Wireless Networks 5 (1999) 429–443

Reconfiguration of carrier assignment in cellular networks

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We consider the problem of updating nominal carrier assignments in cellular networks, which dymamically operate with channel borrowing and reassignments, to match the time-varying offered traffic demands encountered on these systems. Assuming an existing assignment of nominal carriers and the new requirements in each cell, we formulate the problem of obtaining a new assignment such that the number of carriers required to meet the total traffic demand as well as the number of different assignments between the old and the new allocation are minimized. We introduce two approaches to obtain this new assignment. One approach treats the two objectives independently and is applicable to problems with cochannel interference constraints only. This approach produces a new assignment optimized with respect to the first goal, and then rearranges the frequencies of this new allocation so that the number of different assignments with respect to the previous allocation is minimum. A second approach aims at satisfying both goals at the same time and is applicable to problems with any type of interference constraints. The main advantage of this approach is the introduction of a single window parameter which can control the assignments produced, by favoring one goal at the expense of the other. We study several transition scenarios in macrocellular and microcellular environments, and show that in the majority of cases these objectives are conflicting, and that reconfiguration strongly depends on the amount of change of the traffic requirements.

1. Introduction

In the next few years, wireless communication is expected to evolve as the most common medium of access to information services. The issue of augmenting cellular networks capacity has gathered a great deal of attention and among the most promising ways are new layered cell architectures, improved multiple access techniques, and efficient carrier allocation strategies [4,10]. Channel[1] allocation has been extensively studied in the literature and many schemes have been proposed and evaluated [23]. First and second generation cellular networks employ *fixed channel allocation* (FCA) according to which a set of channels is permanently assigned to each cell of the system, based on estimations about the long-term averages of the expected traffic load in every cell. The trend towards better spectrum exploitation favors the adoption of more sophisticated schemes such as *dynamic channel allocation* (DCA).

Pure DCA [5,7,25] assumes that the whole set of carriers belongs to a common pool and the allocations are performed on a call-by-call basis according to criteria that measure frequency reuse, frequency usage and future call blocking probability. While pure DCA under light loads provides better service quality than FCA in terms of blocking probability and handover failure, the choice of the best among the candidate carriers is not always successful, especially at overload conditions [14,25].

The use of several variations of *directed* DCA [1,2,6,8, 13,17], which generally rely on an ordered assignment of *nominal* carriers to cells, has been suggested to overcome this situation. During dynamic operation, the search for a channel to serve a call in a cell is first performed among the ordered nominal channels of that cell. Channel borrowing from neighboring cells can then be applied to serve excess traffic in some cells, as well as intracellular handovers that transfer on-going calls from borrowed carriers to freed nominal carriers. The majority of schemes assumes a uniform nominal assignment and the test environments also assume uniformly distributed traffic. However, in real networks traffic is anything but uniform, and it has been established by [26] that the unpleasant effect of borrowing, that is the locking of carriers in interfering cells, whose throughput is in turn degraded, can be alleviated by allocating the nominal carriers according to the real traffic distribution of the system.

At the presence of such time-varying conditions, reconfiguration, in other words dynamic nominal channels allocation update, is necessary to maintain the system in optimum condition. Similarly to this consideration, in the *hybrid channel assignment* scheme [15], the ratio of the fixed to dynamic channels requires adjustment according to the traffic intensity in each cell. Also, in the *flexible channel assignment* scheme [22], a set of common flexible channels are held for future use, in addition to the permanently assigned channels of each cell. These flexible channels can be distributed to (withdrawn from) cells that present an increase (decrease) in their offered traffic conditions according to a predictive or scheduled policy.

In this paper, we consider the problem of reconfiguring the network of cells to obtain a new assignment of nominal carriers. The procedure for acquiring an actual assignment of carriers aims at meeting the requirements of all cells with the minimum possible number of frequencies. In the general case of non-uniform traffic, the number of channel requirements in each cell are computed according to the arrival rates of new calls and handovers and the expected

[1] Although in systems employing some form of multiple access technique channels and carriers are distinguished concepts, in this paper instead of carrier we will alternatively use the terms channel and frequency to denote the same concept.

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grade of service for each type of calls. For example, the algorithms proposed in [18] are appropriate for producing the input to assignment schemes that generate the new allocations of carriers whenever the arrival rates of both types of calls vary with time. Assuming an existing allocation, and the new traffic requirements of each cell, our objective is to find a new frequency assignment such that (a) the minimum possible number of carriers are used for the new load, and (b) the number of different frequency assignments is minimum, in other words every cell is receiving as many carriers also possessed in the previous assignment as possible.

We present two approaches for determining the new assignment. One approach initially applies a heuristic aiming at the optimization of the first goal for the new traffic requirements independently of the existing nominal assignments. Then this new assignment is mapped to another assignment with equal number of carriers that has minimum number of different assignments, compared to the old assignment. This mapping problem is also equivalent to the transition problem encountered on systems where the allocation of frequencies at the reconfiguration instants is attempting to minimize the average call blocking probability in the cellular area, like in [26]. Thus, we provide a method for transforming the new assignment to another equivalent assignment that will cause a minimum possible number of intra-cellular handovers during the reconfiguration phase, with respect to the old assignment. We also present another heuristic which attempts to optimize both goals at the same time. Numerical examples show that the two goals are conflicting, while the main advantage of the second approach is the provision of a single parameter that can be used for tradeoff selection between these two goals.

The next section describes the cellular network model and discusses several issues arising during the reconfiguration phase. In section 3, the two different approaches for determining the new nominal channel assignment are introduced, and numerical examples to compare the performance of these approaches in macrocellular and microcellular environments are presented in section 4. The paper is concluded with some remarks in section 5.

2. System model

2.1. Cellular network model and operation

Bandwidth in cellular communication networks is divided into a number of disjoint carriers, each one being able to accomodate one or multiple connections when some multiple access technique is used. Considering a continuous spectrum allocation for the system demands, as well as a smooth spacing between the consecutive frequency bands, the available frequencies can be represented by the set of integers $\{1, \dots, F\}$. The area covered by the network is separated into M cells and every cell can have access to every carrier, provided that certain interference limitations are not violated. These constraints are developed for each pair of cells by measurements conducted throughout the geographical area of the cellular system, and the most general representation form is by means of an $M \times M$ *symmetric compatibility matrix* $\mathbf{C} = [c_{ij}]$, introduced in [9]. Each entry c_{ij} of this matrix is a small non-negative integer number denoting the minimum permissible value of separation between frequencies assigned to cells i and j. For example, the cochannel (adjacent channel) constraints for cells i and j are represented by an entry $c_{ij} = 1$ ($c_{ij} = 2$), while the cosite constraints are defined by the diagonal entries of the matrix and are usually set to the same value α, the greatest entry of the matrix.

In the case of directed DCA, two levels of activities are distinguished, differing mainly in the frequency of occurence of the corresponding events. At the *call admission* level, the system, based on the usage of frequencies and slots, dynamically takes decisions about the acceptance or rejection of new incoming calls and handovers, the release or allocation of nominal or borrowed carriers, the best candidate carrier for borrowing, the transfer of calls to recently freed carriers in the form of intracellular handovers, and so on [24]. The decisions at this level are also driven by the existing allocation of nominal frequencies which takes place at a higher level, the *resource allocation* level. At this level, nominal carriers are allocated to cells according to the prevailing traffic conditions in each cell. Allocations of this form are not considered as permanent, rather they serve as a high preference group for each cell to favor the dynamic decisions at the call admission level. The basic advantages by prefering these nominal assignments are good packing of frequencies, higher frequency reuse and consequently increased system capacity.

An assignment of nominal channels to cells during the period $[t_k, t_{k+1})$ can be represented by means of an $M \times F_k$ *assignment matrix*:

$$\mathbf{A}^{(k)} = \left[a_{if}^{(k)}\right], \quad i = 1, \dots, M, \ f = 1, \dots, F_k, \tag{1}$$

where F_k is the frequency span, that is the number of carriers used in that assignment, and $a_{if}^{(k)}$ are variables which can only take the values zero or one, defined as

$$a_{if}^{(k)} = \begin{cases} 1, & \text{nominal carrier } f \text{ is assigned to cell } i \\ & \text{at time interval } [t_k, t_{k+1}), \\ 0, & \text{nominal carrier } f \text{ is not assigned to cell } i \\ & \text{at time interval } [t_k, t_{k+1}). \end{cases} \tag{2}$$

This matrix is known at the call admission level and is used to determine the allocation of frequencies for this certain period of time. Since, however, the environment of cellular networks is time-varying, the traffic averages may change significantly so that a new assignment of nominal carriers may be necessary. In any case, this variation in traffic will more likely take place over larger scales in time, and reconfiguration is expected to be a relatively rare event compared to the frequency of events at the call admission level.

2.2. Assignment of nominal carriers

Given the arrival rates of new calls and handovers during some time interval, and the grade of service of both types of calls, the number of carrier requirements of each cell can be estimated [18]. Assuming that the problems at hand require a number of carriers consistent with available bandwidth, the general procedure for obtaining a channel assignment aims at finding that assignment which satisfies the total number of requirements with the minimum possible number of channels. We let $R^{(k)} = [r_i^{(k)}]$ be an M-dimensional positive integer vector, each component of which stands for the number of frequency requirements placed on the system by cell i at the interval $[t_k, t_{k+1})$. This approach is equivalent to the well-known *Minimum Span Channel Allocation Problem* (MSCAP) and the resulting assignment hopefully achieves allocations of carriers that are as close to the lowest part of the spectrum as possible.

MSCAP is equivalent to a generalized graph coloring problem and thus is $\mathcal{NP}$-complete [12]. Many algorithms for this problem have appeared in the literature, based on procedures that have their grounds on graph theory [9,11, 21,27]. According to the majority of these schemes, the cell requirements are ranked on the basis of some measure that counts their difficulty of assignment. In addition to these schemes, there have been several other proposals based on different heuristic techniques [3,16].

In a time-varying system however, an algorithm applicable to this type of problem should be easy to implement and fast, as well as effective in producing assignments with near-optimal spans. The heuristics in [9,11,21], as well as similar special forms of the procedure introduced in [20], meet the above general requirements. Either of these algorithms can be used for obtaining a minimum span nominal channel allocation for the requirement vector $R^{(k)}$.

2.3. Transition phase

Let $\mathbf{A}^{(k)}$ be an assignment matrix and F_k be the assignment span optimized at time t_k for vector $R^{(k)}$. As traffic varies over time the following effects are likely to appear. While in some cells the demand may increase substantially, always being higher than the corresponding requirements in $R^{(k)}$, in other cells it may decrease resulting in low utilization of their nominal channels. The first cells continuously borrow carriers to meet their demand incurring significant signaling load to the system. Furthermore, the traffic capacity of the system is degraded since on one hand channel borrowing causes locking of carriers in interfering cells whose throughput consequently declines, and on the other hand selecting the best among the candidate channels is not always successful. In such circumstances the requirement vector $R^{(k)}$ is not representative of the prevailing traffic conditions, and thus it is essential to first redefine it and then reconfigure the carrier assignments.

The decision on whether there is a need for updating the nominal carrier assignments should be based on measurements of the arrival rates of new calls and handovers, and the blocking probability of both types of calls at each cell. Each base station (or a special base station dedicated to managing the whole cellular network) may monitor the traffic load in its responsibility area to determine whether the traffic conditions have changed in a way that significantly affects the optimality of the current assignment of nominal carriers. In this paper however, we concentrate on the issues arising once the decision to reconfigure the network at time t_{k+1} has been taken, based on the new requirement vector $R^{(k+1)}$. In macrocellular environments, it is quite reasonable to assume that the transition time instant can be estimated since the traffic changes are expected to follow the changes of the users distribution over the geographical area of the network during the day. This distribution pattern is considered to change relatively slowly and in any case predictably over time. On the other hand, in a microcellular environment the traffic patterns present high variability and the prediction probability is certainly limited.

Let us now turn our attention to the measure that greatly influences the system performance during the transition period. The reconfiguration phase at time t_{k+1} will take the system from the old nominal assignment of matrix $\mathbf{A}^{(k)}$ to the new nominal assignment of matrix $\mathbf{A}^{(k+1)}$ optimized for the new requirement vector $R^{(k+1)}$. When directed DCA is used, there is actually no delay caused by waiting for the release or acquisition of a nominal carrier that is not allocated to the same cell under the new assignment. What really happens in this particular operational model is a change on the selection probabilities of the carriers in each cell. For this reason, some synchronization may be necessary across base stations so that each cell will start to consult the new allocation tables at the same time. During some initial time period however, the occupied carriers of a cell that do not appear as nominal carriers of the same cell in the new assignment matrix, are considered as borrowed carriers and the operation of the system during this period will be away from optimum in terms of the potential traffic capacity. Obviously, the intensity of this disturbance is proportional to the number of different allocations of nominal carriers between the two successive assignment matrices.

Thus, we define the *distance* between two assignment matrices at times t_k and t_{k+1} as

$$\mathcal{D}\big(\mathbf{A}^{(k)}, \mathbf{A}^{(k+1)}\big) = \sum_{i=1}^{M} \left[\min\big(r_i^{(k)}, r_i^{(k+1)}\big) - \sum_{f=1}^{\min(F_k, F_{k+1})} a_{if}^{(k)} \cdot a_{if}^{(k+1)} \right], \quad (3)$$

where the internal sum represents the number of common assignments in those two matrices. As formulated, this definition ignores the part of different assignments in both matrices that are due to the increase or decrease of the requirements in some cells and which will occur anyway. It takes into account *only* the actual different assignments. Concluding, the next allocation state produces the least disturbance to the system when the number of common assignments is maximum or equivalently the distance $\mathcal{D}(\mathbf{A}^{(k)}, \mathbf{A}^{(k+1)})$ is minimum.

3. Minimization of the number of different assignments

We suppose that a network is operating with assignment matrix $\mathbf{A}^{(k)}$ optimized at time t_k for the frequency requirement vector $R^{(k)}$. Let $R^{(k+1)}$, be the updated requirement vector which reflects the changes that have occured to the traffic load of each cell. Our objective is to acquire a new assignment matrix under which the network will operate after the instant t_{k+1} such that:

- the new span of frequencies F_{k+1} is as close to the optimum value for $R^{(k+1)}$ as possible, and
- the number of different assignments between assignment matrices $\mathbf{A}^{(k)}$ and $\mathbf{A}^{(k+1)}$ is as small as possible.

In the majority of cases, these goals are expected to represent two conflicting requirements. In other words, optimizing one objective alone will result in a new assignment matrix $\mathbf{A}^{(k+1)}$, which may be away from the optimum in terms of the other objective. Nevertheless, one would expect that, for small changes in the requirement vector, optimizing one objective only would have little effect on the other goal. However, this is not true and the next lemma strengthens the argument that even for slight changes of requirements, significant disturbance to the system may be possible when only the first goal is optimized.

Lemma 3.1. In hexagonal cellular networks with cochannel reuse distance $\sqrt{3 \cdot N_\mathrm{c}}$ cell radii[2] and cosite constraints greater than unity ($2 \leqslant c_{ii} \leqslant N_\mathrm{c}$), minimizing the span of frequencies of the new assignment matrix for a new requirement vector that differs from the old one by only an elementary increase in the demand of one cell, can result in a number of different assignments that grows linearly with the number of cells of the network.

Proof. We will construct a particular instance of the transition problem. Consider that the cochannel interference cluster size is N_c and at the moment t_k the requirements of each cell are equal to r, $r_i^{(k)} = r$, $i = 1, \ldots, M$. The set of frequencies of every cell i, $i = 1, \ldots, N_\mathrm{c}$ of the cochannel interference cluster is $\{i, i + N_\mathrm{c}, \ldots, i + (r-1)N_\mathrm{c}\}$ at the corresponding assignment with minimum span F_k. These assignments are repeatedly applied to the whole cellular area according to the cochannel reuse pattern. Let us now suppose that one of the cells that possesses frequency rN_c, has one more requirement ($r + 1$ in total), at time instant t_{k+1} and the rest $M - 1$ cells continue to request r frequencies. It is not difficult to check that the new optimum span of frequencies is $F_{k+1} = F_k + 1$, while achieving this minimum value requires at least $(2/N_\mathrm{c}) \cdot M$ reassignments. $\square$

[2] $N_\mathrm{c} = i^2 + i \cdot j + j^2$, i, j positive integers, and typical values for N_c are 3, 7, 12.

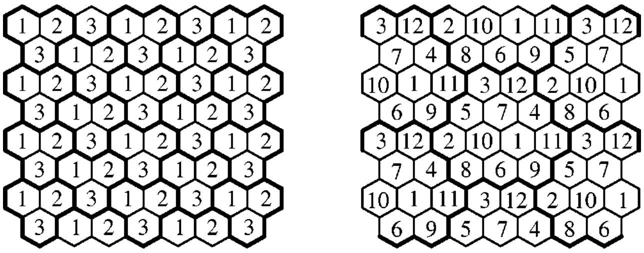

Figure 1. Numbering of cells in cochannel interference clusters with sizes $N_\mathrm{c} = 3$ and $N_\mathrm{c} = 12$.

It is noted that for such a small change in the traffic demand, the reconfiguration of the system is not essential, yet the purpose of this lemma is to demonstrate that the conflict between the two goals can be quite large. The validity of this lemma must be established in the case of general non-hexagonal networks.

In figure 1, we show the amount of different assignments in two examples with a similar change of requests. The numbers inside each cell denote the sequence number of the corresponding cell in the cochannel interference cluster. When the cochannel reuse distance is 3 cell radii ($N_\mathrm{c} = 3$), we further assume that frequencies in the same cell should be two units apart. If one cell with sequence number 3 has one more requirement in the new demand vector, then the new assignment matrix with minimum span $F_{k+1} = F_k + 1$ is obtained by exchanging the last frequency of every cell with sequence number 3 with the last frequency of every cell with sequence number 1 (or 2). This rearrangement calls for exactly $(2/3) \cdot M$ reassignments. When the cochannel reuse distance is 6 cell radii ($N_\mathrm{c} = 12$), we further consider adjacent channel constraints between adjacent cells. If one cell with sequence number 12 has one more requirement in the new demand vector, then the new minimum span assignment matrix is obtained by exchanging the last frequency of every cell with sequence number 12 with the last frequency of every cell with sequence number 10 and the last frequency of every cell with sequence number 9 with the last frequency of every cell with sequence number 8. This rearrangement calls for exactly $(4/12) \cdot M$ reassignments. At this point, it is worthwhile noting that the lemma offers a subestimation of the number of different assignments, and it is possible to construct examples where this number scales with the number of existing assignments.

In the sequel, we describe two different approaches for obtaining a new assignment matrix.

- The first approach attempts to satisfy both goals for the new assignment matrix in one single step. This procedure is applicable to transition problems whose constraints compatibility matrix has a general form.
- The second approach attempts to satisfy the two conflicting goals in two independent steps, one goal at a time. First, a temporary assignment matrix with a minimized span of frequencies for the new demand $R^{(k+1)}$ is constructed, and then a rearrangement of its frequencies follows so that at the final matrix $\mathbf{A}^{(k+1)}$ the number

of different assignments, with respect to the initial matrix $\mathbf{A}^{(k)}$, be minimum. This method is applicable to a significant special set of problems where *only* cochannel constraints are involved.

3.1. The constrained minimum span channel assignment problem

The approach that tries to simultaneously satisfy both objectives deals with the *Constrained Minimum Span Channel Assignment Problem* (CMSCAP), which can be formally stated as a decision problem as follows:

Problem 3.1 (CMSCAP). Given an initial assignment matrix $\mathbf{A}^{(k)}$ with span of frequencies F_k, for the requirement vector $R^{(k)}$ at time instant t_k, a new requirement vector $R^{(k+1)}$ at time instant t_{k+1}, and two positive integers K and L, is there and assignment matrix $\mathbf{A}^{(k+1)}$ such that $F_{k+1} \leqslant K$ and $\mathcal{D}(\mathbf{A}^{(k)}, \mathbf{A}^{(k+1)}) \leqslant L$?

CMSCAP is $\mathcal{NP}$-complete because for

$$L \geqslant \sum_{i=1}^{M} \min\bigl(r_i^{(k)}, r_i^{(k+1)}\bigr)$$

it reduces to the pure MSCAP. We will now present a heuristic for the CMSCAP, which is based on the heuristics for the pure MSCAP provided in [20].

The procedure introduced in [20] decomposes MSCAP into a series of small and manageable elemementary subproblems. At each iteration l of a simplified version of this procedure, one such elementary subproblem is formulated and the number of carriers allocated is equal to the minimum permitted separation width w_l between the frequencies of the same cell. For simplicity we also set w_l equal to the co-site constraint value α for every iteration of the procedure. The allocations of carriers $\{F_{l-1}+1, \ldots, F_{l-1}+w_l\}$ are obtained by applying either *Requirement Exhaustive Strategy* (RES) or *Frequency Exhaustive Strategy* (FES), where F_{l-1} is the greatest frequency already assigned at the previous iteration $l-1$.

More specifically, in the elementary allocation problem at iteration l of the general procedure, each cell can acquire only one frequency from the next available w_l carriers. All requirements, one from each cell (or equivalently all cells), are listed according to the number of existing requests of each cell. According to RES, for every frequency f, $f = F_{l-1}+1, \ldots, F_{l-1}+w_l$, all cells are examined sequentially, starting from the top of the list. If assignment of frequency f to cell j is consistent with previous assignments, then cell j obtains frequency f ($a_{jf} = 1$, $a_{jf_j} = 0$, $f_j = F_{l-1}+1, \ldots, \max(F_{l-1}+w_l, f_j+\alpha-1)$, $f_j \neq f$), while for every cell i, $c_{ij} > 0$, the following assignments are disabled $a_{if_i} = 0$, $f_i = \max(F_{l-1}, f - c_{ij} + 1), \ldots, f + c_{ij} - 1$.

By introducing a window of normalized size h, $0 \leqslant h \leqslant 1$, we modify heuristic RES, so that the new allocations are affected by the previous allocations in the assignment matrix $\mathbf{A}^{(k)}$. The new algorithm also orders the cells in a list according to their existing requirements, and attempts to allocate each of the w_l frequencies $\{F_{l-1}+1, \ldots, F_{l-1}+w_l\}$ at a time to as many cells as possible. However, when it seeks for the next candidate cell to assign the current frequency f, it does not select the first assignment consistent to previous assignments. Instead, it considers the first $H = h \cdot n$ such consistent assignments, where n is the total number of cells that can obtain frequency f without violating any interference constraint. If at least one of these H cells had acquired the same frequency in the previous assignment matrix $\mathbf{A}^{(k)}$, then frequency f is assigned to that cell which is closer to the top of the list, even if it is not the first of the H cells. If none of the H cells had acquired

1. Order cells in a list L in decreasing order of their remaining requirements. Cells with equal number of requirements are randomly ordered.
   For every cell i with zero requirements set $a_{if}^{(k+1)} = 0$, $f = F_{l-1}+1, \ldots, F_{l-1}+w_l$.
   Set $f = F_{l-1}+1$.
2. Compute the number n of cells in the list L for which $a_{if}^{(k+1)} = -1$.
3. If $n = 0$ go to step 6.
   Otherwise, compute the size of window $H = \mathrm{round}(h \cdot n)$. If $H = 0$ set $H = 1$.
4. From the first H candidate cells of list L such that $a_{if}^{(k+1)} = -1$, select cell j as that cell i which is closer to the beginning of the list and such that $a_{if}^{(k)} = 1$.
   If no cell such that $a_{if}^{(k)} = 1$ exists, select cell j as that cell i which is the first of the H candidate cells.
5. Set $a_{jf}^{(k+1)} = 1$, $a_{jf_j}^{(k+1)} = 0$, $f_j = F_{l-1}+1, \ldots, \max(F_{l-1}+w_l, f_j+\alpha-1)$, $f_j \neq f$.
   For every cell $i, c_{ij} > 0$, set $a_{if_i}^{(k+1)} = 0$, $f_i = \max(F_{l-1}, f - c_{ij} + 1), \ldots, f + c_{ij} - 1$.
6. If $f = F_{l-1}+w_l$, stop. Otherwise, set $f = f+1$, and go to step 2.

Figure 2. Algorithm CRES for the lth elementary allocation problem (it assumes that $\mathbf{A}^{(k+1)}$ is initially filled with the flag value -1).

frequency f in matrix $\mathbf{A}^{(k)}$, frequency f is assigned to the first of the H cells as in RES. The algorithm continues to the next frequency $f+1$ when no more allocations of frequency f is possible.

We will refer to this algorithm just presented as the *Constrained RES* (CRES). Its detailed description is given in figure 2, and we note that by setting $H = 1$ it reduces to the simple strategy RES. It is not difficult to check that the time complexity of CRES is O(M^2) given that $w_l \ll M$. For large values h of the window, it is more probable that cells that had been assigned some frequency f in the previous matrix $\mathbf{A}^{(k)}$ will also obtain the same frequency in the new matrix $\mathbf{A}^{(k+1)}$. Consequently, as window h increases, the distance between the old and the new assignment matrices is expected to reduce, a gain probably achieved at the expense of the final span of frequencies, which may be large.

Finally, it is worthwhile noting that similar modifications can be performed to other heuristics for the pure MSCAP to produce heuristics for the CMSCAP. For example, it is not difficult to introduce a similar window parameter to the strategies RES and FES of [9,21] which solve problem MSCAP in total and not the elementary problems of [20] like the procedure in figure 2 does. However, in the case of FES, the corresponding algorithm CFES will select the frequency (to be assigned to a cell) from a window of H candidate frequencies, instead of the cell (to obtain a frequency) from a window of H candidate cells.

3.2. The frequency mapping problem

We will now introduce a different procedure for the reconfiguration of the system at time instant t_{k+1}, which consists of two *independent* and *successive* steps. Initially, a new MSCAP, with requirement vector $R^{(k+1)}$, is formulated and solved at time t_{k+1}, independently of the allocations made at time t_k. Consequently, the new assignments are performed with one and only objective; the minimization of the number of frequencies for the new demand. The result of this step is the transient assignment matrix $\mathbf{B}^{(k+1)}$. Next, a rearrangement of the frequencies of this matrix is performed such that the final matrix $\mathbf{A}^{(k+1)}$ and the previous matrix $\mathbf{A}^{(k)}$ will have as many common allocations as possible.

This procedure can be applied to a certain set of assignment problems where only cochannel interference constraints are present, that is when all the elements of the compatibility matrix $\mathbf{C}$ have values 0 or 1. These constraints just prevent the use of the same frequency in two cells i, j such that $c_{ij} = 1$, while the same frequency cannot be reused in the same cell, that is $c_{ii} = 1$. Obviously, any allocations of a frequency f do not affect or prevent allocations of any other frequency f' except when $f' = f$. As a result, there is no interaction between allocations of nearby frequencies in the assignment matrix $\mathbf{A}^{(k)}$, which can also be seen as an array of F_k columns, each one of size M:

$$\mathbf{A}^{(k)} = \left[A_1^{(k)}\ A_2^{(k)}\ \ldots\ A_{F_k}^{(k)}\right]. \tag{4}$$

Each column $A_f^{(k)}$ is associated with a frequency f, $f = 1, \ldots, F_k$, and the values of its elements determine which cell possesses frequency f. As there is no interference between different frequencies, any exchange of two columns of the assignment matrix is possible without violating any constraint. In fact, the interference constraints continue to hold even after a random reordering of all the columns of the matrix. The following corollary is obviously a straightforward result.

Corollary 3.1. In assignment problems with cochannel interference constraints only, any permutation of the columns of the assignment matrix results in a new assignment matrix for the same problem where the interference constraints are not violated and the span of frequencies is the same.

In the following we will call the initial matrix and the matrix after the reordering of columns *equivalent*.

We will now turn our attention to the problem of rearranging the columns (frequencies) of $\mathbf{B}^{(k+1)}$ to get the equivalent matrix $\mathbf{A}^{(k+1)}$. Considering that every column $B_f^{(k+1)}$ of $\mathbf{B}^{(k+1)}$ just determines one subset of cells which will obtain the *same* frequency in $\mathbf{A}^{(k+1)}$ and not the subset of cells that will obtain frequency f, the problem is reduced to a one-to-one matching of these F_{k+1} subsets (or equivalently columns) of matrix $\mathbf{B}^{(k+1)}$ to the set of frequencies $\{1, \ldots, F_{k+1}\}$. Furthermore, since our objective is to minimize the number of different assignments during the transition phase, this matching should generate, with respect to the previous assignment matrix, the least possible disturbance to the system. This problem which we will hereafter refer to as the *Frequency Mapping Problem* (FMP) can be formulated as follows:

Problem 3.2 (FMP). Given an initial assignment matrix $\mathbf{A}^{(k)}$ with span of frequencies F_k, and a new assignment matrix $\mathbf{B}^{(k+1)}$ with span of frequencies F_{k+1}, find a permutation $(\pi_1, \pi_2, \ldots, \pi_{F_{k+1}})$ of $\{1, \ldots, F_{k+1}\}$, such that for the final assignment matrix

$$\mathbf{A}^{(k+1)} = \left[B_{\pi_1}^{(k+1)}\ B_{\pi_2}^{(k+1)}\ \ldots\ B_{\pi_{F_{k+1}}}^{(k+1)}\right]$$

the distance $\mathcal{D}(\mathbf{A}^{(k)}, \mathbf{A}^{(k+1)})$ is minimum over all possible permutations.

Initially we will consider that $F_k = F_{k+1} = F$, before we proceed to the general case where $F_k \neq F_{k+1}$. This special case is also applicable to the transition problem that arises in systems where the available span of frequencies is the same at all time instants and the non-uniform allocation of frequencies aims at the minimization of the average call blocking probability like in [26]. For FMP there is a natural way of representing all the necessary information. We initially observe that the identities of allocations in each column of matrices $\mathbf{A}^{(k)}$ and $\mathbf{B}^{(k+1)}$ (namely which cells are assigned some frequency) are not essential for determining the optimum solution of FMP. What is of interest is only

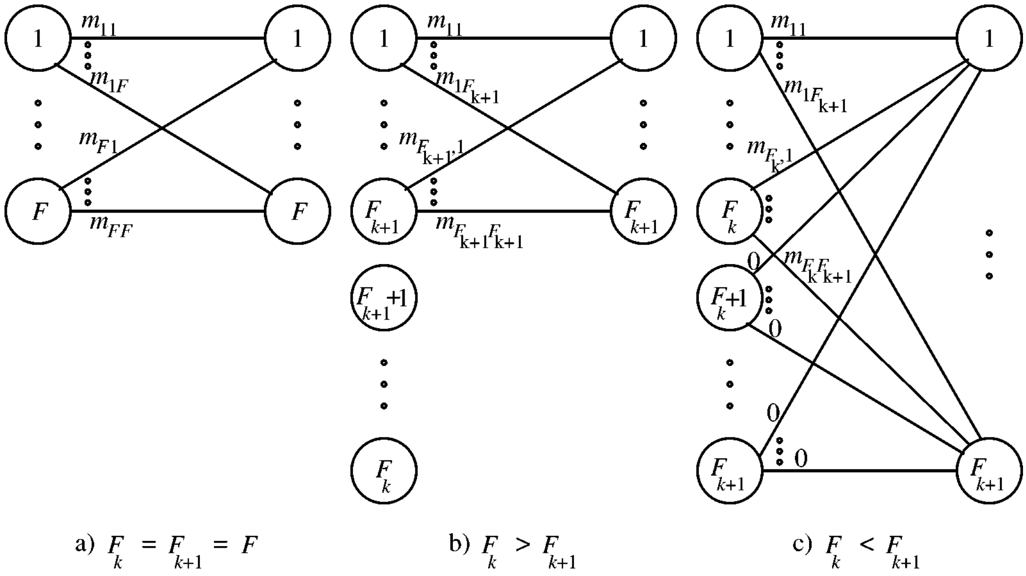

Figure 3. Bipartite weighted graphs for FMP.

the number of allocations (or cells) that each column f of matrix $\mathbf{A}^{(k)}$ has in common with each column f' of matrix $\mathbf{B}^{(k+1)}$, $f, f' = 1, \ldots, F$. This information can be encompassed in an $F \times F$ matrix **M**, whose element $m_{ff'}$ is the number of common cells that frequency f of matrix $\mathbf{A}^{(k)}$ and frequency f' of matrix $\mathbf{B}^{(k+1)}$ have been assigned to

$$M = [m_{ff'}] = \left[\sum_{i=1}^{M} a_{if}^{(k)} \cdot b_{if'}^{(k+1)} \right], \quad f, f' = 1, \ldots, F. \tag{5}$$

Matrix **M** can be considered as the adjacency matrix of a bipartite graph $G = (V, U, E)$ with sets of vertices $V = U = \{1, \ldots, F\}$ and set of edges $E = \{(f, f'), f \in V, f' \in U\}$, like the one appearing in figure 3(a). Every edge $(f, f') \in E$, $f \in V$, $f' \in U$, is assigned a weight equal to the corresponding element $m_{ff'}$ of **M**. We can now easily verify that:

- the solution to FMP, that is finding an assignment matrix $\mathbf{A}^{(k+1)}$ whose columns are just a reordering of the columns of the assignment matrix $\mathbf{B}^{(k+1)}$, such that the distance (3) from matrix $\mathbf{A}^{(k)}$ is minimum, is equivalent to finding a matching[3] of maximum weight in the corresponding bipartite graph.

If edge (f, f') belongs to this maximum matching, then column f' of $\mathbf{B}^{(k+1)}$ should be placed at column f of the final matrix $\mathbf{A}^{(k+1)}$. The aforementioned *Bipartite Weighted Matching Problem* (BWMP), is also known as the *assignment problem* and can be solved in polynomial time. For example the Hungarian method solves BWMP with time complexity O($|V|^3$) [19]. Consequently, there is a polynomial time algorithm for FMP, because its transformation to BWMP can be done in polynomial time.

[3] A matching in a bipartite graph is defined as the set of edges having no common vertex.

We will now consider the general case where $F_k \neq F_{k+1}$. The two cases appear in figures 3(b) and 3(c). When $F_k > F_{k+1}$, the F_{k+1} columns $\mathbf{B}^{(k+1)}$ must be matched to the *first* F_{k+1} frequencies (columns) of $\mathbf{A}^{(k)}$, since we want to keep the new span of frequencies minimum. Thus, all the allocations of frequencies $f > F_{k+1}$ in $\mathbf{A}^{(k)}$ are ignored and the bipartite graph is constructed as in figure 3(b). On the other hand, when $F_k < F_{k+1}$, the set of columns of $\mathbf{A}^{(k)}$ should be extended with $F_{k+1} - F_k$ assumed columns, in order to match again the F_{k+1} columns of $\mathbf{B}^{(k+1)}$ to F_{k+1} frequencies. The weights of the fake edges, namely those that have as a left vertex any of the assumed vertices (columns), should be all set to the same value, e.g., the zero value like in figure 3(c), so that the maximum matching can be determined by the weights of the real edges.

4. Numerical results and discussion

We study the performance of our algorithms with two different cellular configurations; one macrocellular and one microcellular layout. For each layout, we construct several possible transition scenarios, and test our algorithms in a variety of interference constraints. We treat each environment independently since reconfiguration in the microcellular case will normally be required more frequently. Nevertheless, treating both systems together is mainly a matter of additional problem input. The performance measures used in the comparison are the span of frequencies, as well as the number of different assignments during the system transition phase. We use as a basis of comparison the results produced from the solution to two pure MSCAPs at time instants t_k and t_{k+1}, i.e., when the elementary allocation problems are solved with procedure RES [20]. Alternatively, we could use any of the algorithms in [9,11,21] to obtain these results. Then, however, we should study the effect of introducing an appropriate window parameter to these algorithms.

We define the *basic* span of frequencies as the span of the new allocation at time t_{k+1} when this is produced by solving a pure MSCAP. We further define the *basic* distance of assignments as the distance between assignment matrices $\mathbf{A}^{(k)}$ and $\mathbf{A}^{(k+1)}$ when both these matrices are produced by solving two pure MSCAP's with requirement vectors $R^{(k)}$ and $R^{(k+1)}$. For comparing results of varying size stemming from different scenarios we present normalized instead of absolute numbers. In other words, when we present the results of CRES for the frequency span of an assignment, we show the percentage of increase from the basic span at time t_{k+1}. Similarly, when we present results for the distance of assignments we use the normalized number of different assignments which is defined as the ratio of the actual distance and the basic distance. Finally, due to the random ordering of cells with equal number of requirements in list L of figure 2, we ran the algorithm several times (typically 20 times) for each problem and selected the best result.

4.1. Macrocellular environment

We consider the macrocellular layout depicted in figure 4. It consists of 100 cells, and is supposed to cover the geographical area of a city and its suburbs. The area is separated to three different zones, each one consisting of 16 central, 46 semicentral and 38 peripheral cells. Obviously, the central zone covers the downtown of the city, and the second and third zone cover the semicentral areas and the suburbs of the city.

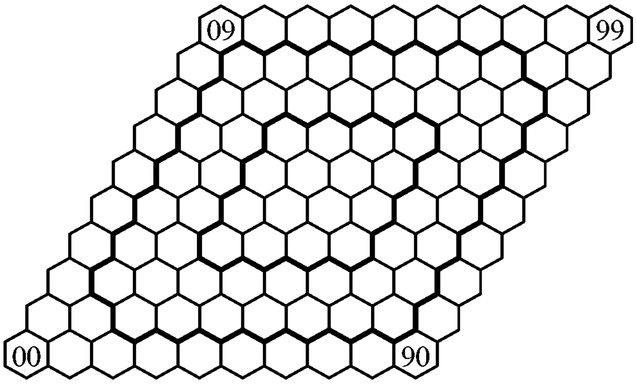

Figure 4. Layout of 100 macrocells.

The transition scenarios used to test the performance of our algorithms are shown in table 1. The symbolism $[a, b]$ denotes that the number of requirements of each cell at the corresponding zone is a random integer variable, uniformly distributed at the interval $[a, b]$. The reader can check that the total demand placed on the cellular area in every scenario remains nearly constant at the value 2000. That is, we study a closed system of 2000 customers who are moving within the borders of the urban area during the day.

The first scenario represents the movement of population from their home at the suburbs to their work at the center of the city during the morning hours. The second scenario represents another change in the demand of each zone of cells during the working hours where at the final state most of the people is found at the center of the city. The third and fourth scenarios are just the inverse population movements of scenarios 2 and 1 and which are expected to take place during the afternoon hours and at the end of work, respectively. Finally, scenarios 5 and 6 correspond to random population movements with mean number of requirements 20 in every cell, and large and small standard deviation respectively.

We consider interference constraints which are combinations of cochannel, adjacent channel and cosite interference. The cochannel constraints are defined by the size of the cochannel reuse distance $\sqrt{N_c}$ with $N_c = 3, 7, 12$. Additional adjacent channel constraints (respectively cosite constraints) of size 2 are considered when acc $= 2$ (respectively csc $= 2$).

Figures 5 and 6 correspond to transition scenario 1 and illustrate the performance of algorithms CRES (percentage of frequency span increase and normalized number of different assignments) for different values of window size h. Figures 7 and 8 show the same results corresponding to transition scenario 2. We note that when RES and optimal mapping is used, the values of frequency span increase are not shown in figures 5 and 7, because the increase shown is computed with respect to these span values.

Concerning the performance of CRES, we first observe that the span of frequencies is increased and the number of different assignments is decreased as the normalized window size h is increased. In addition to that, strategy RES followed by optimal mapping, presents the most disturbance to the system even though it also achieves the best frequency span. Thus, we conclude that the two objectives are conflicting, i.e., attempting to get an optimum perfor-

Table 1
Transition scenarios for the macrocellular environment.

Scenario No.	$R^{(k)}$ Central	$R^{(k)}$ SemiCentral	$R^{(k)}$ Peripheral	$R^{(k+1)}$ Central	$R^{(k+1)}$ SemiCentral	$R^{(k+1)}$ Peripheral
1	$[9, 11]$	$[20, 24]$	$[20, 24]$	$[23, 29]$	$[23, 29]$	$[9, 11]$
2	$[23, 29]$	$[23, 29]$	$[9, 11]$	$[35, 45]$	$[20, 26]$	$[7, 9]$
3	$[35, 45]$	$[20, 26]$	$[7, 9]$	$[23, 29]$	$[23, 29]$	$[9, 11]$
4	$[23, 29]$	$[23, 29]$	$[9, 11]$	$[9, 11]$	$[20, 24]$	$[20, 24]$
5	$[10, 30]$	$[10, 30]$	$[10, 30]$	$[10, 30]$	$[10, 30]$	$[10, 30]$
6	$[17, 23]$	$[17, 23]$	$[17, 23]$	$[17, 23]$	$[17, 23]$	$[17, 23]$

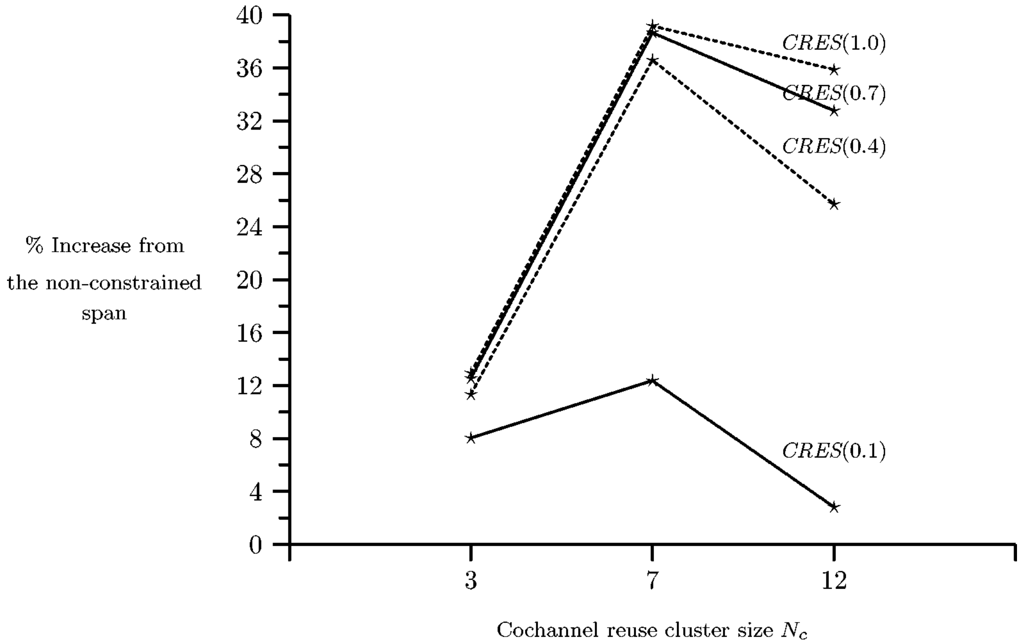

Figure 5. Algorithm comparison on assignment span (macrocellular scenario 1).

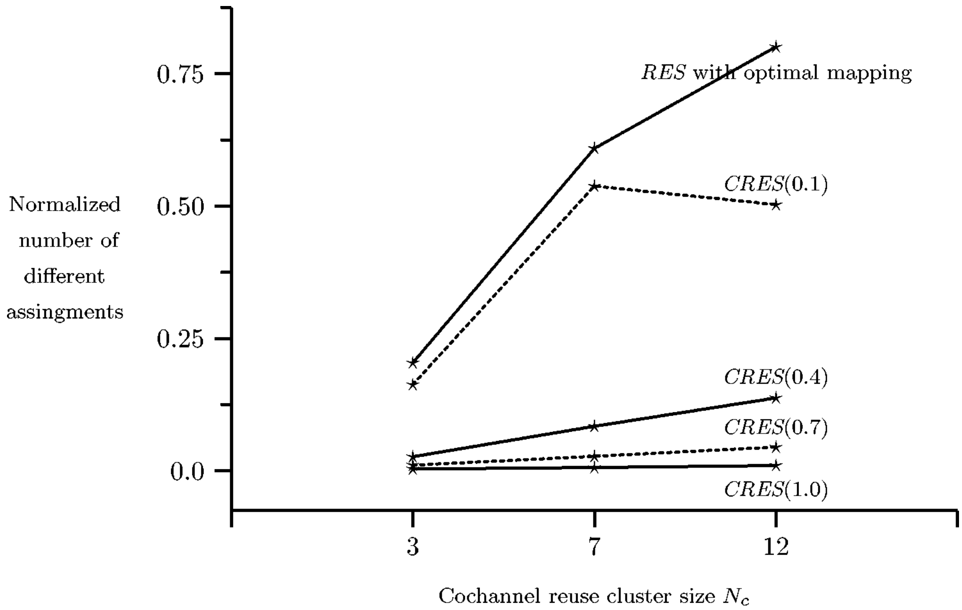

Figure 6. Algorithm comparison on number of different assignments (macrocellular scenario 1).

mance for one goal, results in a poor performance for the other. However, in the second scenario the increase of frequency span does not exceed 7% for all kinds of cochannel interference and all values of h, while in scenario 1 this increase is quite large for some values of h.

From figure 5 we observe that when $N_{\mathrm{c}} = 7$ and $N_{\mathrm{c}} = 12$, this increase is extended up to 40%. In fact, if we suppose that a reconfiguration is acceptable only when the span increase does not exceed 10%, then the normalized number of different assignments should be quite large, above 50% as shown in figure 6. When $N_{\mathrm{c}} = 7$, the last number translates to 740 different assignments for total number of requirements about 2000, clearly a difficult reconfiguration in real networks. In contrast to scenario 1, transition in scenario 2 is quite tractable. When, for example, $N_{\mathrm{c}} = 12$ and $h = 0.4$ the percent increase is just 6% and the normalized number of different assignments is just 5.5% which corresponds to only 100 different assignments when the total number of requirements is about 2000. Also in scenarios 3 and 4, whose results are not shown, the percentage of frequency span increase never exceeds 2.5% when $N_{\mathrm{c}} = 12$, 6.5% when $N_{\mathrm{c}} = 7$, and 4.5% when $N_{\mathrm{c}} = 3$.

Finally, the algorithms behave similarly when additional interference constraints are introduced (csc $= 2$ or/and acc $= 2$). According to figures 9 and 10, CRES presents

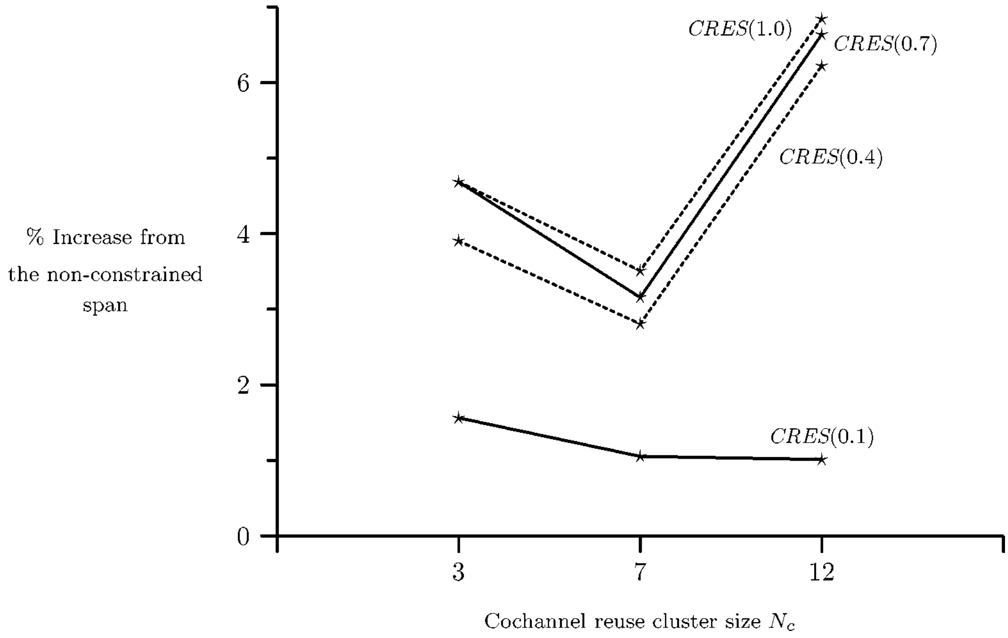

Figure 7. Algorithm comparison on assignment span (macrocellular scenario 2).

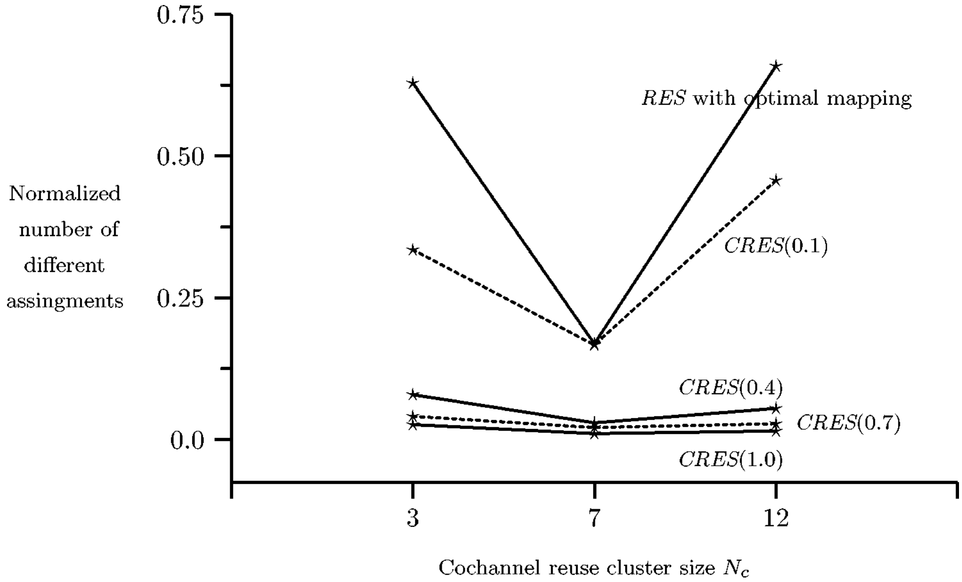

Figure 8. Algorithm comparison on number of different assignments (macrocellular scenario 2).

similar performance in scenario 5 when additional cosite constraints of size 2 are introduced. Once more, when $N_c = 7$ the disturbance during the reconfiguration in scenario 5 is high because the frequency span increase reaches 19.8%. On the contrary, scenario 6 whose requirements are random variables with small standard deviation the percent increase of frequency span never exceeds 5.8% when $N_c = 12$, and the reconfiguration should be a much easier task.

The study of these examples suggests that the choice of the appropriate time instant for reconfiguring the system is a very important decision about whether the outcome of our algorithms will be acceptable to apply or not. For example, while scenario 1 represents a normal traffic evolution during morning hours, it certainly also constitutes a quite abrupt change of the traffic pattern with respect to size. The results for this scenario translate to a high number of different assignments which will normally extend the transition phase. On the contrary, macrocellular scenario 2 represents a less abrupt movement of the population. Thus, in this case the transition phase will be definitely shorter. Summarizing, we conclude that reconfiguration should take place at less abrupt changes of the traffic pattern than that of scenario 1.

4.2. Microcellular environment

The microcellular layout which is similar to the Manhattan grid is depicted in figure 11. It consists of 45 cells of equal size (shaded squares) which cover three horizontal

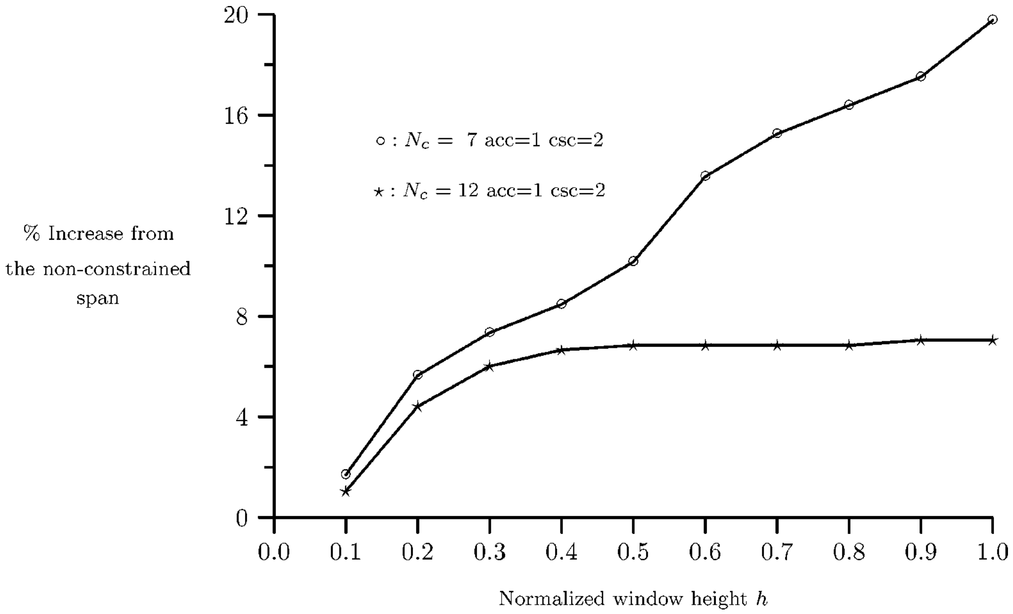

Figure 9. Algorithm comparison on assignment span (macrocellular scenario 5).

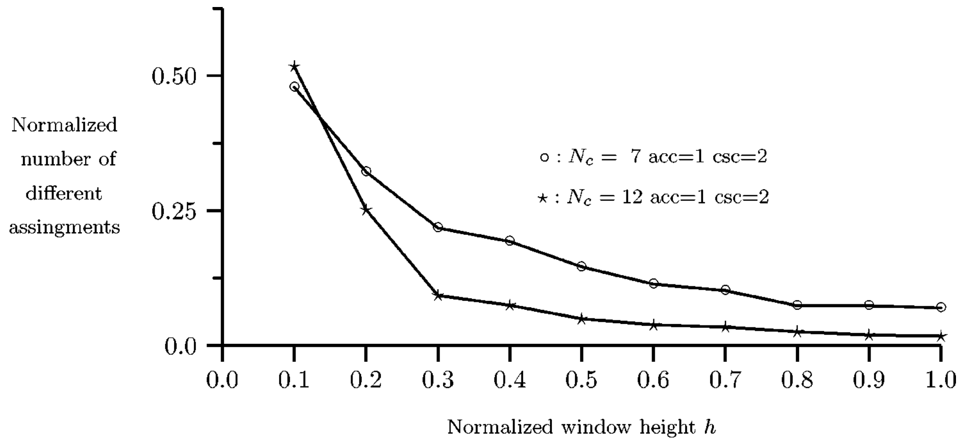

Figure 10. Algorithm comparison on number of different assignments (macrocellular scenario 5).

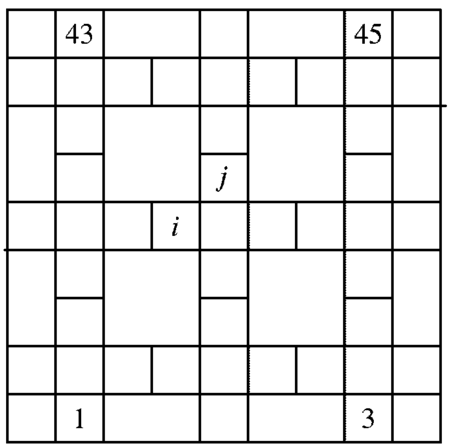

Figure 11. Layout of 45 microcells.

and vertical streets. The white squares represent building blocks covered by a picocellular network whose frequency bands do not interfere with the bands allocated to the microcells. Obviously in a multi-level architecture, the area covered by the layout of this figure can be regarded as a part of one central macrocell of figure 4.

The transition scenarios for this environment are shown in table 2, where the same symbolism for the number of requirements has been adopted. In such a small area it is natural to suppose that the level of traffic is the same along the horizontal and vertical streets. For crossroads, the traffic values are just the average traffic values of the intersected streets. Assuming that this small area is an open system with a varying population of customers, the first (second) scenario corresponds to a uniform increase (decrease) of traffic in all cells. According to the third scenario, the volume of traffic of the horizontal and vertical streets are exchanged while the level of traffic in the crossroads remains the same. Finally, scenario 4 is the same as macro-scenario 5 of table 1.

We consider only one type of cochannel constraints according to which the same channel cannot be reused in

Table 2
Transition scenarios for the microcellular environment.

Scenario No.	$R^{(k)}$ Vertical	Horizontal	Crossroads	$R^{(k+1)}$ Vertical	Horizontal	Crossroads
1	$[14, 18]$	$[8, 12]$	$[11, 15]$	$[19, 23]$	$[13, 17]$	$[16, 20]$
2	$[19, 23]$	$[13, 17]$	$[16, 20]$	$[14, 18]$	$[8, 12]$	$[11, 15]$
3	$[14, 18]$	$[8, 12]$	$[11, 15]$	$[8, 12]$	$[14, 18]$	$[11, 15]$
4	$[10, 30]$	$[10, 30]$	$[10, 30]$	$[10, 30]$	$[10, 30]$	$[10, 30]$

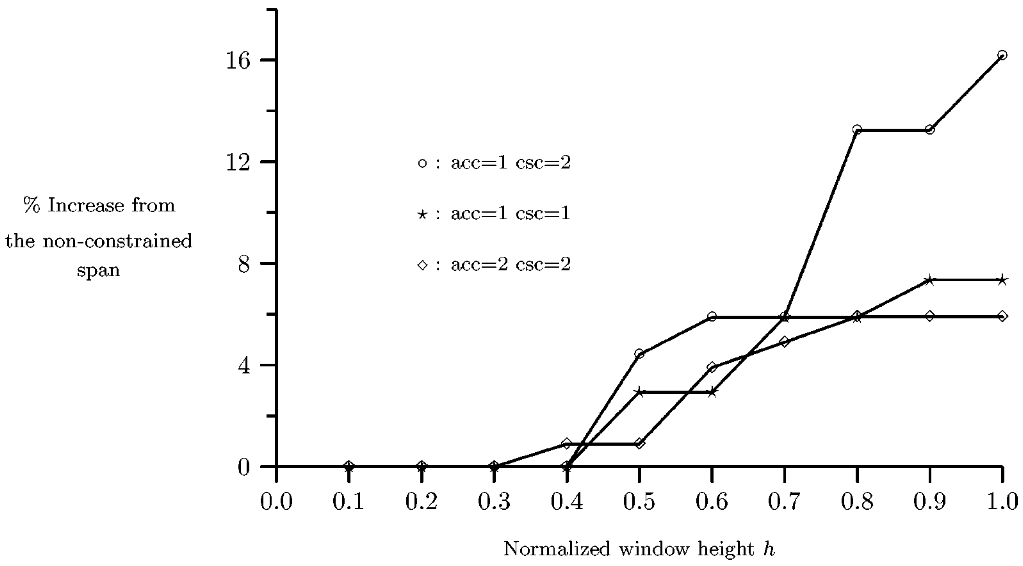

Figure 12. Algorithm comparison on assignment span (microcellular scenario 3).

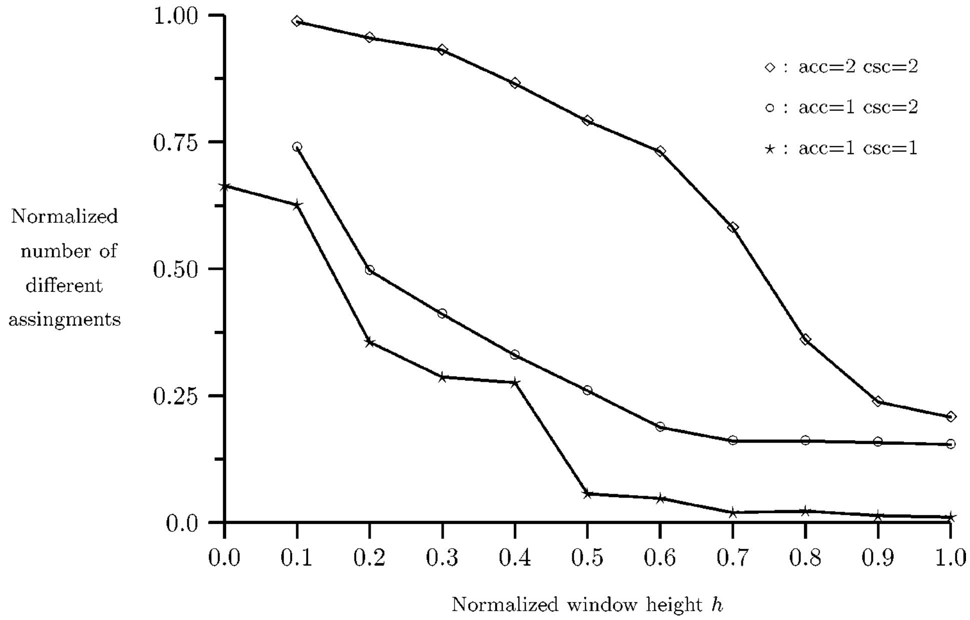

Figure 13. Algorithm comparison on number of different assignments (microcellular scenario 3).

adjacent cells, where adjacency is also assumed between cells i and j of figure 11. When some problems deal with additional adjacent constraints (acc $= 2$), these constraints apply to adjacent cells belonging to the same street. Thus, cells i and j can use adjacent channels even though these cells are considered to be adjacent.

In figures 12–15 which correspond to transition scenarios 3 and 4, we show the performance of our algorithms in terms of the span of frequencies and the number of different assignments, as we vary the normalized window height h. The number of different assignments when $h = 0$ in figures 13, and 15, corresponds to the results of algorithm

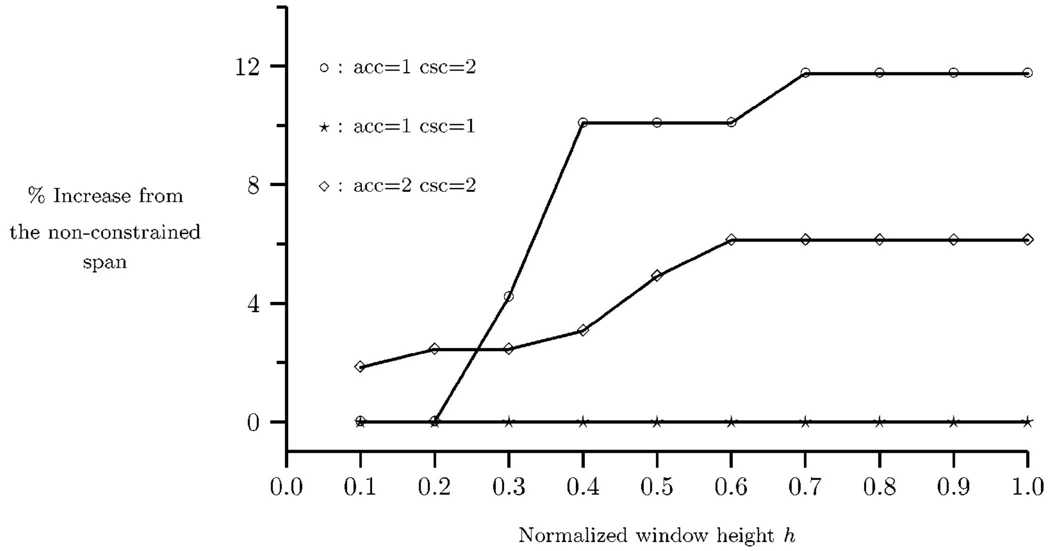

Figure 14. Algorithm comparison on assignment span (microcellular scenario 4).

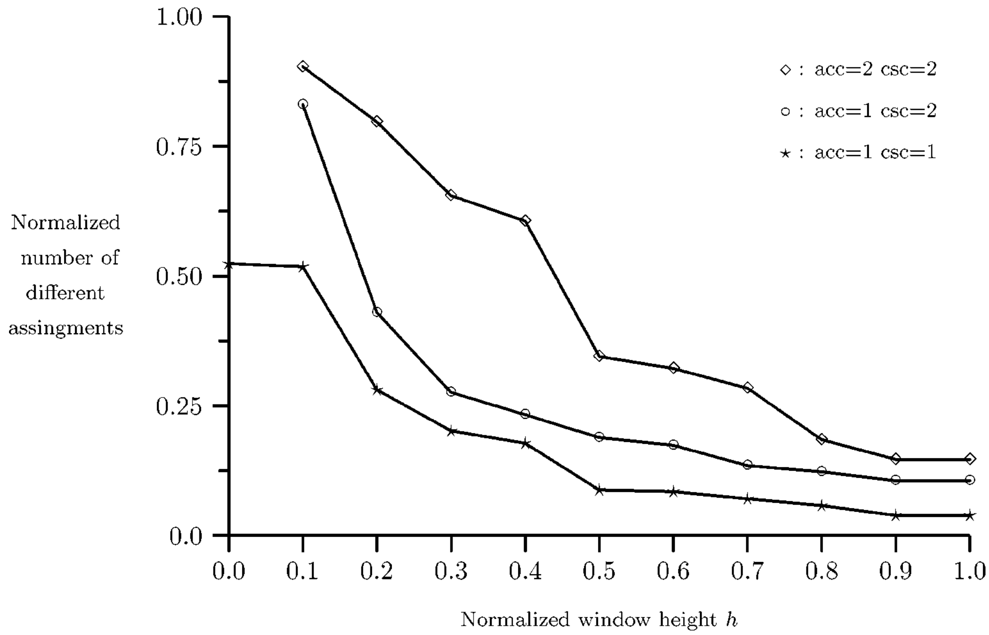

Figure 15. Algorithm comparison on number of different assignments (microcellular scenario 4).

RES followed by optimal mapping. We first observe that these results are in line with the results obtained for the macrocellular environment. The two objectives still appear to be conflicting goals, and the method of maximum matching even though results in minimum frequency span, it also causes the maximum disturbance to the system during the reconfiguration phase. An additional observation is that in the case of cochannel constraints, the effects on the span of frequencies as well as the number of different assignments are least when compared to problems with other constraints also. Additional adjacent channel and cosite constraints cause further unpleasant implications on both measures of comparison. Finally, the behavior of the algorithms in the rest scenarios 1 and 2, is nearly the same. However, the implications on these two measures are even less, which is expected since the changes in traffic are uniform in the whole cellular area.

5. Concluding remarks

We considered cellular networks with an assignment of nominal carriers that dynamically operate with carrier borrowing and reassignments. The time-varying traffic conditions encountered on these systems call for a periodic adjustment of the allocation of nominal carriers in each cell to match the corresponding offered traffic load. Our objective was to use as few carriers as possible to meet the whole set of traffic requirements in each cell, while keeping the number of different assignments between the old and the new allocation to a minimum. We studied two ways for obtaining a new assignment, one of which employs existing algorithms to satisfy the two goals independently of each other. We have shown by numerical examples that although the goal of good packing of frequencies is normally achieved, the disturbance placed on the system during the reconfiguration phase by this approach is significant. Apparently, similar results should be expected if we attempt to pursuit a new assignment optimizing the two objectives independently of each other in a system with more general interference constraints. It would be interesting, however, to design a mapping algorithm similar to the one in section 3.2 for this case. We also presented a new algorithm that attempts to construct the new nominal carrier assignments in a way that simultaneously achieves the stated goals. This algorithm resulted from the introduction of a single window parameter to an existing algorithm for the pure minimum span allocation problem. Similar algorithms can be devised by transforming other heuristics for this problem. This second approach can treat networks with more general intereference constraints, while its main advantage is that it offers a possibility for tradeoff selection between the two objectives. Its performance was tested on macrocellular and microcellular layouts and our main conclusion is that in certain transition scenarios that do not represent quite abrupt changes in the traffic pattern, this approach can be quite effective in matching the nominal carriers to the time-varying traffic needs of each cell.

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