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PAPER

Performance Analysis of Borrowing with Directional Carrier Locking Strategy in Cellular Radio Systems*

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SUMMARY A new carrier based dynamic channel assignment for FDMA/TDMA cellular systems, called *borrowing with directional carrier locking* strategy, is proposed in this paper. When a call arrives at a cell and finds all voice channels busy, a carrier which consists of multiple voice channels can be borrowed from its neighboring cells for carrying the new call if such borrowing will not violate the cochannel interference constraint. Two analytical models, cell group decoupling analysis and phantom cell analysis, are constructed for evaluating the performance of the proposed strategy. Using cell group decoupling (CGD) analysis, a cell is decoupled together with its neigbors from the rest of the network for finding its call blocking probability. Unlike conventional approaches, decoupling enables the analysis to be confined to a local/small problem size and thus efficient solution can be found. For a planar cellular system with three-cell channel reuse pattern, using CGD analysis involves solving of seven-dimenional Markov chains. It becomes less efficient as the number of carriers assigned to each cell increases. To tackle this, we adopt the phantom cell analysis which can simplify the seven-dimensional Markov chain to two three-dimentional Markov chains. Using phantom cell analysis for finding the call blocking probability of a cell, two phantom cells are used to represent its six neighbors. Based on extensive numerical results, we show that the proposed strategy is very efficient in sharing resources among base stations. For low to medium traffic loads and small number of voice channels per carrier, we show that both analytical models provide accurate prediction on the system call blocking probability.
key words: *channel borrowing based dynamic channel assignment, performance analysis*

1. Introduction

In the first generation analog cellular systems, FDMA (frequency division multiple access) is used and each frequency carrier carries only one voice channel. Among various types of channel assignment strategies [1]–[3], the class of channel borrowing based dynamic channel assignments (DCAs) [4]–[6] is shown to be very efficient. Using channel borrowing based DCAs, frequency channels are first allocated to each cell on a nominal basis. When a call arrives at a cell and finds all nominal channels busy, a channel is borrowed from its neighboring cells for carrying the new call if the borrowing will not violate the system cochannel interference constraint. The borrowed channel is then locked in the cochannel cells within the channel reuse distance of the borrowing cell. Among the class of channel borrowing based DCAs that do not require system-wide information, extensive simulations reveal that the borrowing with directional channel locking (BDCL) strategy [7] gives the lowest call blocking probability for systems with both uniform and non-uniform traffic distributions.

For second generation digital FDMA/TDMA cellular systems (e.g. GSM, IS-54), the spectrum is divided into many carriers and each carrier can carry multiple voice channels (or time slots). Each base station is assigned with a number of carriers and a carrier is the basic unit of resource allocation among base stations. Many channel assignment strategies for first generation analog system can be extended to the second generation carrier assignment strategies. Therefore relatively little literature on dynamic carrier assignments can be found. In this paper we propose a new dynamic carrier assignment, called borrowing with directional carrier locking strategy. This strategy is an extension of the borrowing with directional channel locking [7] to a system supporting multiple voice channels per carrier. Using the directional carrier locking strategy, when a call arrives at a cell and finds all voice channels on all nominal carriers busy, a carrier can be borrowed from its neighboring cells for carrying the new call if such borrowing does not violate the system cochannel interference constraint. The borrowed carrier is then locked in the cochannel cells within the channel/carrier reuse distance of the borrowing cell. In the next section, a detailed description of the borrowin with directional carrier locking strategy will be given.

For evaluating the performance of the proposed carrier borrowing strategy, two analytical models are used. Based on the model presented in [8], the cell group decoupling (CGD) analysis is generalized to borrowing with carrier locking strategy in Sect. 3. In CGD analysis, a cell under consideration is decoupled together with its neighboring cells (i.e. cells within its interference range) from the rest of the system. The blocking probability of that cell is found by solving the decoupled system. We show that that the CGD analysis can provide a tight upper bound on the call blocking

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probability of a linear cellular system with single cell buffering. As the number of voice channels per carrier as well as the traffic load increase, the bounding becomes loose.

For planar celluler systems with three cell channel reuse pattern, the CGD analysis becomes generally infeasible due to the complexity in solving the seven-dimensional Markov chains. We extend the original phantom cell analysis in [9] for simplifying the seven-dimensional markov chain to three. We will show that the phantom cell analysis has a lower computational complexity yet still produces accurate analytical results. In Sect. 4, the detailed phantom cell analysis is presented. To find the blocking probability of a cell, two phantom cells are used to represent its six neighboring cells.

In Sect. 5, numerical examples are constructed for evaluating the performance of the borrowing with directional carrier locking strategy. We show that the borrowing with directional carrier locking strategy significantly outperform the fixed channel assignment strategy, which is used as our performance reference. In particular, we show that for low to medium traffic loads and small number of voice channels per carrier, both cell group group decoupling analysis and phantom cell analysis provide accurate prediction on the system call blocking probability. Finally, we conclude the paper in Sect. 6.

2. Borrowing with Directional Carrier Locking

Carrier ordering and immediate carrier reallocation are used in the borrowing with directional carrier locking strategy. Carrier ordering means that all nominal carriers are ordered such that the voice channels on the first carrier has the highest priority to be assigned to the next local call, and the last carrier is given the highest priority to be borrowed by the neighboring cells. Immediate carrier reallocation means that a carrier is reallocated according to the following rules:

- When a call on a nominal carrier terminates and there is another call on a borrowed carrier, the call on the borrowed carrier is switched to the nominal carrier. If no other call on that borrowed carrier, it is released.
- When a call on a nominal carrier terminates and there is another call on a higher order nominal carrier in the same cell, the call in the higher order nominal carrier is reallocated to the newly released lower order carrier.
- When a call on a borrowed carrier terminates and there is another call on a lower order borrowed carrier, the call being carried on the lower order borrowed carrier is switched to this carrier.
- When a carrier is unlocked by the termination of all calls in the interfering cells, any calls on a borrowed carrier or a higher order carrier are immediately switched to this carrier.

When a call arrives at a cell, a voice channel on the lowest available nominal carrier is selected to carry the call. If all voice channels on nominal carriers as well as already borrowed carriers are busy, another carrier is borrowed from neighboring cells if the borrowing will not violate the cochannel interference constraint. By doing this, all active calls are packed towards the lower order nominal carriers such that the load on the higher order nominal carriers is minimized. This facilitate carrier borrowing. This in turn provides very efficient resource sharing among cells.

3. Cell Group Decoupling Analysis

The CGD analysis is applicable to both linear and planar cellular systems. The basic idea of the CGD analysis is to focus on a decoupled system (the cell under investigation and those neigboring cells within its interference range) instead of the whole network. This significantly reduces the problem size. Such decoupling, however, does not cause any significant error in calculating call blocking probabilities. This is because the interaction between the cell under investigation and the further away neighboring cells is negligible (as we shall show later). In this section, we build the analytical model for borrowing with carrier locking strategy using the CGD analysis for both linear and planar cellular systems.

3.1 Linear Cellular Systems

Suppose there are a total of $2m$ distinct carriers available to a linear cellular system (Fig. 1) and they are numbered from 1 to $2m$. Let the same carrier be reused at every other cell. Carriers are divided into two sets such that set A has carriers from 1 to m and set B has carriers from $m+1$ to $2m$. Each cell is assigned with either set A or set B carriers and let the number of voice channels per carrier be z. Each voice channel can be identified through its carrier number and the time slot it occupied.

Let S_i and N_i denote the set of active voice channels and the set of active carriers in cell i. Let $|X|$ denote the number of elements in set X and $\lceil x \rceil$ denote the ceiling function. We have $|N_i| = \lceil |S_i|/z \rceil$ because in the BDCL strategy, voice channels are packed

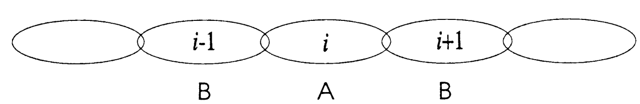

Fig. 1 A linear cellular system with single cell buffering. Cells $i-1$, i and $i+1$ form a decoupled system for cell group decoupling analysis.

towards the lower order nominal carriers. A call attempt arrives at cell i will be blocked if and only if $|N_{i-1} \cup N_i \cup N_{i+1}| = 2m$ and $|S_i| = |N_i|z$. The call blocking probability at cell i is therefore given by

$$B_i = Prob\{|N_{i-1} \cup N_i \cup N_{i+1}| = 2m \text{ and } |S_i| = |N_i|z\}. \quad (1)$$

Applying the CGD analysis to determine the blocking probability at cell i, we form the three consecutive cells $i-1$, i and $i+1$ into a group and assume this group to be decoupled from the rest of the network. It can be shown that the carrier borrowing is non-propagative [8].

Let the call arrivals at cell i be a Poisson process with rate λ_i and channel holding time be exponentially distributed with mean $1/\mu$. Let $P(x_1, x_2, x_3)$ be the steady state probability of the decoupled system that $|S_i| = x_1, |S_{i+1}| = x_2$ and $|S_{i-1}| = x_3$. Let Ω denote the set of all possible states that satisfies $|N_{i-1} \cup N_i \cup N_{i+1}| \leq 2m$ (Fig. 2). Let Ω_B denote the set of blocking states satisfies Eq. (2). We have

$$P(x_1, x_2, x_3) = G^{-1}(\Omega) \prod_{j=1}^{3} \frac{a_j^{x_j}}{x_j!} \quad (2)$$

where

$$G(\Omega) = \sum_{(x_1,x_2,x_3)\in\Omega} \left(\prod_{j=1}^{3} \frac{a_j^{x_j}}{x_j!} \right)$$

and $a_1 = \lambda_i/\mu$, $a_2 = \lambda_{i+1}/\mu$ and $a_3 = \lambda_{i-1}/\mu$. From Eq. (2), the call blocking probability at cell i is

$$B_i = \sum_{(x_1,x_2,x_3)\in\Omega_B} P(x_1, x_2, x_3). \quad (3)$$

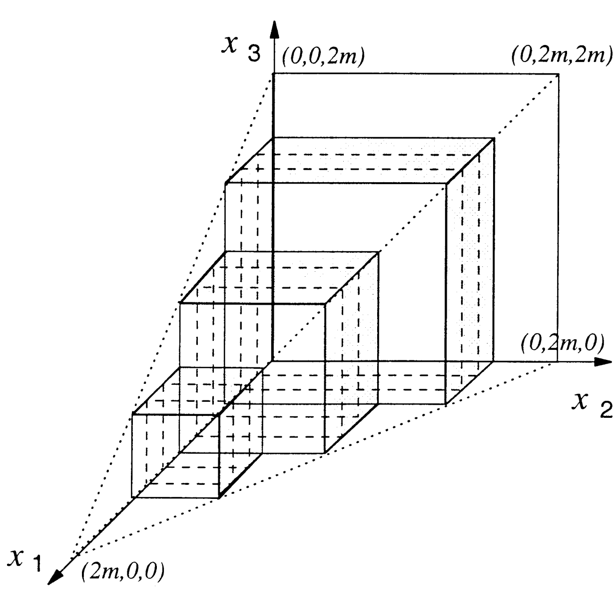

Fig. 2 A three-dimentional markov chain for describing the state space of a decoupled linear system with $z = 3$ voice channels per carrier.

If a system consists of N cells, the overall call blocking probability is

$$\mathbf{B} = \left(\sum_{k=1}^{N} \lambda_k \right)^{-1} \sum_{k=1}^{N} \lambda_k B_k. \quad (4)$$

Theorem 1: For a linear cellular system with single cell buffering, the call blocking probability B_i of an arbitrary cell i obtained by the CGD analysis is an upper bound on the true blocking probability at cell i.

The detailed proof of the above theorem can be found in [8]. Here we only intuitively argue that in the decoupled system, carrier borrowing is easier for cells $i-1$ and $i+1$ because they need to consider only carrier occupancy in cell i. Cell i, however, still needs to consider the carrier occupancies of cells $i-1$ and $i+1$ in order to borrow. This gives a higher carrier occupancies in cells $i-1$ and $i+1$ and so fewer number of carriers are available for cell i than that of the undecoupled system. The blocking probability of cell i obtained from the CGD analysis is therefore an upper bound on the true blocking. It should be noted that we are not able to quantitze how tight the bound is. But the numerical results in Sect. 5 show that the bound is very tight for systems with practical parameters.

3.2 Planar Cellular Systems

A planar cellular system with three-cell channel reuse pattern is shown in Fig. 3. Assume each cell has m nominal carriers and the total number of distinct frequency carriers is $3m$. A call arrives at cell 0 will be blocked if and only if $|\bigcup_{k=0}^{6} N_k| = 3m$ and $|S_0| = |N_0|z$. The call blocking probability at cell 0 is therefore given by

$$B_0 = Prob\left\{ |\bigcup_{k=0}^{6} N_k| = 3m \text{ and } |S_0| = |N_0|z \right\}. \quad (5)$$

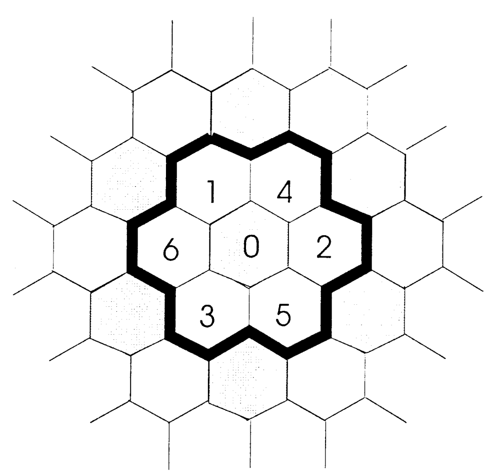

Fig. 3 A planar cellular system with three-cell reuse pattern. Cells 0 to 6 form a decoupled system for cell group decoupling analysis and phantom cell analysis.

Let $\mathbf{x} = (x_0, x_1, \cdots, x_6)$ and let $P[\mathbf{x}]$ be the steady state probability of the decoupled system (consisting of cells 0 to 6) that $|S_0| = x_0, |S_1| = x_1, \cdots, |S_6| = x_6$. Let Ω denote the set of states with $|\bigcup_{k=0}^{6} N_k| \leq 3m$. We futher let $y_1 = |N_0|+|N_1|+|N_4|, y_2 = |N_0|+|N_4|+|N_2|, y_3 = |N_0|+|N_2|+|N_5|, y_4 = |N_0|+|N_5|+|N_3|, y_5 = |N_0|+|N_3|+|N_6|$ and $y_6 = |N_0|+|N_6|+|N_1|$. To make the analysis tractable so that a product-form solution is available for numerical computation, we approximate the blocking condition shown in Eq. (5) by the condition that at least one y_i is equal to $3m$ and $x_0 = |N_0|z$. Let Ω_B denote the set of states with at least one $y_i = 3m$ and $x_0 = |N_0|z$, and Ω_A denote the set of states satisfies Eq. (5). We can see that Ω_B is a subset of Ω_A and with regard to this the blocking probability obtained by taking Ω_B as the set of blocking states is a lower bound on that using Ω_A. In Sect. 5, the effect of this approximation on system's blocking performance will be studied. Let $a_i = \lambda_i/\mu$ be the traffic intensity at cell i. A seven-dimensional Markov chain is used to model the decoupled system and the steady state probability $P[\mathbf{x}]$ is given by

$$P[\mathbf{x}] = G^{-1}(\Omega) \prod_{j=0}^{6} \frac{a_j^{x_j}}{x_j!} \tag{6}$$

where

$$G(\Omega) = \sum_{\mathbf{x}\in\Omega} \left(\prod_{j=0}^{6} \frac{a_j^{x_j}}{x_j!} \right).$$

The blocking probability at cell 0 is therefore

$$B_0 = \sum_{\mathbf{x}\in\Omega_B} P[\mathbf{x}]. \tag{7}$$

The overall call blocking probability of a system is given by a similar expression as in Eq. (4).

4. Phantom Cell Analysis

When the CGD analysis is applied to a planar cellular system with three-cell channel reuse pattern in the previous section, it involves solving the seven-dimensional markov chains. The computational complexity is very high especially when the number of carriers assigned to each cell is large. To cut down the computational complexity, we concentrate on the phantom cell analysis in this section. Phantom cell analysis is first proposed in [9] for analog system that each voice call occupies a single carrier. For evaluating the performance of borrowing with directional carrier locking strategy, we extend the phantom cell analysis to handle multiple voice calls per carrier in a planar cellular system.

Consider the same system with three-cell channel reuse pattern shown in Fig. 3. Let cells 1, 2 and 3 form the cell group A and cells 2, 4 and 6 form the cell group B. A carrier can be borrowed by cell 0 from either cell groups. A borrowing from say cell group A is successful only if that carrier is free in all three cells of group A, or equivalently, that carrier must be free in the cell (in cell group A) with the highest carrier occupancy. (This is due to the use of carrier ordering and immediate carrier reallocation.) Instead of direct modeling the seven-cells' decoupled system, we consider only three cells: the cell under investigation (cell 0), phantom cell $\mathcal{A}$ and phantom cell $\mathcal{B}$. Phantom cell $\mathcal{A}$ and phantom cell $\mathcal{B}$ represent the cell with the highest carrier occupancy in cell groups A and B respectively. These two phantom cells can take one of the two relative positions: side-by-side or opposite. By conditioning on their relative positions, the blocking probability of cell 0 can be found. Note that the approach we use here is a simpler version of that in [9]. Before we proceed, let us first find out the call arrival rates in the phantom cells.

4.1 Call Arrival Rates in Phantom Cells

First we need to find out the voice channel occupancy in a phantom cell. Based on that, the carried load in the phantom cell can be derived. Assume the carried load is equal to the product of the call arrival rate to the phantom cell and the call blocking probability at the phantom cell. The call arrival rate can then be found.

Let random variable M_k denote the channel occupancy of cell k and $M_{\mathcal{A}}$ and $M_{\mathcal{B}}$ denote the channel occupancies of phantom cells $\mathcal{A}$ and $\mathcal{B}$. Let a_k be the traffic intensity at cell k. Assume $P[M_k = i]$ the probability of i active calls in cell k is given by the truncated Poisson distribution

$$P[M_k = i] = \left[\sum_{j=0}^{3mz} \frac{(a_k)^j}{j!} \right]^{-1} \frac{(a_k)^j}{(3mz)!}. \tag{8}$$

Consider phantom cell $\mathcal{A}$, since $\mathcal{A}$ is the cell with the highest channel occupancy in cell group A, its occupancy is given by $M_{\mathcal{A}} = \max[M_1, M_2, M_3]$. Therefore

$$P[M_{\mathcal{A}} \leq i] = P[M_1 \leq i, M_2 \leq i, M_3 \leq i].$$

Assume the channel occupancies of cells 1, 2 and 3 are independent, we have

$$P[M_{\mathcal{A}} \leq i] = \prod_{k=1}^{3} P[M_k \leq i]$$

and

$$P[M_{\mathcal{A}} = i] = \prod_{k=1}^{3} P[M_k \leq i] - \prod_{k=1}^{3} P[M_k \leq i-1], \tag{9}$$

where $0 \leq i \leq 3mz$. The expected number of busy voice channels in $\mathcal{A}$, or the carried traffic load in $\mathcal{A}$, is given by

$$E[M_{\mathcal{A}}] = \sum_{i=0}^{3mz} i \cdot P[M_{\mathcal{A}} = i]. \tag{10}$$

Let $\gamma_{\mathcal{A}}$ be the call arrival rate to cell $\mathcal{A}$. In equilibrium,

$$\mu E[M_{\mathcal{A}}] = \gamma_{\mathcal{A}}(1 - P[M_{\mathcal{A}} = 3mz]).$$

Rearranging the above equation, we have

$$\gamma_{\mathcal{A}} = \frac{\mu E[M_{\mathcal{A}}]}{1 - P[M_{\mathcal{A}} = 3mz]}. \tag{11}$$

$\gamma_{\mathcal{B}}$ is given by a similar expression.

4.2 Analytical Model

The two phantom cells can take one of the two possible relative positions: side by side or opposite. If they are at side by side position, a call attempt at cell 0 will be blocked if and only if $|N_0|+|N_{\mathcal{A}}|+|N_{\mathcal{B}}| = 3m$ and $|S_0| = |N_0|z$. If the two phantom cells are at opposite position, the blocking condition becomes $|N_0 \cup N_{\mathcal{A}} \cup N_{\mathcal{B}}| = 3m$ and $|S_0| = |N_0|z$.

Let us consider the side by side position first. Let $P(x_0, x_1, x_3)$ be the steady state probability that $|S_0| = x_0, |S_{\mathcal{A}}| = x_1$ and $|S_{\mathcal{B}}| = x_2$. Let $\rho_0 = \lambda_0/\mu, \rho_1 = \gamma_{\mathcal{A}}/\mu$ and $\rho_2 = \gamma_{\mathcal{B}}/\mu$. Let Ω be the set of states with $|N_0| + |N_{\mathcal{A}}| + |N_{\mathcal{B}}| \leq 3m$. $P(x_0, x_1, x_2)$ is given by

$$P(x_0, x_1, x_2) = G^{-1}(\Omega) \prod_{j=0}^{2} \frac{\rho_j^{x_j}}{x_j!} \tag{12}$$

where

$$G(\Omega) = \sum_{(x_0,x_1,x_2)\in\Omega} \left(\prod_{j=0}^{2} \frac{\rho_j^{x_j}}{x_j!} \right).$$

Let Ω_B denote the set of blocking states with $|N_0| + |N_{\mathcal{A}}| + |N_{\mathcal{B}}| = 3m$ and $|S_0| = |N_0|z$. Then the call blocking probability of cell 0 when the two phantom cells are at side by side position is

$$B_{side} = \sum_{(x_0,x_1,x_2)\in\Omega_B} P(x_0, x_1, x_2). \tag{13}$$

Next we consider the two phantom cells are at opposite position. The steady state probability is given by the same expression as in Eq. (12) where Ω is the set of all possible states with $|N_0 \cup N_{\mathcal{A}} \cup N_{\mathcal{B}}| \leq 3m$. Again let Ω_B denote the set of blocking states that $|N_0 \cup N_{\mathcal{A}} \cup N_{\mathcal{B}}| = 3m$ and $|S_0| = |N_0|z$. The blocking probability of cell 0 when the two phantom cells are at opposite position is

$$B_{opp} = \sum_{(x_0,x_1,x_2)\in\Omega_B} P(x_0, x_1, x_2). \tag{14}$$

Conditioning on the relative positions of the two phantom cells, the blocking probability at cell 0 can be expressed as

$$B_0 = P_{side}B_{side} + (1 - P_{side})B_{opp}, \tag{15}$$

where P_{side} is the probability that the two phantom cells are at side by side position. P_{side} can be found by assuming that the probability a phantom cell is at a particular cell position in a cell group is equal to the ratio of the call arrival rate of that cell to the total call arrival rates of that cell group.

Again the overall blocking probability of a system is given by a similar expression as in Eq. (4).

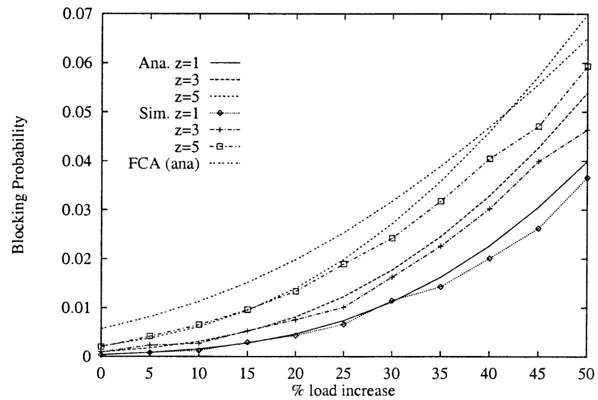

Fig. 4 Performance of CGD analysis in a 20-cell linear network with base traffic load 150 calls/hr/cell and mean call holding time 3 minutes. The total number of voice channels per cell is 15. The number of voice channels per carrier varies with $z = 1, 3$ and 5 respectively.

5. Numerical Examples

5.1 Linear Cellular System Using CGD Analysis

We first consider a linear cellular network consisting 20 cells with single cell buffering. Assume the number of voice channels that can be accommodated by a given spectrum is fixed and is independent of the number of voice channels per carrier z. Let all cells have the same 15 nominal voice channels and the call holding time be exponentially distributed with mean 3 minutes. The number of nominal carriers per cell is determined by the ratio $15/z$. Figure 4 shows the blocking performance of the proposed strategy under the uniform traffic distribution with different values of z. The blocking performance of fixed channel assignment (FCA) with 15 channels per cell is also plotted as a reference. The base traffic load is set at 150 calls/hr/cell. The x-axis shows the percentage traffic increase over the base load in each cell. Consider Fig. 4. Assume the system has 0.01 call blocking probability requirement. Then the maximum carried load per cell is 150 calls/hr using fixed channel assignment, 172 calls/hr (i.e. about 15% load increase) using the proposed strategy with $z = 5$, 187 calls/hr using $z = 3$, and 195 calls/hr using $z = 1$.

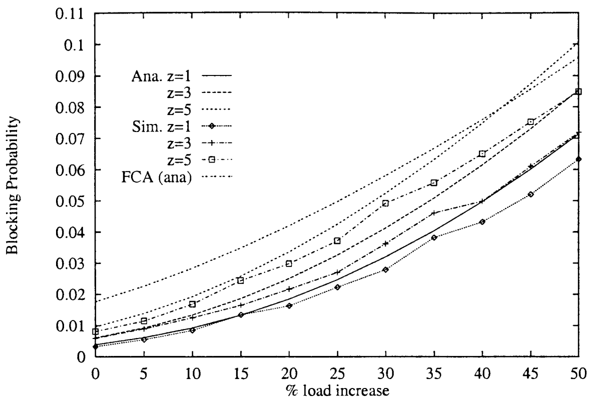

Fig. 5 Performance of CGD analysis in a 20-cell linear network under non-uniform traffic distributions with mean call holding time 3 minutes. The total number of voice channels per cell is 15. The number of voice channels per carrier varies with $z = 1, 3$ and 5 respectively.

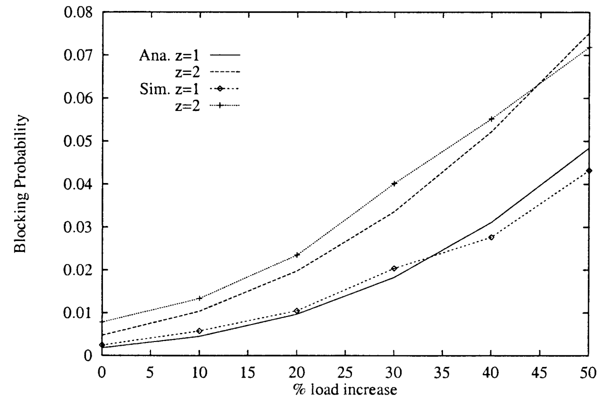

Fig. 7 Performance of CGD analysis in a 49-cell planar network with base traffic load 50 calls/hr/cell and mean call holding time 3 minutes. The total number of voice channels per cell is 6. The number of voice channels per carrier varies with $z = 1$ and 2 respectively.

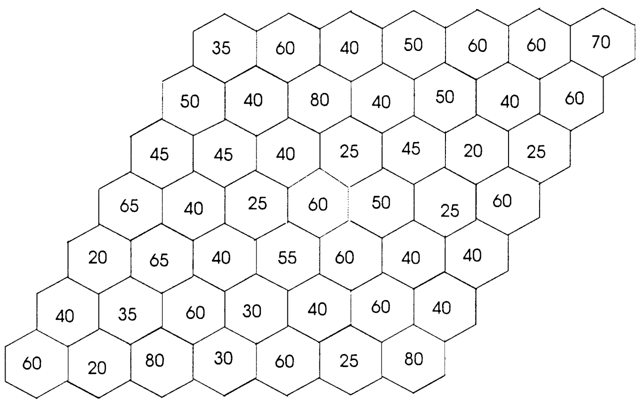

Fig. 6 A 49-cell cellular network with three-cell channel reuse pattern for CGD analysis. The number inside each cell represents the basic traffic load (in calls/hr) under the non-uniform traffic distribution.

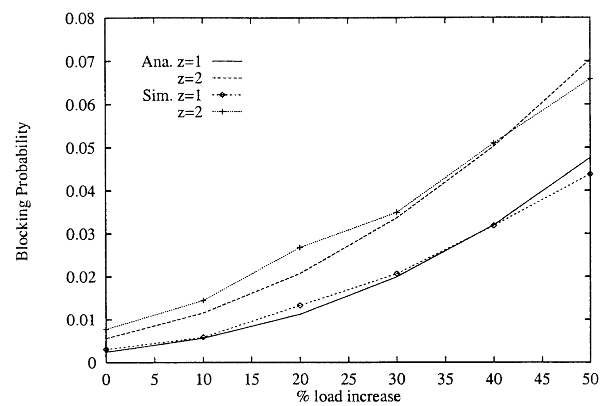

Fig. 8 Performance of CGD analysis in a 49-cell planar network under non-uniform traffic distributions (shown in Fig. 6) with mean call holding time 3 minutes. The total number of voice channels per cell is 6. The number of voice channels per carrier varies with $z = 1$ and 2 respectively.

Figure 4, it can be seen that there is a good agreement between the analytical and simulation results. As expected, the analytical results provide tight upper bounds on the true blocking probabilities in all cases. The bounds become less tight as the traffic load increases. This is because the assumption (used in the CGD analysis) that the blocking probability at cell i depends only on its two immediate neighboring cells is not accurate at high traffic load.

From the figure, we can see that at the same traffic load, the larger the value of z, the higher the call blocking probability is. This observation is quite obvious as with large value of z, less number of carriers are available for sharing. Therefore the carrier borrowing scheme becomes less efficient. At $\lambda = 150 \times 1.3 = 195$ calls/hr/cell, the blocking probabilities are 0.011, 0.016 and 0.024 for $z = 1$, 3 and 5 respectively.

Similar results are obtained for a non-uniform traffic distribution with a call arrival rate distribution given by

[140 160 120 140 110 190 130 220 210 130 80 40 140 180 160 220 130 140 110 150].

The blocking probability against the percentage load increase is shown in Fig. 5.

5.2 Planar Cellular System Using CGD Analysis

A 49-cell planar cellular system shown in Fig. 6 is considered. Owing to the high computational complexity of the CGD analysis for planar cellular systems, 6 nominal voice channels are assigned to each cell. Two cases are considered: (a) a uniform traffic distribution with base traffic load 50 calls/hr/cell; (b) a non-uniform traffic distribution with call arrival rates shown inside each cell (Fig. 6). The blocking probabilities against traffic rates for $z = 1$ and 2 are plotted in Figs. 7 and 8.

Two approximations used in the CGD analysis account for the accuracy of the analytical results: (a) the approximation of the blocking condition Eq. (5) by

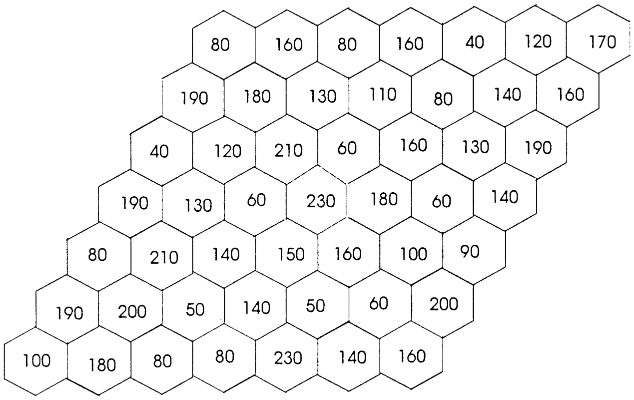

Fig. 9 A 49-cell cellular system with three-cell channel reuse pattern for phantom cell analysis. The number inside each cell represents the basic traffic load (in calls/hr) under the non-uniform traffic distribution.

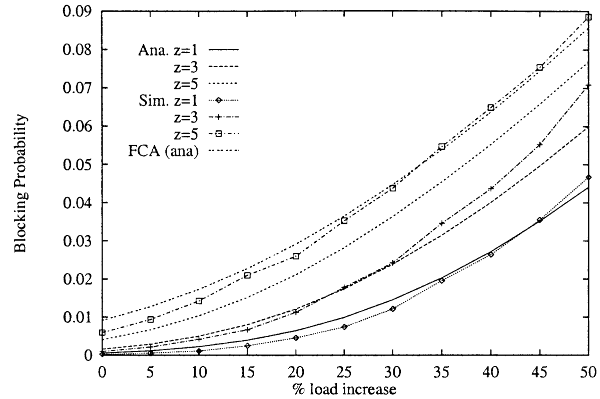

Fig. 10 Performance of phantom cell analysis in a 49-cell planar network with 160 calls/hr/cell and mean call holding time 3 minutes. The total number of voice channels per cell is 15. The number of voice channels per carrier varies with $z = 1, 2$ and 3 respectively.

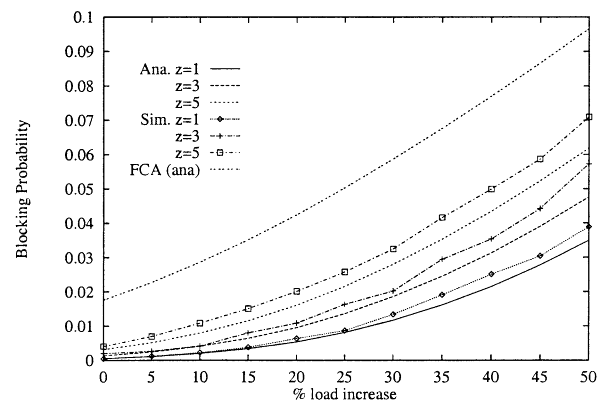

Fig. 11 Performance of phantom cell analysis in a 49-cell planar network under non-uniform traffic distributions (shown in Fig. 9) with mean call holding time 3 minutes. The total number of voice channels per cell is 15. The number of voice channels per carrier varies with $z = 1, 2$ and 3 respectively.

the condition that at least one y_i is equal to $3m$ and $|S_0| = |N_0|z$; (b) the approaximation that the further away cells' influence on the decoupled system is insignificant. The effect of approximation (a) is to underestimate the true blocking probability because the set of blocking states with at least one y_i equal to $3m$ and $|S_0| = |N_0|z$, is a subset of the set of blocking states with the condition Eq. (5). The effect of approximation (b) is, on the contrary, to overestimate the true blocking probability. From Figs. 7 and 8, good aggreements between simulation and analytical results are obtained for $z = 1$. This is because the effect of both approxmations are not significant for $z = 1$. As z increases to 2, the analysis becomes less accurate.

5.3 Planar Cellular System Using Phantom Cell Analysis

The same 49-cell planar cellular system is used and assume the number of nominal voice channels per cell is 15. We compare the analytical and simulation results under uniform traffic distribution with base load 160 calls/hr/cell in Fig. 10. The results for a non-uniform traffic distribution (the call arrival rates are shown inside each cell in Fig. 9) are plotted in Fig. 11. The blocking performance of using FCA with 15 voice channels per cell is also shown.

For both uniform traffic and non-uniform traffic distributions, phantom cell analysis produces accurate prediction on blocking probability as compared to the simulations for $z = 1$ and 3. For large values of z, phantom cell analysis becomes less accurate and in particular underestimates the blocking probabilities for both uniform and non-uniform traffic systems when $z = 5$. For uniform traffic distribution, FCA gives a comparable blocking performance to that of the BDCL strategy with $z = 5$. As z further increases, the blocking performance of BDCL can be worse than that of using FCA. For non-uniform traffic distribution, the performance gain of using BDCL is very large compared to FCA because we have assumed all cells have the same 15 voice channels for FCA.

Those results also indicate that carrier borrowing allows resource sharing among cells at the penalty of carrier locking in the donor cells. As the number of voice channels per carrier increases, the carrier borrowing penalty also increases. Under some circumstances, it may not be profitable to borrow because the borrowing penalty may outweigh the borrowing gain. Besides, there are extra processings involved in carrier borrowing. To acheive a better performance, a rule can be designed to decide when to borrow and when not to borrow.

From all numerical results, we can see that a small value of z allows a more efficient carrier sharing and so a lower system blocking can be obtained. On the other hand, for a fixed spectrum, a larger number of carriers (as a result of smaller z) would mean more bandwidth is wasted in guard bands and a larger number of transcievers are required for different frequency carriers at base stations. Therefore, there is a tradeoff between the system performance and the cost of implementation.

6. Conclusions

For a digital cellular systems using FDMA/TDMA, a new dynamic carrier borrowing scheme called borrowing with directional carrier locking strategy has been proposed in this paper. For evaluating its performance, two analytical models, namely cell group decoupling analysis and phantom cell analysis, have been adopted. These two analytical models were previously proposed for evaluating the performance of a system using only single voice channel per carrier. Both analytical and simulation results of using the proposed carrier borrowing strategy were obtained. We found that using the proposed strategy, the system call blocking probability can be significantly reduced as compared to that using fixed channel/carrier assignment. Besides, good agreements between analytical and simulation results were observed for systems with a small number of voice channels per carrier z. For a given fixed number of voice channels per cell, a small value of z gives a large number of carriers per cell. This in turn gives the system a higher flexibility in sharing carrier resources among base stations. For a practical system, a small value of z implies a higher hardware cost and less flexible in supporting higher bit rate data traffic. Therefore, an optimal design of z depends on the tradeoff of the system performance and the implementation cost involved.

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