal to P, then the check can be based on relations (2) and (3) for every mobile j receiving on forward channel l and on relations (4) and (5) for every base station receiving on reverse channel l. If power control is allowed then we find those powers, if there exist, that satisfy the threshold constraints based on some results described in [25], which will be discussed in detail in next subsection. If the constraints are satisfied then we accept the proposed connection and try to find the next candidate connection that possibly can make use of the same channel, repeating the same procedure. If not, then we reject the proposed connection and try to find another possible candidate connection among the remaining unassigned mobiles. In the latter case we can either repeat this procedure until no candidate mobile that could probably be assigned to this channel exists or limit the repetition of the afore mentioned procedure to a prespecified number (max_repeat). At this point by limiting the number of candidate mobiles for assignment on a channel we decrease the running time of the algorithm, without affecting substantially the capacity of the system since if the addition of the first candidate mobile in the system violates the threshold constraints then, in accordance to the way that the candidate connections are chosen, it is unlikely that there exists another possible connection to be accommodated on that channel.

Then we choose a new free channel and repeat the above procedure for the remaining unassigned mobiles, until all of them are accommodated. In the following we outline the main steps of the algorithm:

step1 Find the first available free channel l.

step2 For each unassigned mobile j create its preference list L_j.

step3 For each unassigned location j construct the trade-off t_j.

step4 Find the maximum among all the trade-offs t_j's. The connection indicated by this maximum (mobile j, base station i_j) is the next candidate connection.

step5 Check if the new configuration (old active links and the new proposed connection) satisfies the threshold constraints.

- If all constraints are satisfied mark location j as "assigned" and delete base station i_j from the preference lists of all the remaining unassigned mobiles. Go to step3.

If power control is allowed then specify the powers that satisfy the constraints of all the mobiles assigned to channel l, according to the method described in the following section.

• If some constraint is violated then reject that candidate connection and go to step4. Repeat this procedure either until you exhaust all the possible candidate connections or until you check the first *max_repeat* candidates.

step6 Choose a new free channel and repeat from step2 until all the mobiles are assigned.

Note that in the end of the algorithm's operation all mobiles are assigned. The performance criterion is how many channels have been used by this assignment.

3.2 Power Assignment Procedure

In this subsection we describe how the power assignment is done when the power is a controllable parameter. In the context of the algorithm described in section 3.1 the power assignment procedure is invoked every time that we have a set of mobiles associated with base stations and we want to find if there exist transmitted powers such that all those links can be active simultaneously. If this is possible we want to find a transmission power vector, denoted by $\mathbf{P}$, such that in a given channel the (C/I) ratios at all receivers using that channel are larger than a prespecified threshold T. The power assignment scheme is described here for the forward link and is based on some results presented in more detail in [25]. For the reverse link a similar procedure can be followed.

In the following we consider a configuration of q mobiles, already associated with base stations. For simplicity (without loss of generality) we assume that the q mobiles are numbered from 1 to q, while we number the base stations such that mobile i is associated with base station i. Note that at every step of the algorithm every mobile j, $1 \leq j \leq q$, is associated with a base station i_j, $1 \leq i_j \leq M$, where $i_j \neq i_k$ for $j \neq k$ and therefore the above assumption is always valid.

First we define the link gain matrix $\mathbf{G} = \{G_{ij}\}$. At some given instant with q mobiles $\mathbf{G}$ will be a qxq square matrix. Now rewriting relation (3) for $j = 1, \ldots, q$ in a matrix form we get,

$$\frac{1+T}{T}\mathbf{P} \geq \mathbf{ZP}, \tag{6}$$

where

$$\mathbf{Z} = \{Z_{ij}\} \quad and \quad Z_{ij} = \frac{G_{ij}}{G_{ii}}. \tag{7}$$

A carrier to interference ratio γ is defined to be achievable in the cochannel set of the q mobiles if there exists a power vector $\mathbf{P}$ such that $(C/I)^{f}_{jl} \geq \gamma$ for all mobiles j using this channel. An important result, [25], is that the largest achievable (C/I) ratio γ^* is related to the spectral properties of matrix $\mathbf{Z}$ as

$$\gamma^* = \frac{1}{\lambda^* - 1}, \tag{8}$$

where λ^* is the largest real eigenvalue of matrix $\mathbf{Z}$. The power vector $\mathbf{P}^*$ achieving this maximum was found to be the eigenvector of $\mathbf{Z}$ corresponding to the eigenvalue λ^*.

Therefore the problem of checking if there exist transmitted powers such that the mobiles under consideration can use the same channel satisfying the threshold constraints is reduced to finding the largest eigenvalue λ^* of the corresponding $\mathbf{Z}$ matrix. The complexity of such a procedure applied to a configuration with q mobiles associated with the corresponding base stations is $O(q^3)$ [20]. Then we can calculate the maximum achievable γ^* according to relation (8). If $\gamma^* \geq T$ then the powers of the q mobiles trying to use the same channel are assigned according to $\mathbf{P}^*$. If $\gamma^* < T$ then there is not positive power vector such that the q mobiles belonging to the cochannel set of channel l can use the same channel.

3.3 Complexity

For large networks with large number of base stations M the most time consuming and complex part of the algorithm is the one that checks if, after the selection of the next candidate connection, the new configuration satisfies the threshold constraints in the system (step 5 of the algorithm) and does the power assignment to the base stations and mobile that are active on the channel under consideration. By taking into consideration the power control procedure that involves the identification of the largest eigenvalue of the matrix Z (defined in the previous subsection) and the corresponding eigenvector, the complexity of the algorithm turns out to be of the order $O(NM^3)$. In extreme cases where we may have a small number of base stations and a large number of mobiles and/or a very non-uniform distribution of traffic to the different base stations the most time consuming part of the algorithm will be the one of identifying the measures t_js and the next candidate connection (steps 3 and 4 of the algorithm) and the complexity of the algorithm may turn out to be in worst case of the order $O(N^2M)$.

3.4 Two-Way Channel Assignment Procedure

There are several versions of the two-way channel assignment problem depending on the constraints we pose. All the analog cellular systems, that are based on FDMA, employ Frequency Division Duplexing (FDD) and therefore they use different bands for the establishment of the forward and reverse connections. Hence in those systems a channel is prespecified as forward or reverse and it can be used only in one direction. Similarly all the existing digital cellular systems (i.e. GSM in Europe, IS-54 and IS-95 in North America, PDC in Japan), independently of the multiple access method that they use (FDMA/TDMA/CDMA), they employ the FDD and therefore they use unidirectional channels, too [16]. This is mainly due to the fact that most of the existing digital cellular systems operate in the frequency bands originally allocated for analog systems and in order to allow smooth transition from the analog systems to the digital ones, the FDD technique is employed for the digital cellular systems.

This is certainly not a physical constraint since in principal the same channel can be used in both directions simultaneously in sufficiently spatially separated locations. In the future digital systems this constraint can be eliminated, that is the same channel may be used for a forward connection by some mobiles and for a reverse connection by some others. By allowing a channel to be used in both directions (bidirectional channels) rather arbitrary frequency bands can be allocated (frequency - duplexed systems need symmetric pairs of bands separated by several MHz) and the system is more flexible to adjust to traffic asymmetries that may occur. In telephony the traffic requirements are usually symmetrical in both directions of communication, while in data communications a high level of asymmetry may occur in the traffic generated in the forward and reverse connections (i.e. during data base retrieval, file transfer). The flexibility of using a channel for a forward or reverse connection on demand results in a dynamic allocation of the available radio frequency spectrum to the forward and reverse connections, therefore allowing the systems to adapt themselves to various traffic situations. Most of the digital cordless systems used today (CT2 Common Air Interface, DECT, PHS) employ the Time Division Duplexing (TDD) [16, 9], thus simplifying frequency planning.

Moreover another constraint, usually imposed, that affects the system capacity is that a mobile should communicate with the same base station in both directions. If we ignore the practical constraints imposed in specific systems, each mobile may use any channel and base station for each one of the reverse and forward connections.

In the following we are going to describe how the afore mentioned resource allocation algorithm can be applied in the different versions of the two-way channel assignment problem. Initially we assume that each channel can be used in one direction only (either as forward or as reverse channel) and that each mobile may use any base station for the forward and reverse connection. Then the two-way channel assignment problem is reduced to the solution of the forward and reverse channel assignment problems separately and therefore the total number of channels needed to accommodate all the mobiles in the system is equal to the sum of the forward and reverse channels.

If we impose the constraint that each mobile should communicate with the same base station in both directions then the same algorithm can be applied but each time we consider a pair of channel, one forward channel l_1 and one reverse channel l_2. A new candidate connection is accepted if the new configuration (old active links and the new proposed connection) satisfy the threshold constraints in both directions. Then mobile j communicates with base station i_j on l_1 in forward direction and on channel l_2 in reverse direction.

In the following lets consider the case where a channel can be used in both directions and each mobile may use different base stations for the forward and reverse connection. In this case for every physical mobile we consider two virtual mobiles, one for the forward link and one for the reverse link. Therefore in a system with N physical mobiles we consider $2N$ different virtual mobiles. The modifications in the algorithm proposed in subsection 3.1 are the following. For every unassigned virtual mobile j we construct the trade-off t_j for making the connection of virtual mobile j with the "nearest" available base station i_j. These trade-offs are different for the two different virtual mobiles that correspond to the same physical mobile. In those trade-offs we take into consideration a measure of the interference caused to the receiver of the candidate connection by the other transmitters on this channel (those transmitters can be both base stations and mobiles), as well as a measure of the interference caused by the transmitter of the new candidate connection to the other receivers already receiving on this channel. For a virtual mobile j that corresponds to a forward connection we have:

$$t_j = \frac{G_{i_j j}}{F_j},$$

where

$$F_j = \max\left\{ \sum_{k \in B_f^l} G_{kj} + \sum_{v \in A_r^l} H_{vj}, \sum_{u \in A_f^l} G_{i_j u} + \sum_{k \in B_r^l} R_{k i_j} \right\},$$

where $H_{ij}(R_{ij})$ denotes the path loss coefficients between any two mobiles(base stations) i and j, B_f^l denotes the set of base stations already using channel l in the forward direction, A_r^l denotes the set of mobiles already using the channel l in the reverse direction, A_f^l denotes the set of mobiles already using the channel l in the forward direction and B_r^l denotes the set of base stations already using channel l in reverse direction.

Similarly for a virtual mobile j that corresponds to a reverse connection we have:

$$t_j = \frac{G_{i_j j}}{F_j},$$

where

$$F_j = \max\left\{ \sum_{k \in B_r^l} G_{kj} + \sum_{v \in A_f^l} H_{vj}, \sum_{u \in A_r^l} G_{i_j u} + \sum_{k \in B_f^l} R_{k i_j} \right\}.$$

After the new candidate connection is selected we check if the new configuration, old active links plus the new proposed connection, satisfies the threshold constraints at all the receivers. In the case of fixed powers the check can be based on the corresponding expressions that give the (C/I) ratios at the mobiles and the base stations, when we consider bidirectional links. In the case of power control the power assignment procedure described in section 3.2 can also be applied here. In fact, at any given instant of q virtual mobiles we have q transmitters (these transmitters could be both mobiles and base stations) associated with q receivers and we want to find a power vector $\mathbf{P}$ for the q transmitters that satisfy the (C/I) ratios at all the receivers. Following the same steps as in section 3.2 we conclude that the power vector (if there exist such a vector) which satisfies all the (C/I) ratios at the receivers should be such that

$$\frac{1+T}{T}\mathbf{P} \geq \mathbf{YP}, \tag{9}$$

where $\mathbf{Y} = \{Y_{ij}\}$ and Y_{ij} is the path loss coefficient between transmitter i and receiver j normalized by the path loss coefficient between transmitter i and receiver i. The same results presented in section 3.2 hold here, too, and therefore the problem is reduced again to finding the largest eigenvalue of matrix $\mathbf{Y}$.

4 Performance Evaluation

In this section we compare the performance of JRAA, in terms of traffic capacity, with the corresponding performance of a conventional cellular system with fixed channel assignment (FCA), where all the channels are allocated following the same reuse pattern, as well as with the performance of traffic-adaptive dynamic channel assignment algorithms, that adapt the channels to the number of active users in each cell in the system. We obtain the traffic capacities in the forward and reverse directions, under the application of JRAA algorithm, by simulation for both the cases of fixed powers and controllable powers and we study the effect of power control on the system capacity. Moreover we observe a considerable improvement on the traffic capacity that is achieved by our algorithm over what can be achieved by many different fixed and dynamic channel assignment strategies, due to the joint consideration of the channel, base station and power assignment problem. The problem of two-way channel assignment is also studied and similar results are obtained.

In subsection 4.1 we discuss some bounds on the performance of the Maximum Packing (MP) and Clique Packing (CP) techniques, that are used in the literature as traditional benchmarks on the minimum number of channels required to carry all calls, given the number of calls of all cells in a conventional cellular system with fixed powers, under any traffic-adaptive dynamic channel assignment scheme, where the quality is guaranteed by the reuse distance. We also combine the MP and CP strategies with the reuse partitioning concept in order to achieve better performance bounds. In subsection 4.2 we compare by simulation JRAA with different traffic-adaptive dynamic channel assignment schemes.

4.1 Maximum Packing, Clique Packing and Reuse Partitioning

4.1.1 Maximum Packing (MP)

We consider that the whole coverage area in the system is divided into M cells, where a cell c_i defines the area covered by the corresponding base station i, $i = 1, \ldots, M$. Therefore we can assume a cellular cover $\mathcal{C} = (c_1, c_2, \ldots, c_M)$. The occupancy of the system is described by a vector $\mathbf{s} = (s_1, s_2, \ldots, s_M)$, where s_i is the number of active calls in cell c_i. Assume that in order to satisfy the constraint (3) for all mobiles in the system we must use a reuse factor at least equal to N_1. Maximum Packing (MP) is the method that accepts every call to which a channel can be assigned without violating the reuse constraints, regardless of the number of reassignments involved [21]. A particular occupancy vector $\mathbf{s}$ is said to be admissible under maximum packing if and only if there is an allocation of s_i channels to cell c_i, $i = 1, 2, \ldots, M$, which respects the reuse constraints. Denote by $\mathcal{S}_{\mathcal{MP}}$ the set of admissible vectors.

A set of cells that all interfere with each others is called a clique. Denote by D the set of all cliques in the network $\mathcal{C}$. Obviously for calls generated in cells that belong to the same clique we must assign distinct channels. Lets denote by $L_{MP}(\mathbf{s})$ the minimum number of channels needed to satisfy all the reuse constraints for a given occupancy vector $\mathbf{s}$ under the maximum packing policy. Then $L_{MP}(\mathbf{s})$ satisfies the following

$$L_{MP}(\mathbf{s}) \geq \max_{d \in D} \left\{ \sum_{c_i \in d} s_i \right\}. \tag{10}$$

In a linear network with a reuse factor equal to N_1 a channel can be used simultaneously by two cells if they are separated by k-cells such that $N_1 = k + 1$ (k-cell separation rule). For a linear network it is known that $\max_{d \in D}\{\sum_{c_i \in d} s_i\} = \max_{c_i \in \mathcal{C}, i+k \leq M}\{s_i + \ldots + s_{i+k}\}$ and $L_{MP}(\mathbf{s}) = \max_{c_i \in \mathcal{C}, i+k \leq M}\{s_i + \ldots + s_{i+k}\}$.

4.1.2 Clique Packing (CP)

Consider again the cellular network $\mathcal{C}$ and assume that there are L available channels in the system. Define: $\mathcal{S}_{\mathcal{CP}} = \{\mathbf{s} : \forall d \in D, \sum_{c_i \in d} s_i \leq L\}$. In general $\mathcal{S}_{\mathcal{MP}} \subseteq \mathcal{S}_{\mathcal{CP}}$. The clique packing strategy (CP) accepts a new call in cell c_j if and only if the network state $\mathbf{s} \in \mathcal{S}_{\mathcal{CP}}$ at the time of arrival is such that $\mathbf{s} + \mathbf{e}_j \in \mathcal{S}_{\mathcal{CP}}$, where $\mathbf{e}_j$ denotes the unit coordinate vector of length M containing a "1" at the jth position and 0's elsewhere [21]. For a given occupancy vector $\mathbf{s}$ the minimum necessary number of channels under the CP strategy is given by the expression on the right hand side of relation (10). In linear networks every state achieved by clique packing is also achieved by maximum packing [21]. That is, for linear networks : $\mathcal{S}_{\mathcal{CP}} = \mathcal{S}_{\mathcal{MP}}$. But in general CP violates the reuse constraints and therefore has no practical application. However if the probability of states $\mathcal{S}_{\mathcal{CP}} - \mathcal{S}_{\mathcal{MP}}$ is sufficiently small it can serve as an approximation to MP.

4.1.3 Reuse Partitioning and Maximum Packing (RPMP)

In this section we combine the concepts of maximum packing and reuse partitionong in order to provide a more efficient spectrum reuse in cellular systems.

In the following we assume that we use R different reuse factors, denoted by $N_i,\ i = 1, \ldots, R$. Then a cellular cover is denoted by $\mathcal{C}^{\mathcal{R}} = (c_1^1, \ldots, c_1^R, \ldots, c_M^1, \ldots, c_M^R)$, where by c_i^j we denote the zone-j of cell c_i, $i = 1, \ldots, M$ and $j = 1, \ldots, R$. The occupancy vector of the system is described by a vector $\mathbf{s} = (s_1^1, \ldots, s_1^R, \ldots, s_M^1, \ldots, s_M^R)$, where by s_i^j we denote the number of active calls in zone-j of cell c_i. A particular vector $\mathbf{s}$ is said to be admissible if and only if there is an allocation of s_i^j channels to zone-j of cell c_i, $j = 1, \ldots, R$ and $i = 1. \ldots, M$, which respects the reuse constraints in all zones. We denote by $\mathcal{S}^{\mathcal{R}}_{\mathcal{RPMP}}$ the set of all admissible vectors in network $\mathcal{C}^{\mathcal{R}}$ under the maximum packing policy. Let also denote by D^R the set of all cliques in the network $\mathcal{C}^{\mathcal{R}}$. Obviously for calls generated in zones (subcells) belonging to the same clique we must assign distinct channels. Lets denote by $L_{RPMP}(\mathbf{s})$ the minimum number of channels needed to satisfy all the reuse constraints for a given occupancy vector $\mathbf{s}$ under the maximum packing policy in a network with R different reuse factors. Then $L_{RPMP}(\mathbf{s})$ satisfies the following: $L_{RPMP}(\mathbf{s}) \geq \max_{d \in D^R} \left\{ \sum_{c_i^j \in d} s_i^j \right\}$.

4.1.4 Reuse Partitioning and Clique Packing (RPCP)

In this section we apply the clique packing strategy in a reuse partitioned system with R zones. Consider again the cellular network $\mathcal{C}^{\mathcal{R}}$ and assume that there are L available channels in the system. Define: $\mathcal{S}^{\mathcal{R}}_{\mathcal{RPCP}} = \{\mathbf{s} : \forall d \in D^R, \sum_{c_i^j \in d} s_i^j \leq L\}$. In general $\mathcal{S}^{\mathcal{R}}_{\mathcal{RPMP}} \subseteq \mathcal{S}^{\mathcal{R}}_{\mathcal{RPCP}}$. The RPCP strategy accepts a new call in subcell c_j^i if and only if the network state $\mathbf{s} \in \mathcal{S}^{\mathcal{R}}_{\mathcal{RPCP}}$ at the time of arrival is such that $\mathbf{s} + \mathbf{e}_{(j-1)R+i} \in \mathcal{S}^{\mathcal{R}}_{\mathcal{RPCP}}$, where $\mathbf{e}_j$ denotes the unit coordinate vector of length (M*R) containing a "1" at the jth position and 0's elsewhere. In general RPCP violates the reuse constraints. However if the probability of states $\mathcal{S}^{\mathcal{R}}_{\mathcal{RPCP}} - \mathcal{S}^{\mathcal{R}}_{\mathcal{RPMP}}$ is sufficiently small it can serve as an approximation to RPMP.

4.2 Numerical Results

We are going to apply these allocation strategies on a linear system with a (C/I) threshold of 18 db and two different reuse factors of 1 and 2, as well as on a planar system with a

(C/I) threshold of 18 db and two reuse factors of 1 and 7. In the linear system the base stations are uniformly placed on the line and the distance between two successive base stations is assumed to be equal to one unit, while for the planar system we consider 49 base stations placed in such positions that the whole structure resembles a 7 by 7 cellular lay out. We approximate the performance of MP and RPMP by the CP and RPCP strategies respectively, since they give, in general, an upper bound of the traffic capacities that can be achieved by MP and RPMP, as we explained in the previous subsections.

In figure 2 we present the capacities (number of mobiles per channel) of the forward and reverse channels, versus the number of mobiles that are randomly and uniformly distributed on a linear system with 12 base stations. For the FCA, CP and RPCP strategies the forward

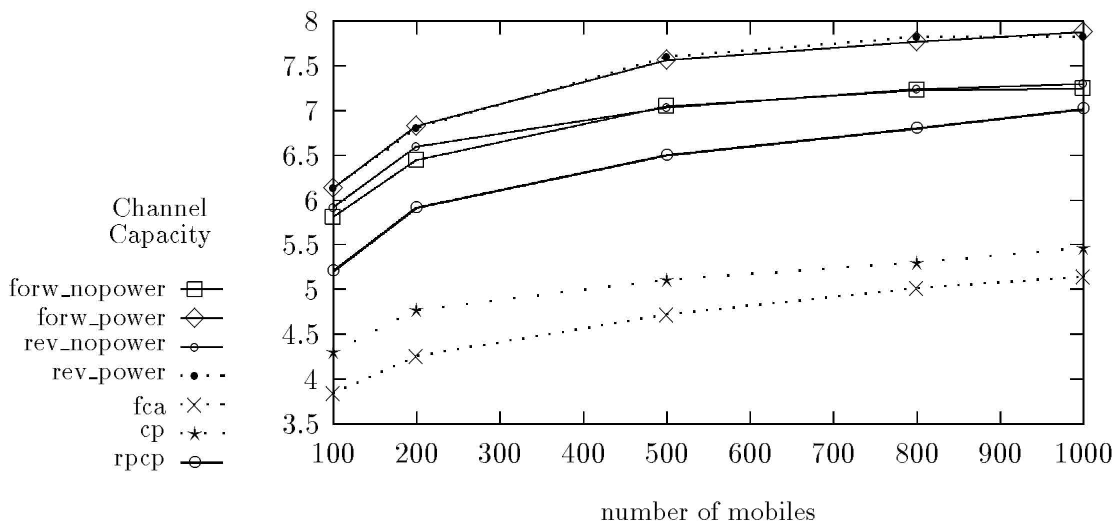

Figure 2: One way channel assignment for a linear system with 12 base stations, $(C/I) \geq 18db$ and reuse factors $N_1 = 1$ and $N_2 = 2$.

and reverse channel assignment are exactly equivalent and therefore they are represented by the same lines in the graph. However for the JRAA we simulated separately the forward and reverse channel assignment for both the cases of power control and non power control. As we see from figure 2, in any case, the forward and reverse channel capacities are very close to each other. This does not mean that the forward and reverse channel assignments are necessarily the same, but it means that on the average we need about the same number of channels for the forward and reverse connections in the system.

As we see from figure 2 CP strategy behaves much better than FCA resulting to higher channel capacities. This was expected since CP is a dynamic channel assignment scheme that accepts every call to which a channel can be assigned without violating the reuse constraints, regardless of the number of reassignments involved. Moreover we confirm the large improvements on the channel capacity that can be achieved by the use of the reuse partitioning concept. The increase on the channel capacity achieved by RPCP over the one that corresponds to the CP strategy is about 30%. The JRAA outperforms all these strategies resulting, for the case of fixed powers, in an increase on the channel capacity of about 10% over the maximum channel capacity that may be achieved by the RPCP strategy. Furthermore the expected number of channels when the powers are controllable parameters is lower than the corresponding value for the case of fixed powers resulting to an extra increase of 5-10% on the corresponding channel capacity. Similar qualitative results can be observed in figure 3 where we plot the capacities of the forward and reverse channels versus the number of mobiles that are randomly and uniformly distributed on a planar system with 49 base stations. In this case the traffic that corresponds to the inner

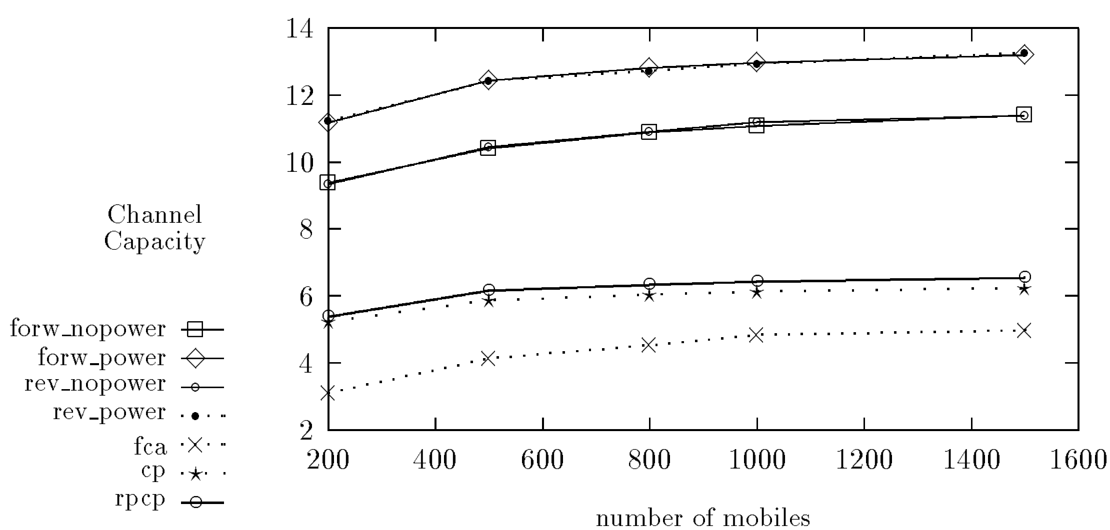

Figure 3: One way channel assignment for a planar system with 49 base stations, $(C/I) \geq 18db$ and reuse factors $N_1 = 1$ and $N_2 = 7$.

zone of the cell, and therefore the assignment of those mobiles is done according to reuse factor of 1, represents only a small portion of the total traffic (actually only 5% of the total traffic (as calculated in [17]). This explains the fact that the improvement on the channel capacity achieved by RPCP over that achieved by CP is only 5%. In [17] we have seen that by choosing different reuse factors we may achieve higher traffic capacities. However as we see from figure 3 the JRAA improves the channel capacity by 100% over the one that can be achieved by RPCP with reuse factors of 1 and 7.

The way that JRAA works resembles, in some sense, the reuse partitioning concept. By assigning each time to the channel under consideration the unassigned mobile with the maximum t_j, which is a function of the received desired signal as well as of the interference from the other transmitters to the candidate receiver and to the other receivers by the candidate transmitter, we result to an allocation such that: the mobiles close to the base stations are assigned a channel which is reused very densely, while the mobiles that are far from the base stations use channels that are reused more sparsely. This allocation is very similar to the one achieved by strategies based on the reuse partitioning concept (i.e. RPCP). However the JRAA outperforms the RPCP because the JRAA gives the flexibility to a mobile to get connected to another neighboring base station instead of getting associated with the closest base station. Therefore we allow base stations with many mobiles close to them to get uncongested by assigning some of the mobiles to neighboring base stations with lower traffic density around them. The feature of "base station selection" combined with the power control feature which is an integral part of the JRAA further improves the performance of the system especially in the cases of nonuniform traffic patterns. Next we apply the JRAA on a linear system with 25 base stations and (C/I) threshold of 14 db in order to gain some insight on how the "base station selection" feature combined with the "power control" feature of the JRAA results in a decrease on the necessary number of channels. We consider N mobiles distributed as follows: $N/5$ mobiles are randomly and uniformly distributed within a unit length around each one of the base stations 3,8,13,18,23. In the following table we present the number of forward channels under the RPCP strategy (denoted by L_{RPCP}) and under the JRAA (denoted by L_{JRAA}), as well as the number of mobiles N_d that are not associated with the closest base station during the operation of the JRAA. The following results are averages over 10 experiment repetitions.

N	L_{RPCP}	L_{JRAA}	N_d
100	20	16.9	24.7
200	40	33.4	48.5
400	80	64.6	103.2
800	160	124.9	215.5

In the following graph 4 we present the channel capacity for several versions of the two-way channel assignment mentioned in subsection 3.4, versus the number of mobiles distributed randomly in a linear system with 12 base stations. The corresponding graph for a planar system with 49 base stations is depicted in figure 5.

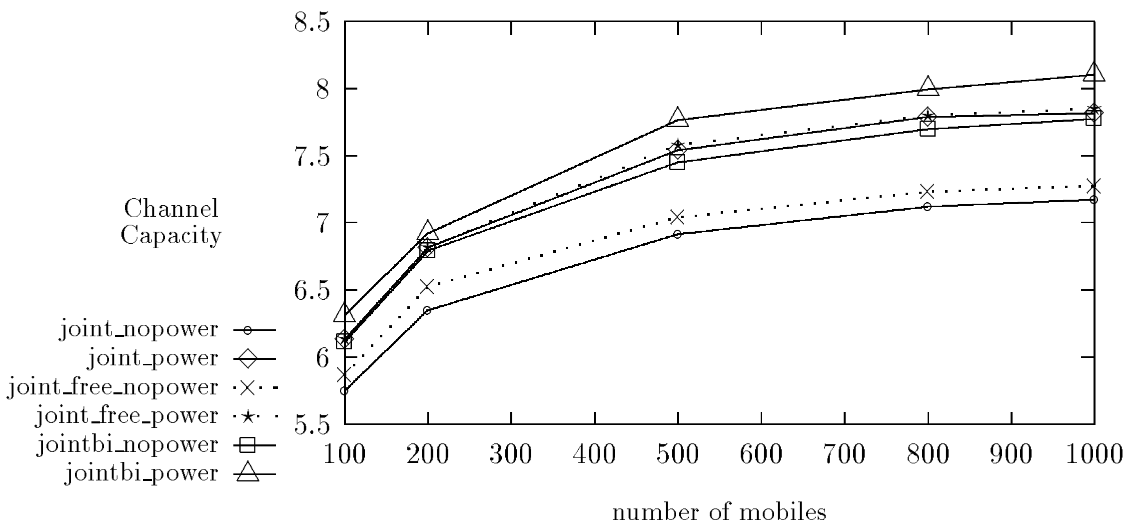

Figure 4: Linear system with 12 base stations, $(C/I) \geq 18db$ and reuse factors $N_1 = 1$ and $N_2 = 2$.

The lowest curve in the graph (labeled by joint_nopower) corresponds to the case that each channel can be used in one only direction and a mobile must use the same base station for the forward and reverse connections under the assumption of fixed powers, while the curve labeled by joint_power represents the corresponding case when the powers are controllable parameters. The curves labeled by joint_free_nopower and joint_free_power reflect the channel capacities for the non power and power control cases respectively, under the assumption that each mobile uses any base station for its reverse and forward connection. The remaining two curves, denoted by jointbi_nopower and jointbi_power, correspond to the

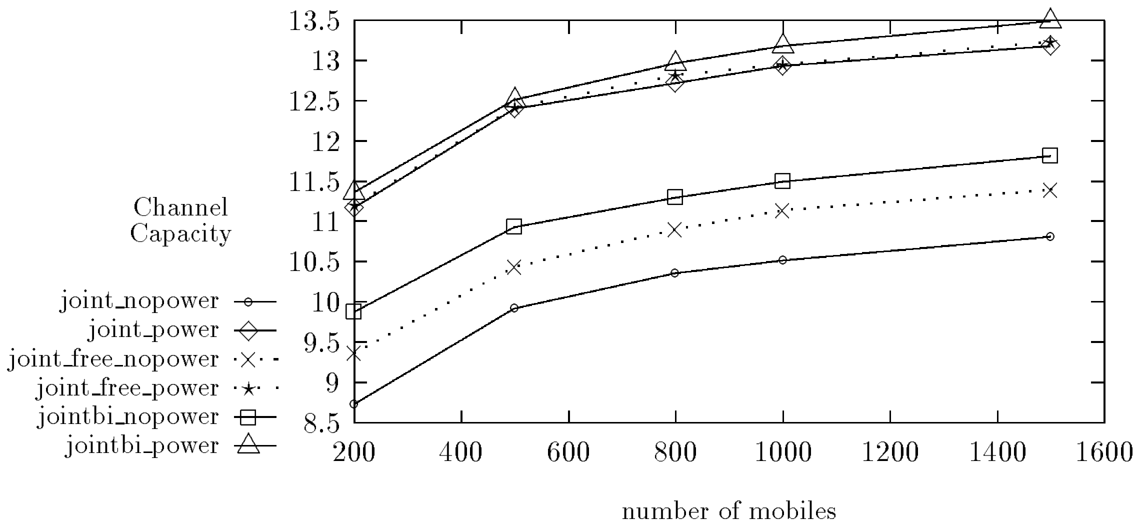

Figure 5: Planar system with 49 base stations, $(C/I) \geq 18db$ and reuse factors $N_1 = 1$ and $N_2 = 7$.

cases that we use bidirectional channels. The differences on the performance of the systems represented in the latter graph are due to the different constraints that we have posed in each of these systems. From figure 4(5) we confirm that the power control increases the channel capacity by 10%(20%) when we use unidirectional links and by 5%(15%) if we consider bidirectional links. Moreover the use of bidirectional links, by itself, results in an extra increase of up to 10% on the channel capacity compared to the one that can be achieved by using unidirectional links.

5 Discussion

The problem of joint channel base station and power assignment in a wireless network with arbitrary number of mobiles and base stations has been considered here. In general, the optimal resource allocation in such a network is a hard optimization problem. A procedure similar to the one described in [18] that achieves the optimal assignment for a system with two base stations, in the sense that minimizes the number of channels needed to establish communication for all mobiles, becomes intractable as the number of mobiles and base stations increases.

In this paper we have proposed a joint resource allocation algorithm (JRAA) that makes the channel base station and power assignment in a general wireless network. The algorithm allocates as many mobiles as possible to every available channel in the system, according to some heuristic rules, making simultaneously the base station assignment and the power selection. The traffic capacities for the forward and reverse channel, as well as for the several versions of the two-way channel assignment have been obtained through simulation. The corresponding numerical results for the performance of the JRAA indicate that with the integration of channel base station and power assignment, significant improvements on the traffic capacity are obtained, over what can be achieved by dynamic channel allocation strategies.

The JRAA considers every time the static problem and depends on the full knowledge of the gain (loss) in all propagation paths, both intended base-mobile paths and unwanted, interference paths. Estimating these gain would require a significant measurement effort and the amount of data that would have to be managed by the central controller would be enormous in a large network. Therefore the JRAA mainly aims to quantify the limits on the gains that can be achieved through joint power control and channel and base station assignment. Further studies should be devoted to developing algorithms that use only limited path gain information and could be operated in a distributed fashion based on information that can be derived from local measurements in every base station.

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