Management Scheme for Improving the Radio Spectrum Utilisation in Cellular Systems

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Abstract: *A fundamental problem in cellular communications systems is the adaptation of the channel allocation to the traffic fluctuations. Traffic adaptation may be achieved by a computationally efficient solution to the following problem: "Given the radio spectrum available, the cell structure, the current traffic conditions, and an already established allocation of channels to cells, find a new allocation that is more suitable for handling the current traffic conditions, taking into account the previous allocation and subject to the restrictions arising from the interference conditions". In this paper, we suggest efficient solutions to this problem and present some indicative results.*

1. Introduction

Legacy and future cellular communications systems (e.g., the future versions of the Global System for Mobile communications-GSM [1], or the Universal Mobile Telecommunications System - UMTS [2]) should be able to cope with heavy traffic loads. Hence, efficient utilisation of the scarcely available radio spectrum becomes a fundamental problem. Currently, cellular systems use static allocation schemes (Fixed Channel Allocation - FCA). The allocation is determined by the traffic expected in each cell and it usually takes into account peak hour traffic data. Two major improvements may be envisaged for future cellular systems, both motivated by the fact that the traffic load is time-variant. First, the reconfiguration of the frequency allocation in various time zones of the day (mid-term reconfigurations) so as to adapt to traffic variations. Second, the application of a Dynamic Channel Allocation (DCA) strategy [3,4] that may constantly rearrange the frequency allocation.

In this paper we present an essential component of a radio spectrum management scheme that is suitable for performing fast, and thus applicable in real-time, channel allocation reconfigurations in various time-zones of the day (mid-term reconfigurations). Starting from a *basic* version of the spectrum allocation problem that is targeted to fixed traffic loads, we define, optimally formulate and solve an *extension* that is suitable for handling time variant loads. In general, we envisage a radio spectrum management scheme that will comprise mid-term reconfiguration algorithms for handling major traffic variations (expected to be encountered among different time-zones of the day), DCA algorithms for handling short-term or local traffic fluctuations (expected to be encountered within a time-zone in the day).

Performing mid-term reconfigurations requires that the *basic* version of the traffic adaptive channel allocation problem is solved. This problem concentrates on finding the best possible allocation of channels to cells for a given structure of the cellular system and a specific traffic load. We may assume that the traffic load considered characterises the (new) traffic conditions that will be valid in a time-zone of the day. The corresponding load vector may be composed of the channels required per cell in order to optimise a quality criterion (associated with the overall blocking probability). The system should be able to solve the basic version of the traffic adaptive channel allocation problem in real-time, so as to quickly adapt the channel allocation to the traffic variations. In this paper the quality criterion for this problem is the maximisation of the accommodated channel requests in the system. However, our schemes can readily be combined with other criteria such as the minimisation of the overall blocking probability in the system. The main advantage of this problem is that it aims at handling a fixed load vector, which may be assumed to characterise the (new) traffic conditions in a particular time-zone of the day. An *extension* to this problem may yield a more suitable formulation for handling time variant loads.

An additional objective when handling time-variant traffic loads through successive reconfigurations of the channel allocation pattern may be the acquisition of each new allocation by minimally disturbing the existing (already established) one. The practical meaning of the new requirement is that the network should be charged with the minimum possible management effort. Hence, every new allocation should be implemented by performing the minimum number of alterations in the already existing allocation of channels to cells. This *extended* version of the traffic adaptive spectrum allocation problem (*total reconfiguration of channel allocation* - TRCA) may be generally described as follows: “Given the cell coverage, for each cell the number of channels that are required for keeping the blocking probability in the cell within acceptable range, the frequency reuse distance constraints, the set of available channels, and an existing allocation of channels to cells, find a new allocation of channels to cells that maximises the total number of accommodated channel requests, by performing the minimum number of alterations on the already established allocation”.

In this paper we formally state, in section 2, and provide solutions, in sections 3 and 4, the aforementioned (Aggregate Channel Allocation -ACA and TRCA) problems. Through appropriate reductions we will prove that both problems are *NP*-complete [5,6]. In this respect, in sections 3 and 4 we will obtain computationally efficient (and hence, applicable in real-time) solutions. In section 5 numerical results and will be presented and in section 6 concluding remarks will be drawn.

2. Problem Statement

2.1. Aggregate Channel Allocation -ACA

We are given the structure of the cellular system in the form of a graph $G(V,E)$. The set of nodes $V=\{v_1,v_2,\ \ldots,v_{|V|}\}$ represents the cells of the system. Each edge of the set E connects neighbouring cells. We denote by C the set of available channels in the system.

Lets assume that the set $D=\{a_1,a_2,\ \ldots,a_{|V|}\}$ provides the number of channels required by the cells of the system within a certain time-zone of the day (i.e., the number of channels allocated in each cell so that a quality criterion is optimised). The requirement is to find an allocation of channels to cells $A=\{A_1,A_2,\ldots,A_{|V|}\}$ ($A_i\subseteq C$ is the set of channels allocated to cell v_i) that maximises the number of accommodated channel requests subject to the following constraints: First, the allocation A should preserve the channel reuse distance restrictions, i.e., $A_i\cap A_j=\varnothing$ if $d(v_i,v_j)<d_{\max}$ for all $(v_i,v_j)\in V^2$. Second, the total number of channels allocated in a particular cell (according to A) should not exceed the total number of channel requests. Hence, the condition $|A_i|\le a_i$ $(i=1,\ldots,|V|)$ should also be valid. The resulting problem may be stated as follows:

Problem 1 [Aggregate Channel Allocation - ACA]: Given a collection of channels C, a graph $G(V,E)$, representing the cell structure, the minimum channel reuse distance $d_{\max}$ and for each cell v_i $(i=1,\ldots,|V|)$ the number of channel requests a_i, find an allocation A of channels to cells (where

$A=\left\{A_1, A_2, \ldots, A_{|V|}\right\}$ and $A_i \subseteq C$ $(i=1,\ldots,|V|)$), that maximises the total number of accommodated requests $\sum_{i=1}^{|V|}|A_i|$, while satisfying the restrictions $A_i \cap A_j = \varnothing$ if $d(v_i, v_j) < d_{\max}$ and $|A_i| \leq a_i$ $(i=1,\ldots,|V|)$.

2.2. Total Reconfiguration of Channel Allocation - TRCA

The problem above is effective in handling a certain (static) traffic condition, that is, a given (time invariant) traffic demand. Nevertheless, in the rest of this section we will specify an extension to this problem that results in a scheme that is more suitable for handling the changing with time traffic conditions.

We denote by A the allocation of frequencies to cells, that is established throughout the network at a certain point in time. Let $\left(\tilde{b}_1, \tilde{b}_2, \ldots, \tilde{b}_{|V|}\right)$ represent the new load vector. From this load vector we obtain the demand vector, denoted as $\left(a_1, a_2, \ldots, a_{|V|}\right)$, that designates for each cell the required number of channels with respect to an optimisation criterion, i.e., preservation of blocking probability within acceptable range. Through the reconfiguration mechanism a new allocation of channels to cells $\tilde{A}=\left\{\tilde{A}_1, \tilde{A}_2, \ldots, \tilde{A}_{|V|}\right\}$ should be imposed. Set $\tilde{A}_i$ comprises the channels allocated to cell u_i in allocation $\tilde{A}$. This allocation should possess the following properties. First, it should be compliant to the frequency reuse distance constraints. Second, it should maximise the number of accommodated channel requests. Third, the already established allocation should be taken into account. That is, $\tilde{A}$ should be obtained by performing the minimum possible number of alterations in A. The practical meaning of this requirement is to adapt to the traffic variation as soon as possible, and to avoid having to perform massive network originated handovers. The resulting problem may be stated as follows.

Problem 2 [Total Reconfiguration of Channel Allocation - TRCA]. Given a collection of channels $C=\{c_1, c_2, \ldots, c_{|C|}\}$, a graph $G(V,E)$ which describes the cell coverage of an area, the minimum distance *d* between cells which are allowed to use the same frequency, for each cell v_i $(i=1,\ldots,|V|)$ the load b_i (from where we obtain the required number of channels a_i), an allocation A of frequencies to cells (where $A=\left\{A_1, A_2, \ldots, A_{|V|}\right\}$, $A_i \subseteq C$ $(i=1,\ldots,|V|)$ and $A_i \cap A_j = \varnothing$ if $d(v_i, v_j) < d$), find a new allocation $\tilde{A}=\{\tilde{A}_1, \tilde{A}_2, \ldots, \tilde{A}_{|V|}\}$ ($\tilde{A}_i \subseteq C$ $(i=1,\ldots,|V|)$, $|\tilde{A}_i| \leq a_i$ and $\tilde{A}_i \cap \tilde{A}_j = \varnothing$ if $d(v_i, v_j) < d$), such that the amount $\sum_{i=1}^{|V|}|\tilde{A}_i|$ is maximised by performing the minimum possible number of alterations in A.

The solutions to the two problems defined in this section, namely ACA and TRCA, will be the subject of sections 3 and 4, respectively.

3. Aggregate Channel Allocation

3.1. Optimal formulation

The problem of aggregate channel allocation may be optimally solved by reduction to a *0-1 linear programming* problem [7]. This problem aims at accommodating the maximum possible number of channel requests in the system. The set of constraints guarantees that the frequency reuse constraint will be satisfied and that each cell will not be assigned more channels than those it actually needs. Since *0-1* linear programming problems are *NP*-complete the existence of an optimal algorithm that may be applied in real-time is unlikely. Therefore, in order to solve *ACA* in real-time, and hence, to enable the system to dynamically handle major traffic variations, a “fast” near-optimal algorithm should be devised.

3.2. Computationally efficient solution

A computationally efficient algorithm for real-time solution of ACA problem could have as its focal point the allocation of each channel in the appropriate set of cells at a given phase of the algorithm. In order to avoid the computation of such sets during the algorithm execution, we may use as a basis an initial partition of the cells of the system, which may be obtained prior to the algorithm application. In other words, we introduce an (off-line) step in which the cell structure is pre-processed, in order to obtain a colouring or covering of the corresponding graph (see off-line segment in figure 1). The outcome of this step will be further processed during the main phases of the algorithm (see upper box in the on-line segment in figure 1) so as to determine the appropriate set of cells that should acquire the channels that are being allocated in the particular phases. The initial partitioning of the cell structure may consist of sets of cells $(V_1, V_2, \ldots, V_m)$ such that ($i = 1, \ldots, m$) each set will comprise cells that can use the same frequency at the same time.

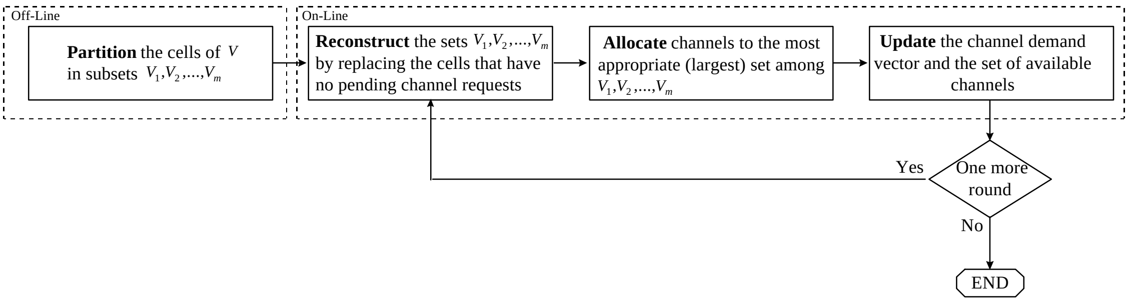


Figure 1: High level solution of the ACA problem

4. Total Reconfiguration of Channel Allocation

The solution to TRCA (*Problem 2*) may be provided through a two phase process (see figure 2).

In the first phase, the aim is to maximise the number of accommodated channel requests in the system. Therefore, a new allocation of channels to cells may be found, based on the algorithms of the previous section. In other words, the first phase of the solution of the TRCA is considered to be an instance of the ACA problem. Hence, any efficient algorithm for the ACA may be applied in the first phase of the TRFA problem. Lets assume that the outcome of this phase is a new allocation of frequencies to cells $\tilde{A}_{init}$. However, the ACA problem does not take into account the already established allocation.

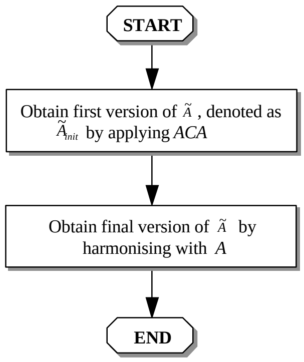


Figure 2: Description of solution of the TRCA problem

In this respect, the new allocation may be markedly different, a fact that will cause significant overhead until the network adapts to the traffic variation. Hence, the second phase of the solution of TRCA should be targeted to the “harmonisation” of the new allocation with the previous one. The outcome of this phase will be the pursued allocation $\tilde{A}$.

4.1. Optimal formulation

The harmonisation phase of the TRCA scheme may be optimally solved through a reduction to a *0-1 quadratic programming problem* [8]. The objective of this problem is to bring the two allocations as close as possible. The set of constraints guarantees that the frequency reuse distance constraints will be preserved and that each cell will possess the same number of channels in allocations $\tilde{A}_{init}$ and $\tilde{A}$. Unfortunately, the optimal formulation of the harmonisation phase of TRCA is *NP*-complete. Hence, we describe in the following a computationally efficient heuristic solution.

4.2. Harmonisation Phase - Version I

A computationally efficient solution could be derived for TRCA problem by reduction to a *flow problem*. The corresponding algorithm would aim at the maximisation of the number of cells that would retain the same channels in both allocations A and $\tilde{A}$.

4.3. Harmonisation Phase - Version II

An alternative way to solve TRCA problem is by reduction to a *weighted matching problem* [5] also known as *the assignment problem* which can be solved by polynomial complexity methods. A complementary step that would yield further improvements is the application of a local filtering algorithm that takes as an input the allocation that derives from the weighted matching problem and examines on a per cell basis if further improvement could be achieved.

6. Results

In this section we assess the performance of the proposed algorithms. Our focus is to provide some indicative examples on the behaviour of the heuristic TRCA formulation in adapting the channel allocation to traffic variations. The network topology used for our experiments was a 7×7 square (Manhattan) grid network (figure 3). Regarding the traffic demand we assumed a simple scenario (table I). There are two load vectors that the network has to accommodate. The load is initially heavier on the periphery of the network (Area A in figure 3). Gradually it shifts towards the centre of the structure, i.e., the traffic demand is directed to Area C in figure 9 through Area B. From these load vectors we obtain the corresponding channel requests for every cell of our network that guarantees that the blocking probability will remain within acceptable range.

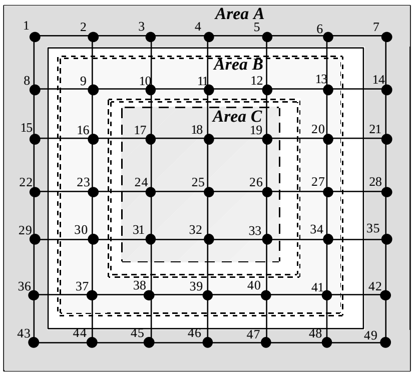
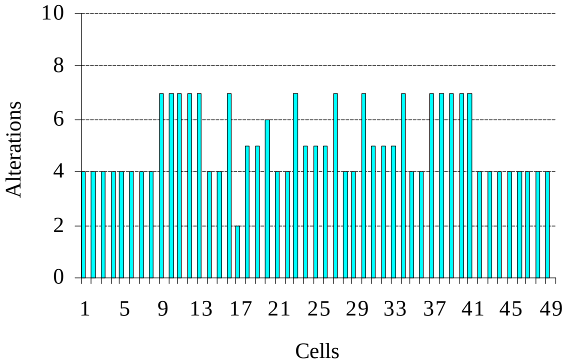


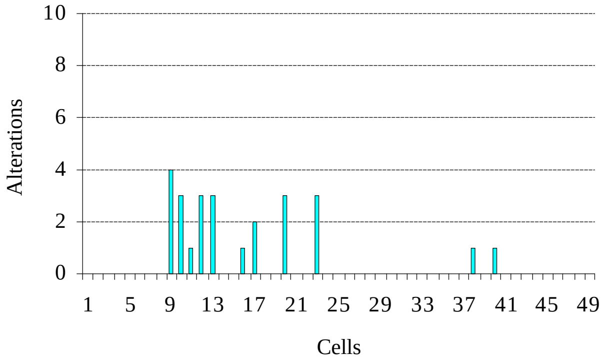
Figure 3: 7x7 square grid cell structure

Table I: Traffic demand per area in the two periods during the day

Area	Load 1	Load 2
A	750	225
B	450	750
C	300	1125

Figure 4(a) depicts the number of alterations required for the transition from *Load 1* to *Load 2* in case the harmonisation phase is not applied, while figure 4(b) depicts the corresponding number in case the harmonisation phase is applied. Due to computational complexity reasons obtaining an optimal solution was not feasible. From the obtained results we conclude that the heuristic version of the harmonisation phase appears effective in reducing the required number of alterations in the channel allocation pattern.





(a) **(b)**

Figure 4(a)-(b): Number of alterations required per cell for the transition from Load 1 to Load 2 after (a) the first phase of TRCA, and (b), the harmonisation phase of TRCA

6. References

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