ADVANCED FREQUENCY PLANNING TECHNIQUES FOR TDMA AND GSM NETWORKS

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ABSTRACT

With the increasing popularity of cellular telephony service, providers are having to support more and more users with limited infrastructure. Nowhere, is it more apparent than the limited resource of "Spectrum." With the amount of money being spent in acquiring the rights to use pieces of spectrum, it is imperative that this resource be used in the most cost-effective manner to provide excellent quality of service to as many users as possible. In this article we address the classic spectrum utilization problem of frequency planning. We present a new and novel method for solving this problem for TDMA systems such as GSM and North American cellular systems.

The past work in this area has focussed on either: 1) Using an idealized hexagonal grid system or 2) Using an idealized modeling of the RF environment. In our approach we make no assumptions about the size, shape, configuration, or the position of the cell sites. Also we use direct drive-test data that reflects all the non-uniformity and unpredictability of the real RF environment. We develop new algorithmic techniques that can handle the complexity of the actual terrain and drive-test data and take advantage of the existing non-uniformity in arriving at the solution. Using direct drive test data and avoiding idealized assumptions guarantees a good in-field performance of the frequency plan generated by our technique. Our results show significant improvement over solutions obtained from classical reuse patterns and frequency planning techniques. Using our techniques we have created frequency plans that have 75% more RF capacity with little or no degradation in C/I and C/A performance compared to an existing reference plan.

I. INTRODUCTION

In a wireless cellular network, radio frequencies are used to carry voice or data between base stations and mobiles. The traffic in today's cellular network is usually too high to allow the usage of a channel for one call at a time. Same radio channels must be used simultaneously for more than one call. This is known as "channel reuse" and cells using the same channel are called "cochannel cells". Besides interference caused by cochannel cells, cells using adjacent frequencies can also cause certain amount of interference, which usually is significantly lower than the cochannel interference, but still not desirable in certain cases. Hence, careful planning of these limited number of radio frequencies becomes an important issue in today's TDMA and GSM network planning. A good frequency planning methodology will be able to either decrease the interference level in a cellular network thus increase the quality of service or increase the capacity of the network by assigning maximum number of frequencies possible to each sector while maintaining the interference level below tolerable threshold.

Frequency assignment problem has been very well studied in both industry and academia. In different categories of frequency assignment problems, fixed frequency assignment problem is still the basis for obtaining any kind of good frequency assignment. In industry, we observed that the popular approach is to start the assignment with the classical $N = 7$ or $N = 4$ reuse patterns [8], while in academia, most approaches are focused on solving the graph coloring problem formulated from the frequency assignment problem [1,2,5,6,9]. The classical reuse patterns are based on ideal propagation condition that assumes the sector coverages are equally sized hexagons. It also assumes each sector has exactly the same antenna configuration. Real systems are a mixture of sites with different sizes due to different propagation condition. Many sites have different number of sectors and different orientations for the antennas. All these factors make the solutions obtained from reuse patterns far away from the optimal assignment possible, even after careful manual adjustments.

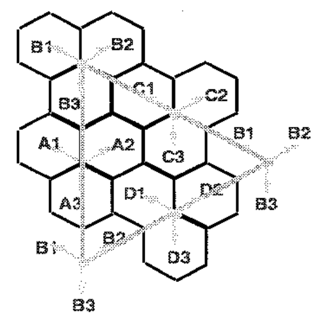

Figure 1: Reuse pattern when N = 4

In graph coloring approach, a graph representation of a cellular network is constructed by,

1. each vertex represents a sector,
2. an edge exists between two vertices if and only if channel separation constraint exists between the two sectors they represent.

The objective then is to find a feasible assignment to each vertex where all the separation constraints are satisfied and uses least amount of frequency channels among all feasible assignments [9]. This formulation has its own disadvantages. First, all constraints are binary, that is, two sectors can either have the same frequency or have different frequencies once the problem is formulated. This is not flexible enough as it may lead to infeasible situation when the operator is willing to tolerate more interference in exchange of supporting more user traffic. Second, all constraints are pairwise where it can not model the situation that every pair of

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sectors are allowed to have the same frequency while the same frequency can not be used among a group of sectors. This is caused by the aggregation of co-channel interferences from multiple sectors. Also, graph coloring problem can not model interference from adjacent channels.

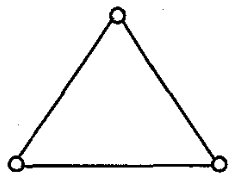

Figure 2: Each pair of nodes can be assigned the same frequency while all three nodes can not be assigned the same frequency. This cannot be modeled by the graph-coloring formulation.

In this paper, we remedy these shortcomings by incorporating the following new approaches:

1. Drive test data reflecting the real propagation condition is used as input to solve the assignment problem. Hence, the solution obtained fits well in the real network when implemented.

2. New integer programming model is formulated to maximize the worst C/I or average C/I performance among all the drive test points. Interferences from multiple co-channel sectors and adjacent-channel sectors are incorporated into the formulation. There are no binary constraints as in the graph coloring problem. The objective is to minimize the interference level in the network for any given number of frequencies.

3. Since frequency assignment problem is a highly complex problem, any kind of resulting formulation usually leads to an NP-complete problem. This makes it almost impossible to obtain the optimal solutions when the problem size is large. Hence, we devised a decomposition algorithm which decomposes the network into smaller parts to be solved almost independently. We have found this approach to be very effective in cutting down the running time and obtaining good solutions.

In the experiments performed, frequency plans having the same, 15%, 40% or 75% more RF capacities are generated to compare to one existing plan. Numerical results given by leading RF design software shows the new solutions having either better or no degradation in C/I and C/A performance (see Figures 4-8 and Table 1).

II. DRIVE TEST DATA

The input for the new frequency assignment technique is data collected from drive test. Drive test is a procedure of recording signal strengths and timing events when driving across a cellular network. It is frequently performed during network deployment and operation stages. The reason is that no propagation model, no matter how well fitted, can be accurate enough to predict the signal strength in every corner of the network. Field measurement becomes necessary to adjust and make sure the system works properly during operation.

The data requested by the new algorithm can be obtained by driving through the network in need of improving frequency plan. At each drive test point, signal strengths above noise floor from different sectors are recorded. Points chosen should be representative across the network, i.e., by optimizing the C/I performance on these points, C/I performance of the whole network can be expected to be optimized. Sometimes, driving test the whole network becomes too expensive and in this case propagation predictions can be incorporated with the measured data.

The drive test data is used to formulate the integer programming formulation which will be described in the next section and to calculate signal to interference ratio, or C/I at each drive test point. C/I is the most important measure in terms of guarantying sufficient quality of service in the network. The way to calculate C/I at each dirve test point given any frequency assignment is explained as follows.

Let P_{kj} be the signal strength in dBm received from sector j at point k. Also, assume P_{ki} be the best power in dBm at point k and it is from sector i. Then the interference from sector j at point k is calculated by $I_{kj} = 10^{P_{kj}/10}$ if sector i and sector j are assigned the same frequency. $I_{kj} = 10^{(P_{kj}-m)/10}$ if sector i and sector j are assigned adjacent frequencies where m is the next channel mask and $I_{kj} = 0$ otherwise. C/I at point k is then equal to

$$P_{kj} - 10\log\sum_j I_{kj} \tag{1}$$

where interferences from multiple sectors and adjacent channels are summed.

III. INTEGER PROGRAMMING FORMULATION

Use the drive test data described above, we can formulate our frequency assignment problem into an integer programming problem.

Let X_i be the frequency group number assigned to cell i. Let K be the set of testing points and at each point k, J_k be the set of sectors where potential interference comes from. Also, let i_k be the best server at point k, i.e. the sector where strongest signal comes from. Then, the fixed frequency group assignment problem can be formulated as follow:

where N is the number of frequency groups available, c is the channel separation requirement for frequencies assigned to adjacent sectors, and d_{kj} the power decrement in milliwatts if the interference is from adjacent channel. It is computed as $d_{kj} = P_{kj}(1-10^{-m/10})$. The purpose of the second and third set of constraints is to take care of the special situation where frequency group 0 and group $N-1$ are adjacent to each other.

The above formulation is an integer programming problem since X_j must be integers and the presence of absolute value constraints. N is typically 21 for a TDMA system and 12 for a GSM system. On the other hand, the

$$
\begin{array}{lll}
min & Z & \\
\text{subject to:} & Z_{kj} \geq P_{kj} - |X_{i_k} - X_j| d_{kj} & j \in J_k, k \in K \\
& Z_{kj} \geq P_{kj} - (N - X_{i_k} + X_j) d_{kj} & j \in J_k, k \in K \\
& Z_{kj} \geq P_{kj} - (N + X_{i_k} - X_j) d_{kj} & j \in J_k, k \in K \\
& P_{ki_k} Z \geq \sum_{j \in J_k} Z_{kj} & k \in K \\
& 0 \leq X_{i_k}, X_j \leq N-1 & Z_{kj} \geq 0 \\
& |X_i - X_j| \geq c & \text{if i, j are adj. sectors}
\end{array}
$$

formulation allows us to use any number of groups as it is only a constant in the formulation. So we can easily test the feasibility of for example, N =6, 5 or 4 assignment or anything in-between in a TDMA North American Cellular system.

If there are multiple groups assigned to the same sector, extra constraints $|X_{i1} - X_{i2}| \geq d$ must be added for frequency groups assigned to the same sector where d is the channel separation requirement for channels assigned to the same sector. The separation constraints between sectors need to be repeated for every group assigned.

The objective function Z is taken as the inverse of worst C/I here. We can also change it to average C/I or the one-sided difference from a given C/I threshold. These can all be formulated into a linear objective function.

IV. DECOMPOSITION ALGORITHM

The integer programming problem formulated takes too long to solve once the network becomes large. So a decomposition algorithm is devised to decompose the network into smaller sub-networks. The key to a decomposition approach is to partition in the area where the potential interference across the two parts of the network is minimized. By doing so, we don't loss much of the global optimality after we piece the optimal solutions for each sub-network back into one solution.

A network flow problem is formulated as follows: each node represents one sector in the network, The capacities on the arcs in the network is represented by $W(i,j)$. The physical interpretation of $W(i,j)$ is that it represents the "interference weight" between sector i and j. The larger $W(i,j)$, the higher degree in reality they will cause interference to each other, if assigned the same channel or adjacent channels.

One way to define $W(i,j)$ is to let $W(i,j)) = max(C - a(i,j), 0)$ where $a(i,j)$ = minimum(C/I values among all the points having sector i as the best server, sector j as potential interferer or vice versa). The lower the value $a(i,j)$ is, the more potential interference can be between sector i and j. C is a constant and usually can be set as any upper bound for $a(i,j)$. For those pairs of sectors i, j where $a(i,j)$ is not defined, $W(i,j) = 0$ since this means there is no potential interference between these two sectors.

Find node i^*, j^* such that the distance between them is the largest among all pairs in the network. Then, a maximum flow problem is solved using node i^* as the source and node j^* as the sink. The standard algorithm for solving a maximum flow problem is the labeling algorithm [7]. When the labeling algorithm terminates with a maximum flow, it also gives a partition of the network where the sum of $W(i,j)$ on arcs across these two partitions is the minimum among all possible partitions having i^*, j^* in different partitions. This is called the max-flow-min-cut property.

In this problem, when the sum of $W(i,j)$ on arcs across two partitions is minimized, it means the sum of "interference weights" we defined between two parts of the network is minimized. This in turn means the potential interference between two parts of the network is minimized.

Before applying this decomposition algorithm, a pre-processing is performed to identify disconnected parts of the given network. Then, the algorithm can be applied to decompose each connected parts of the network. When solving the frequency assignment problem on the decomposed sub-network, any approaches can be used though we choose to use the integer programming approach described in the last section due to its advantages. In terms of combining the solutions on decomposed problems together, we could either fix the sectors where their frequencies have already been assigned by previously solved sub-problems, when we are solving a decomposed subproblem, or we could solve each subproblem independently, then use some kind of adjustment algorithm to piece each solution back in a way that the cross interference is minimized.

Figure 3 shows a flow chart of how the decomposition algorithm works in solving the frequency assignment problem.

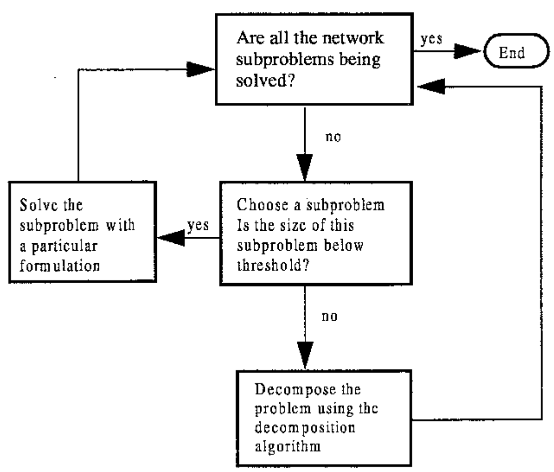

Figure 3: Flow chart of the decomposition algorithm

V. EXPERIMENT RESULTS

Using the integer programming formulation and the decomposition technique described, we performed an experiment on part of an existing TDMA network which has about 280 sectors. Solutions using 21, 18, 15, 12 groups, corresponding to N = 7, 6, 5, 4 reuse respectively, are generated to compare to the existing solution.

Comparison measures used are the percent of total coverage area with C/I above 17 dB and number of sectors with less than 10% of the area having C/I below 17 dB. In the histograms, the x-coordinate is the percent of area within a sector having C/I value below 17 dB and y-coordinate is the number of sectors.

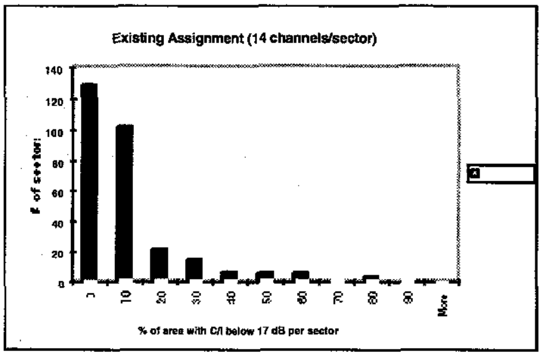

Figure 4: Histograms for existing assignment

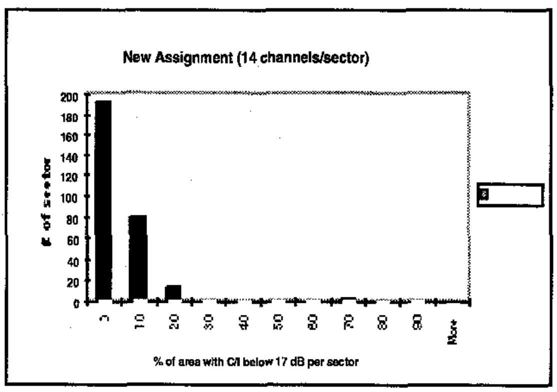

Figure 5: Histograms for new 14 channels/sector assignment

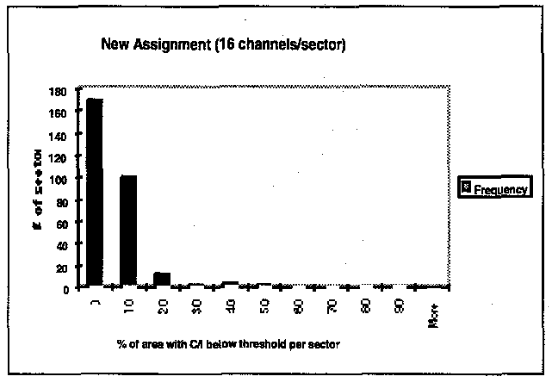

Figure 6: Histograms for new 16 channels/sector assignment

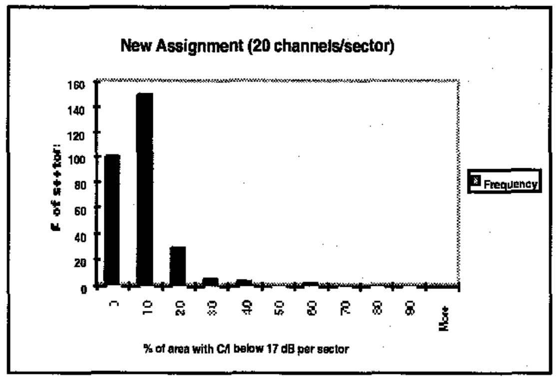

Figure 7: Histograms for new 20 channels/sector assignment

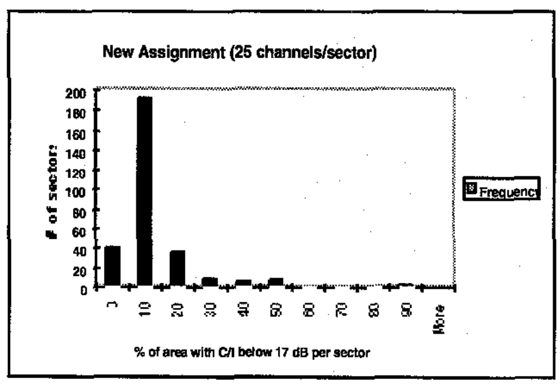

Figure 8: Histograms for new 25 channels/sector assignment

Numerical results are summarized in the following table.

	current assignment	14 channels per sector	16 channels per sector	20 channels per sector	25 channels per sector
% of area above 17 dB	79.4%	94.4%	92.1%	85.9%	79.7%
# of sectors below 10%	229	270	267	248	230

Table 1: Numerical results for all the assignments

The histograms and table above show that the new solution with the same RF capacity as the current assignment has 15% more of the area with C/I above 17 dB and 18% more sectors with 10% or less area having a C/I below 17 dB. At the other end, new solution with 75% more RF capacity than the current assignment shows similar interference level as the current assignment. This indicates the new technique devised has significant advantage over current methodologies. One point though is that the performance measures used assumes the worst case scenario, that is all the frequencies assigned are being used at the same time in the network. In reality, this is not true many of the times. However, for comparison purpose, these still serve as meaningful measures.

VI. CONCLUSION

New techniques using drive test data, integer programming formulation and decomposition technique are presented for solving the fixed frequency assignment problem. In the paper, advantages have been shown over some classical approaches. Numerical results also demonstrated its effectiveness. Future research will extend this to other types of frequency assignment problems.

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