Synopsis

Efficient Channel Assignment Techniques in Cellular Mobile Networks

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1 Introduction

In recent years, mobile computing has emerged as an important topic of research, because of the need for ubiquitous computing even when people are on move. Use of small hand-held devices for communicating multi-media signals, e.g., voice, video, data, by mobile users has become increasingly popular and widespread over the last few years. The need for such an advanced level of tetherless mobile multimedia services has motivated researchers in this area to develop wireless networks that can not only provide the integrated services, but also can support the facilities of dynamically locating the mobile terminals as well as efficient message routing among them.

Depending on the availability of infrastructure, mobile communication networks can broadly be classified in two distinct groups : cellular and ad hoc. In a cellular network, the whole region is divided into a number of cells (geographical areas) each of which is controlled by a base station (BS). Each base station is in-charge of communicating with all the mobile users currently present within its cell boundary. Communication between a mobile terminal and the base station is wireless in nature, while the base stations themselves are connected by a wired network, in general. A number of mutually adjacent cells may be grouped together to form a location area (LA) which is controlled by a mobile switching center (MSC). In a cellular environment, communication is effected through a channel which may use the basic techniques of frequency division and/or time division and/or code division multiplexing.

In contrast to this, ad hoc networks do not have any such base station, but only the mobile terminals themselves are responsible for controlling the communication among various mobile users [30, 47]. The nodes in an ad hoc network communicate with one another over scarce wireless channels in a multi-hop fashion. Such a network is particularly useful in military applications as well as in several civilian applications like disaster relief, distance education to remote rural areas, remote medical advice etc., where installation of a base station is either economically not viable or very difficult due to terrain which are not easily accessible.

Wireless ad hoc networks have also become attractive in recent years as a candidate technology for the development of low-power sensor networks in various applications [14, 53, 34, 12, 54]. The ad hoc network is adaptable to the highly dynamic topology resulting from the mobility of network nodes and the changing propagation conditions. Route maintenance [51, 50] and host enumeration are key requirements for such an ad hoc network. Two fundamental problems that arise for the network to be self-organizing are leader election and initialization [46, 47, 48, 49]. The leader election problem deals with identifying one of the nodes in the ad hoc network as the leader and informing all other nodes of the identity of this elected leader. The initialization problem is to assign a distinct number (id) in the range 1 to n (if there are n nodes in the network).

Mobility management and bandwidth management are two major research issues in a cellular mobile network. Mobility management consists of two basic components : location management and handoff management. Location management handles tracking of mobile terminals and delivering the incoming calls to the mobiles [4, 5, 1, 2, 7, 6, 21]. Handoff management deals with providing continuity of a call in progress with the required Quality of Service (QoS), even when the users move from the coverage area of one base station to that of another base station [65, 68, 69, 59].

With the ever-increasing number of mobile users and a preassigned communication bandwidth, the problem of efficiently using the radio spectrum for cellular mobile communication has become a critical research issue in recent years [3, 18, 19, 20, 41, 43, 55, 33, 8, 56]. The key factor in the reuse of radio spectrum in the cells is the channel interference. Neglecting other influencing factors, we assume that the channel interference is primarily a function of frequency and distance. A channel can simultaneously be used by multiple base stations, if their mutual separation is more than the *reuse distance*, i.e., the minimum distance at which two signals of the same frequency do not interfere. In a cellular environment, the reuse distance is usually expressed in units of number of cells. Based on that, three types of interference are generally taken into consideration : i) *co-channel interference*, due to which the same channel is not allowed to be simultaneously assigned to a pair of cells which are not sufficiently far apart, ii) *adjacent channel interference*, for which adjacent channels are not allowed to be assigned to certain pairs of cells simultaneously, and iii) *co-site interference*, which implies that any pair of channels assigned to the same cell must be separated by a certain minimum value. The task of assigning frequency channels to the cells satisfying the frequency separation constraints with a view to avoiding channel interference and using as small bandwidth as possible is known as the *channel assignment problem* (CAP). In its most general form, the CAP is equivalent to the generalized graph-coloring problem which is a well-known NP-complete problem [31].

Because of the NP-complete nature of the CAP, researchers attempted to develop more and more time-efficient heuristic or approximate algorithms for the CAP which, however, cannot guarantee optimal solutions. Sometimes, it may so happen that some approximate algorithms over-estimate the number of frequencies by more than 100 percent [28]. An even worse feature of these approximate algorithms is that many of them do not supply any information about how far their results are away from the optimality [25]. Furthermore, in heuristic approaches like genetic algorithm [10, 52, 40, 16, 17, 15], the process always terminates after a certain number of iterations. Hence, a prior idea about lower bounds on bandwidth will help the procedure a lot. Also, in the neural network [39, 36, 23, 61, 24] and simulated annealing approaches [22, 42], the techniques start from known lower bounds and improve the results in each iteration. Therefore, whatever be the heuristic approach, it is very useful to have a better idea about the lower bounds on the minimum number of frequencies needed for a solution to the CAP.

2 The CAP and its Different Formulations

We use here the same model to represent a CAP as described in [58], [60], [35]. This model is described by the following components :

1. A set X of n distinct cells, with cell numbers $0, 1, \cdots, n-1$.
2. A demand vector $W = (w_i)(0 \leq i \leq n-1)$ where w_i represents the number of channels required for cell i.
3. A frequency separation matrix $C = (c_{ij})$ where c_{ij} represents the minimum frequency separation requirement between a call in cell i and a call in cell j $(0 \leq i, j \leq n-1)$.

4. A frequency assignment matrix $\Phi = (\phi_{ij})$, where ϕ_{ij} represents the frequency assigned to call j in cell i ($0 \leq i \leq n-1$, $0 \leq j \leq w_i - 1$). The assigned frequencies ϕ_{ij}'s are assumed to be evenly spaced, and can be represented by integers ≥ 0.

5. A set of frequency separation constraints specified by the frequency separation matrix :
   $|\phi_{ik} - \phi_{jl}| \geq c_{ij}$ for all i, j, k, l (except when both $i = j$ and $k = l$).

Based on this model a channel assignment problem P can be characterized by the triplet (X,W,C). A frequency assignment Φ for P is said to be *admissible* if ϕ_{ij}'s satisfy the component 5 above for all i, j, where $0 \leq i \leq n-1$ and $0 \leq j \leq w_i - 1$. The *span* $S(\Phi)$ of a frequency assignment Φ is the maximum frequency assigned to the system. That is,

$$S(\Phi) = \max_{i,j} \phi_{ij}.$$

Thus, one possible formulation of CAP is to find an admissible frequency assignment with the minimum span $S_0(P)$, where $S_0(P) = \min\{S(\Phi) |\ \Phi \text{ is admissible for } P\}$. $S_0(P)$ will then be the lower bound on bandwidth for the given assignment problem. The objective of this formulation is to assign frequencies to the cells satisfying the frequency separation constraints as specified by the component 5 above, in such a way that the required system bandwidth becomes *optimal.* This class of assignment problem is known as the *minimum span* frequency assignment and we denote this as the *first category* of CAP.

There exists a different formulation of CAP where we look for the channel assignment when the bandwidth B of the system is given, which may even be smaller than the required lower bound on bandwidth for the given problem. Depending on B, it may or may not be possible to satisfy all the channel demands of each cell unless B is sufficiently large. Thus, a solution to this variant of CAP may, in general, leave some blocked calls. However, the objective in this case is to minimize the call blocking as far as possible. This class of assignment problem is known as the *fixed bandwidth* frequency assignment and we denote this as the *second category* of CAP.

In both the above formulations of the CAP, the primary objective was to achieve the best possible assignment, i.e., either an optimal assignment (for the first category of CAP), or an assignment with minimal call blocking (for the second category of CAP). There is, however, another class of problems of real-life importance known as Perturbation-Minimizing Frequency Assignment Problem (PMFAP) [64] which is described as follows.

Assume that initially an assignment has been obtained for a given network to satisfy the required channel demands. After some time, demands of some of the cells may be changed due to i) newly generated calls, or ii) a handoff situation [65, 68, 69, 59], or iii) completion of some ongoing calls. The objective of this variant of CAP is to accommodate these small changes in demands; but while doing so, the number of changes in the existing assignment should be minimized, while meeting the desired Quality of Service (e.g., percentage of call blocking, call setup time).

3 Review of Earlier Works

Some of the researchers attempted to solve the first category of CAP from a graph theoretic view point, and proposed many heuristics [60, 38]. Later improved approximate algorithms using neural networks, simulated annealing, tabu search [13, 32, 44] and genetic algorithms, have also been proposed to solve both the first and second categories of CAPs. For the first category of CAP, these approximate algorithms first determines an ordered list of all calls and then assign channels deterministically to the calls so as to minimize the required bandwidth [60, 38, 15, 9]. For the second category of CAP, given the bandwidth of the system, these approximate algorithms formulate a cost function such as the number of calls blocked by a given channel assignment, and then tries to minimize this cost function [22, 42, 39, 52, 40, 36, 23, 61, 44]. The advantage of the first category of algorithms is that the derived channel assignment always fulfills all the interference constraints for a given demand; but it may be hard to find an optimal solution in case of large and difficult problems, even with quite powerful optimization tools. On the other hand, for the second category of algorithms, it may be impossible to minimize the cost function to the desired value of zero with the minimum number of channels, in case of very hard problems. In [10], the authors combined both of the above methods in order to combine their advantages and proposed the combined genetic algorithm (CGA) that generates a call list in each iteration, and evaluates the quality of the generated call list following the Frequency Exhaustive Assignment (FEA) strategy.

In the neural network approach [39, 36, 23, 61, 24], an inherent disadvantage is that it may easily converge to local optima, and hence optimal solutions cannot always be guaranteed. The simulated annealing approach [22, 42] guarantees global optimal solution asymptotically, but the rate of convergence is rather slow. The genetic algorithm approach

[10, 52, 40, 16, 17, 15], however, sometimes provides a global optimal solution with a relatively faster rate of convergence.

In order to compare the performance of several algorithms for channel assignment, some well-known benchmark instances defined on a 21-node cellular network (commonly known as Philadelphia benchmarks) are widely used in the literature [9, 15, 10, 23, 36, 38, 52, 60, 62, 64, 37, 67]. Among the eight Philadelphia benchmark instances, it is relatively easier to derive the optimal solution for the six problems than the problems 2 and 6, because in all those six cases the required number of channels is primarily limited by the co-site interference constraint only. Most difficult is, however, to get the optimal solution for the other two Philadelphia benchmark instances - problems 2 and 6. In fact, problems 2 and 6 are regarded as the most difficult ones in the literature [10], [9]. For example, the assignment algorithm given in [52] required 165 hours of computing time for problem 6 on an unloaded HP Apollo 9000/700 workstation, but giving only a non-optimal solution with 268 channels (optimality requires only 253 channels). Later, however, the authors in [10] proposed an algorithm which provided an optimal solutions for both problems 2 and 6 with a running time of 8 and 10 minutes, respectively on the same workstation. Among the later works, the FESR (Frequency Exhaustive Strategy with Rearrangement) algorithm in [64] and the Randomized Saturation Degree (RSD) heuristic presented in [9] also produce only non-optimal solutions to the benchmark problems 2 and 6. However, combining their RSD heuristic with a Local Search (LS) algorithm, the authors in [9] were able to find an optimal solution for problem 2 but not for problem 6. Most recently, an efficient heuristic algorithm has been proposed in [15] which also produced non-optimal results for problems 2 and 6 with 463 and 273 channels respectively.

Therefore, for both the first and second categories of CAP, development of time efficient heuristics to deal with these difficult problems, e.g., problems 2 and 6, are still called for. For the first category of CAP, we need to develop algorithms which would require a bandwidth equal to the lower bound of the problem. On the other hand, for the second category of CAP, given the bandwidth equal to the lower bound, the algorithm should preferably provide call blocking equal to zero.

A first step towards finding a lower bound on bandwidth has been discussed in [27]. The lower bounds introduced there are, however, generated exclusively by co-channel constraints. In [25], Gamst presented some lower bounds on bandwidth for the problem taking into account the additional adjacent channel and co-site constraints. Some of these bounds are particularly useful when applied to combinations of co-channel and adjacent channel constraints, while some others considered the additional co-site constraints also. Improving the results by Gamst, Tcha, Chung and Choi [63] presented some results on the lower bound which, however, do not explicitly include the co-site constraints. In [62], the authors derived a lower bound which, in some cases, is tighter than those presented in [25] considering all the co-channel, adjacent channel and co-site constraints. These lower bounds are defined on a general network of arbitrary cell structure. However, these lower bounds when applied to the special case of hexagonal cellular networks with 2-band buffering (where the channel interference does not extend beyond two cells) are not always found to be very tight. Since most of the known benchmark instances including the Philadelphia problems are defined on the hexagonal cellular networks with a 2-band buffering restriction, a tighter estimate of the lower bound on bandwidth for these special cases is still called for.

4 Scope of the Thesis

In this thesis, we first consider the problem of finding new lower bounds on bandwidth for the hexagonal cellular networks with 2-band buffering. We consider here all the interference criteria (i.e., the co-channel, adjacent channel and co-site constraints) for both homogeneous and non-homogeneous demands on the cells of hexagonal cellular networks. Next, we develop efficient channel assignment algorithms for both the first and second categories of CAP. We then extend these ideas to solve the Perturbation-Minimizing Frequency Assignment Problem (PMFAP), the objective of which is to cope up with the short-term changes in demands on the cells. We present below a brief outline of our work on each of the above issues.

4.1 Lower Bound on Bandwidth

4.1.1 Homogeneous Demand on Hexagonal Cellular Networks

We first find new lower bounds on the bandwidth for a hexagonal cellular network with 2-band buffering and homogeneous demands w (i.e., the number of channels required for every cell is equal to w). In order to account for a 2-band buffering, we have used three parameters s_0, s_1 and s_2, which are the minimum frequency separations required to avoid interference for calls in the same cell, or cells at distances one and two, respectively. We have found expressions for lower bound on bandwidth for different relative values of s_0, s_1 and s_2. The new lower bounds presented here are always either equal to or tighter than those in [62, 25, 63] when applied to the special case of hexagonal cellular networks with homogeneous demand and 2-band buffering.

4.1.2 Non-homogeneous Demand on Hexagonal Cellular Networks

We next find lower bounds on bandwidth for the cases of hexagonal cellular network and 2-band buffering with the non-homogeneous demand vector $W = (w_i)$ where w_i is the channel requirement for cell i. Let $w = max(w_i)$, $i = 1, 2, \cdots, n$. It is evident that the minimum bandwidth required to satisfy the homogeneous demand w, is an *upper bound* on the minimum bandwidth requirement with the demand vector $W = (w_i)$. It is also evident that a trivial *lower bound* on bandwidth is $(w - 1)s_0$. However, this lower bound is not always tight for all values of s_0, s_1, s_2, and W for a 2-band buffering. We find expressions for tighter *lower bound* on bandwidth for different relative values of s_0, s_1, and s_2.

4.1.3 Non-hexagonal Cellular Networks

We also find new tighter lower bounds for the non-hexagonal cellular networks. Based on the interference criteria, we reconstitute a subset of the network in a hierarchical way to find the lower bounds for the general network. We show that the established lower bounds are either exactly equal to or tighter than those presented in [62, 25].

4.2 Channel Assignment Techniques

4.2.1 Homogeneous Demands

We present an algorithm for solving the channel assignment problem in its most general form using the elitist model of genetic algorithm (EGA). We then show how this general approach can conveniently be applied to the special case of hexagonal cellular network with homogeneous demands on the cells. For this special case, our approach essentially identifies a small subset of cells of the network. We apply the EGA on this subset of cells to find its assignment, and next repeat the assignment for the whole network. The proposed technique has a faster rate of convergence as the EGA here is applied to a small subset of cells only, instead of the network as a whole. Based on this technique, we have proposed three different frequency assignment schemes which results in an improvement upto 25% in bandwidth over the earlier results.

4.2.2 Non-Homogeneous Demands

We show how our method for homogeneous demands can also be used to solve the channel assignment problem with non-homogeneous demand vector $W = (w_i)$. Based on different relative values of s_0, s_1, and s_2, we categorize some problems as *easy problems* and some as *relatively difficult problems.* For these easy problems, e.g., Philadelphia problems 3 and 7, the required bandwidth is mainly determined by the maximum demand w_{max} in W. It reveals the fact that in terms of bandwidth requirement the case is almost equivalent to the cellular networks having homogeneous demand w_{max}. Consequently, these problems with non-homogeneous demands can be solved very efficiently using the technique of homogeneous channel assignment with much less computation time (e.g., Philadelphia problems 3 and 7 can be optimally solved requiring less than a second on a DEC Alpha station 200 4/233).

For other relatively difficult problems, EGA can still be applied but the computation time required to get the optimal solution may be very high. For example, the computation time required to solve the two difficult problems - Philadelphia problems 2 and 6 varied between 12-80 hours for different runs on the same workstation. For such difficult problems, we propose two new approaches; one based on *critical block* and the other based on *coalesced CAP*, as discussed below.

A) Critical Block approach

We first introduce the notion of a *critical block* of hexagonal cellular network. For a network with a given demand vector and frequency separation constraints, we present an algorithm for finding its critical block. A novel idea of partitioning (through a linear integer programming (IP) formulation) the critical block into several smaller sub-networks with homogeneous demands has been introduced which provides an elegant way of assigning frequencies to the critical block. This idea of partitioning is then extended for assigning frequencies to the rest of the network. The proposed algorithm provides an optimal assignment for all well-known benchmark instances including the most difficult two. In this approach, we need only around a few seconds for channel assignment of all the six benchmark instances other than problems 2 and 6, on an unloaded Sun Ultra 60 workstation. For the benchmark problems 2 and 6, however, our algorithm needs around 60 seconds and 72 seconds of running time, respectively on the same workstation, in contrast to about 8 and 10 minutes respectively [10], on an unloaded HP Apollo 9000/700 workstation.

B) Coalesced CAP Approach

We next present an elegant technique for solving the channel assignment problem (CAP) which can be applied even to a cellular network with no regular hexagonal structure. This algorithm falls under the second category of algorithms as discussed above. This technique first maps a given problem P to a modified problem P' (*Coalesced CAP*) on a small subset of cells of the network, offering a much reduced search space. This helps solving the problem P' by applying approximate algorithms more efficiently. This solution to P' is then used to derive the solution to the original problem P. However, based on the solution obtained for P', we may have two possible situations : 1) if the solution to P' provides zero call blocking, an admissible channel assignment for P can immediately be derived from the solution to P', 2) if all requirements for P are not satisfied by the solution to P', then call blocking may result. An algorithm is then presented for this latter situation which is an appropriately modified version of the *Forced Assignment with Rearrangement (FAR)* operation reported in [64]. Application of this Modified FAR (MFAR) operation to well-known benchmarks always generates optimal results for all of them. Also, the computation time is improved even over the critical block approach discussed above. For instance, we need only around 10 and 20 seconds on an unloaded DEC Alpha station 200 4/233, for the benchmark problems 2 and 6, respectively to get an assignment (with a bandwidth equal to the lower bound) with call blocking equal to zero. This may be contrasted to the earlier works [52] which, using a bandwidth equal to the lower bound, failed to provide call blocking equal to zero for problem 6. Moreover, as a bye-product of this approach we will see that there will be, in general, some unused or redundant channels. These redundant channels may effectively be utilized to solve Perturbation-Minimizing Frequency Assignment Problem (PMFAP) [64] as discussed in the following subsection.

4.2.3 Perturbation-Minimizing Assignment

We finally consider the channel assignment problem in the framework of perturbation-minimizing frequency assignment problem (PMFAP) [64]. Let α be the maximum allowable number of changes in the existing frequency assignments to accommodate a new call. We extend our concept of the *Coalesced CAP* as proposed above and use somewhat similar techniques for perturbation minimization as in [64] to devise an algorithm for assigning as many newly generated channel demands as possible, keeping the number of reassignment per new call below the predefined value α. We show that it is possible to do a trade off between the value of α and the required computation time for the assignment, so that depending on a particular application requirement (e.g., percentage of call blocking, call setup time) one can appropriately tune the algorithm with a proper choice of α. Application of the proposed methodology to well-known benchmark instances results lesser perturbation in existing assignments than the earlier ones [64], while keeping the number of blocked calls almost unchanged. However, the computation time in our approach appears to be slightly higher than that in [64] for certain problems.

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