Research Article
Models for Call Acceptance Based on Handoff Guarantees

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Call admission control (CAC) is important for cellular wireless networks to provide quality-of-service (QoS) requirements to users. Static and adaptive CAC schemes, respectively, make unrealistic assumptions about the distributions of the handoff call arrival process and the number of users in a cell. Handoff arrivals are usually assumed to follow Poisson process in static CAC schemes for Poisson new call arrivals and exponentially distributed call holding and cell residence times. We use a simple proof to show that this assumption of Poisson handoff arrival process is not justified for a two-cell wireless network. In general, we find that the handoff process can be captured by a two-dimensional Markov chain. We propose a novel adaptive CAC scheme for the two-cell system which accepts a new call if it can guarantee, with a certain probability, that a user's call will be maintained irrespective of its (his/her) movement in the system. Then, we extend this adaptive scheme for multiple-cell network. We develop another variant of this adaptive scheme which we call fractional adaptive scheme. Both the adaptive and fractional adaptive schemes are found to outperform the guard channel scheme in controlling the handoff failure probability in a cellular wireless network.

1. INTRODUCTION

Call admission control (CAC) is a strategy to provide high QoS to users by limiting the number of call connections into a communication network, to a profitable level, while reducing network congestion, depending on the availability of resources. In cellular wireless networks, another factor comes into play, the possibility of dropping a connected call due to the mobility of users. It is more irritating for a user's call not to be completed due to handoff failure than the call to be blocked during the new call attempt. Therefore, handoff calls are prioritized over new calls. It has been found that prioritizing handoff calls over new calls results in the decrease of the number of handoff failures and the call dropping probabilities. However, prioritizing handoff calls over new calls results in the increase of the new call blocking probability. A good CAC scheme for a wireless cellular network has to balance the call blocking and the call dropping probabilities in order to provide the desired QoS requirements. The design of CAC algorithms for mobile cellular wireless networks is especially challenging given the limited and highly variable resources, and the mobility of users encountered in such networks.

CAC schemes for cellular wireless networks have been extensively studied in the literature. Those studies can be broadly classified into two categories—static schemes and distributed schemes. In the literature, static CAC schemes, which are mainly guard channel schemes, are generally studied for a single cell [1–4]. On the other hand, in distributed CAC schemes [5–9], which are also called adaptive CAC schemes, a call is accepted in the target cell depending on the number of calls in the target cell and the number of calls in the neighboring cells. Ahmed [10] and Ghaderi and Boutaba [11] provided comprehensive surveys on static and adaptive CAC schemes.

In the guard channel schemes, a call is accepted in a cell if the number of ongoing calls in the cell is below a threshold value. In these schemes, the interarrival times of new and handoff calls are generally assumed to be distributed according to exponential, hyper-exponential, gamma, phase type, or Markovian arrival process (MAP) functions. Hong and Rappaport [2] analyzed a guard channel scheme by approximating the channel holding time distribution with an equivalent exponential distribution for uniformly distributed velocity for mobile users which is not quite realistic. Ramjee et al. [4] proposed fractional guard channel scheme

(FGCS), where a new call is accepted in a cell with a particular probability depending on the number of calls in the cell. Leong et al. [3, 12] analyzed integration of voice and data calls for fractional guard channel scheme with bandwidth allocation and update of the number of guard channels with traffic variation. The approximation of higher-dimensional Markov chains to lower-dimensional Markov chains in [3, 12] may cause inaccuracy. Alfa and Li [1, 13] studied guard channel schemes where new and handoff calls are assumed to follow MAP distribution and cell residence times, and call holding durations are assumed to follow phase type distribution. However, their models [1, 13] are computationally demanding and actually intractable using reasonable computing resources as they keep track of the phase of the channel holding time of each call which makes the state-space large. Chou and Shin [14] developed and analyzed a cutoff priority scheme for supporting multilevel QoS by introducing upgrade/degrade frequency (UDF). UDF is generated based on approximation using a discrete time absorbing Markov chain which could be exactly determined using a continuous time absorbing Markov chain. Chen et al. [15] proposed dynamic multiple thresholds for new/handoff real-time and nonreal-time calls with periodic exchange of information between neighboring base-stations for providing relative QoS priority. The thresholds in [15] are computed assuming fixed numbers of arrivals and departures in a period of time which has no justification. In some of the guard channel schemes such as schemes of Guerin [16], Lau and Maric [17], Hong and Rappaport [2], Lin et al. [18], Li and Alfa [19], Tekinay and Jabbari [20], Yoon and Un [21], and Haung et al. [22], calls queue when they cannot be allocated free channels, which reduces new call blocking and handoff dropping probabilities. Gavish and Sridhar [23] and Fang and Zhang [24] analyzed the new call bounding scheme which accepts a new call if the number of ongoing new calls is below some threshold value and there is a free channel in the cell.

Naghshineh and Schwartz [8] developed a distributed scheme for only voice calls whereas Mišić et al. [7], Epstein and Schwartz [25], and Ghaderi and Boutaba [5] developed distributed schemes for multiple classes of calls. In these schemes, a new call is accepted in a cell after determining the probabilities of successful handoff of calls in the current and the neighboring cells in some time ahead. The binomially distributed number of ongoing calls in a cell is approximated with normal distribution in [5, 8, 25] and Poisson distribution in [7]. The approximation of binomial distribution by normal distribution may cause inaccuracy as normal distribution has negative tail. The approximation of the binomial distribution by Poisson distribution is unrealistic when the mean and variance of the binomial distribution differ more than ten percent. In the scheme of Levine et al. [6], new calls are admitted in a cell by computing the influence of the ongoing calls in the current and neighboring cells using shadow cluster concept which is complex. In [5, 9], time is divided into control periods. In the scheme of Wu et al. [9], new calls are accepted in a control period with some probability which is computed by solving a diffusion equation. Calls accepted in a control period with some

probability in the schemes of Ghaderi and Boutaba [5] and Wu et al. [9] can result in under utilization of the channels in a cell.

In static CAC schemes, a cell is studied to approximate the whole cellular network. In static schemes, a new call is admitted in the target cell depending only on the number of calls in that cell. On the other hand, in distributed CAC schemes, the numbers of calls in the target cell and the neighboring cells are considered for accepting a new call in the target cell. In this paper, we first study a cellular system which consists of two cells. We study the two-cell wireless network to understand how the two-cell system works with the goal in mind to use the results in approximating a cellular network consisting of more than two cells.

In static CAC schemes, exponentially distributed handoff interarrival time is usually assumed for exponentially distributed call holding duration and cell residence time. However, Chlebus and Ludwin [26], Rajaratnam and Takawira [27], Sohraby [28], Sidi and Starobinski [29], and Hegde and Sohraby [30] showed non-Poisson handoff arrivals for Poisson new call arrival and exponentially distributed cell residence time and call holding duration due to blocking. Hegde and Sohraby [30] analyzed blocking probability using single and multidimensional Markov chains for single and multiple cells. Their emphasis was on one and two cells as the computations become complex for larger number of cells. Their model, which captured handoff rate to a cell for multiple cells by cell residence time and the number of ongoing calls in the neighboring cells, was used to analyze blocking probability for bursty traffic. We also use a two-cell model like Hegde and Sohraby [30] but our focus is to develop models for call acceptance based on handoff guarantees. Fang [31] analyzed handoff arrival process and channel holding time for general distributed cell residence time and call holding duration but could not provide analytical expressions for new and handoff call blocking probabilities. On the other hand, we use a simple proof to show that the assumption of exponentially distributed handoff call interarrival time is unrealistic for the case when interarrival time for new calls, call holding duration, and cell residence time all follow exponential distribution. We demonstrate that the handoff call interarrival time does not follow exponential or hyperexponential distribution even if new call interarrival time, call holding duration, and cell residence time are exponentially distributed. In general, we find that the handoff arrival process is better captured by a two-dimensional Markov chain. We consider how the number of ongoing calls in the neighboring cell affects a cell in the two-cell system which is not considered for guard channel scheme in the literature. In our CAC scheme, handoff calls are accepted whenever a handoff call arrives, and there is at least one free channel. On the other hand, when a new call arrives we get the probability of dropping the call in the neighboring cell if we predict that it needs to handoff based on a table which is computed offline. We admit a new call in our scheme if this probability is not more than some threshold value. In other words, our scheme accepts a new call in a cell if a guarantee can be provided with some probability that the call will be successfully handed

off if it moves to the neighboring cell. We carry out the transient analysis for our proposed two-cell system using matrix geometric method [32] to compute the probability of dropping the candidate call in the neighboring cell if the candidate call needs to handoff in the neighboring cell. These dropping probabilities are computed for different number of ongoing calls in the current cell and the neighboring cell. These values of handoff drop probabilities for candidate call in the neighboring cell are stored in a table. Using simulation study, we determine the thresholds for accepting a new call for exponentially distributed new call interarrival time, call holding, and cell residence times to provide the required QoS of handoff failure probabilities. Our method is designed for offline computation since our schemes are mainly suitable for designing call admission controller whereas other distributed schemes can be considered as operational schemes as they use online computation. Our CAC algorithm needs to look up a table for the handoff dropping probability of a candidate call being dropped for unavailability of a free channel in the neighboring cell if the candidate call is accepted. Checking the table, the CAC algorithm can decide about the acceptance of the call. We find that our adaptive CAC scheme for the two-cell system better controls the admission of new calls by keeping lower the new call blocking probability and better channel utilization than the guard channel scheme for maintaining the handoff call dropping probability below some threshold value.

We extend our adaptive CAC scheme for two-cell wireless network to a cellular wireless network consisting of multiple cells. We approximate the neighbors of the target cell with one cell and the target cell as another cell for the two-cell system. We find that this approximation better controls the handoff call dropping probability than the guard channel scheme. We develop another variant of this adaptive scheme which we call fractional adaptive scheme for a cellular wireless network consisting of more than two cells. Our schemes for a multiple-cell wireless network are found to outperform the guard channel scheme in controlling handoff failure probability. Fractional adaptive scheme is found to better control the handoff failure probability than the adaptive scheme.

The rest of the paper is organized as follows. In Section 2, we show the steady-state analysis of guard channel scheme for the two-cell system. Our proposed adaptive model for the two-cell system, the approximation model and its variant fractional adaptive scheme for a multiple-cell wireless network are explained in Section 3. Section 4 presents our analytical and simulation results, and Section 5 concludes the paper.

2. STEADY-STATE ANALYSIS OF GUARD CHANNEL SCHEME FOR TWO-CELL SYSTEM

A cellular wireless network consists of many cells. If a Markov chain is used to model the whole cellular wireless network, the state-space of the Markov chain becomes exponentially large. In the literature, a cell is generally studied to approximate the whole network with the assumption that both
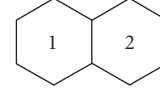
the new and handoff calls are of same distributions such as Poisson, phase type, or MAP. However, we study a two-cell system to understand how the two-cell system works with the goal in mind to use the modeling technique for developing adaptive schemes in Section 3.

In this section, we develop and analyze the guard channel scheme for the two-cell system. We assume that a call is completed in the cell where it is generated or in the neighboring cell. We denote the two cells as cell 1 and cell 2 as shown in Figure 1. We assume that a user can only move from cell 1 to cell 2 and from cell 2 cell 1. These two cells are identical and each cell has C channels. g ($0 \leq g < C$) number of channels are reserved as guard channels for only handoff calls in each cell. A handoff call is accepted in a cell if there is any free channel in that cell. On the other hand, a new call is accepted in a cell if the number of ongoing calls in that cell is less than $K = C - g$. Moreover, we assume that the new call arrival to a cell follows Poisson distribution with mean λ_n. Both call holding time (the time duration a completed call needs) and cell residence time (the time a caller spends in a cell) are assumed to follow exponential distribution with means $1/\mu$ and $1/\eta$, respectively. Channel holding time (the time a call occupies a channel in a cell) of a call in a cell is the minimum of the cell residence time and the call holding duration. As a result, the channel holding time of a call in a cell is also exponentially distributed with mean $1/\mu_c = 1/(\mu + \eta)$. We follow these assumptions about the total number of channels in a cell and statistical distributions of new call arrival process, call holding duration, and cell residence time throughout this paper.

We consider a continuous time Markov chain (CTMC) for the two-cell system. The state space of this CTMC is $\{(i, j) : 0 \leq i, j \leq C\}$, where i and j represent, respectively, the total number of calls in cells 1 and 2. The summation of the number of calls in both cells cannot be more than $2C - g = C + K$ (i.e., $0 \leq i + j \leq 2C - g$) as there are g number of guard channels in both cells 1 and 2. An example of the CTMC and possible transitions in the CTMC are shown in [33]. The CTMC has the following generator matrix:

$$Q = \begin{bmatrix} B_0 & U_0 & & & & \\ D_1 & B_1 & U_1 & & & \\ & D_2 & B_2 & U_2 & & \\ & & \ddots & \ddots & \ddots & \\ & & & D_{C-1} & B_{C-1} & U_{C-1} \\ & & & & D_C & B_C \end{bmatrix}. \quad (1)$$

Here, B_i ($0 \leq i \leq C$) is an $L_i \times L_i$ matrix, where $L_i = C+1$ for $0 \leq i \leq K$ and $L_i = 2C - i - g + 1 = C + K - i + 1$ for $K + 1 \leq i \leq C$. D_i ($1 \leq i \leq C$) and U_i ($0 \leq i \leq C - 1$) are $L_i \times L_{i-1}$ and $L_i \times L_{i+1}$ matrices, respectively. B_i, D_i, and U_i

FIGURE 1: The two-cell system.

represent, respectively, no change, a decrease by one, and an increase by one in the number of ongoing calls in cell 1.

The structure of B_i is shown in Table 1. The diagonal element $B_i(j, j)$ for $0 \leq j < L_i$ of B_i represents no change in the number of ongoing calls in cells 1 and 2. The super-diagonal element $B_i(j, j+1)$ for $0 \leq j < K$ of B_i represents an increase in the number of ongoing calls in cell 2 by one for accepting a new call. The subdiagonal element $B_i(j, j-1)$ for $0 \leq i < C$, $0 < j < L_i - 1$ of B_i represents a decrease in the number of ongoing calls in cell 2 by one for a call completion. On the other hand, the subdiagonal element $B_C(j, j-1)$ for $0 < j < L_C - 1$ of B_C represents a decrease in the number of ongoing calls in cell 2 by one for a call completion or an unsuccessful handoff to cell 1.

The diagonal element $D_i(j, j)$ of D_i for $1 \leq i \leq K$, $0 \leq j \leq C - 1$ or $K + 1 \leq i \leq C$, $0 \leq j \leq L_i - 1$ represents a call completion in cell 1. On the other hand, the diagonal element $D_i(C, C)$ of D_i for $1 \leq i \leq K$ represents a call completion in cell 1 or an unsuccessful handoff to cell 2. The handoff from cell 1 to cell 2 is captured by the super-diagonal element $D_i(j, j+1)$ of D_i for $1 \leq i \leq K$, $0 \leq j \leq C - 1$, or $K + 1 \leq i \leq C$, $0 \leq j \leq L_i - 1$. D_i ($1 \leq i \leq K$) has the following structure:

$$D_i = \begin{bmatrix} i\mu & i\eta & & & & \\ & i\mu & i\eta & & & \\ & & i\mu & i\eta & & \\ & & & \ddots & \ddots & \\ & & & & i\mu & i\eta \\ & & & & & i\mu_c \end{bmatrix}. \quad (2)$$

D_i ($K + 1 \leq i \leq C$) has the following structure:

$$D_i = \begin{bmatrix} i\mu & i\eta & & & & \\ & i\mu & i\eta & & & \\ & & i\mu & i\eta & & \\ & & & \ddots & \ddots & \\ & & & & i\mu & i\eta \\ & & & & & i\mu & i\eta \end{bmatrix}. \quad (3)$$

The diagonal element $U_i(j, j)$ of U_i for $0 \leq i \leq K - 1$, $0 \leq j \leq C$ represents an increase in the number of ongoing calls in cell 1 by acceptance of a new call. The handoff from cell 2 to cell 1 is captured by the subdiagonal element $U_i(j, j-1)$ of U_i for $0 \leq i \leq C - 1$, $1 \leq j \leq L_i - 1$. U_i ($0 \leq i \leq K - 1$) has the following structure:

$$U_i = \begin{bmatrix} \lambda_n & & & & & \\ \eta & \lambda_n & & & & \\ & 2\eta & \lambda_n & & & \\ & & \ddots & \ddots & & \\ & & & (C-1)\eta & \lambda_n & \\ & & & & C\eta & \lambda_n \end{bmatrix}. \quad (4)$$

U_i ($K \leq i \leq C - 1$) has the following structure:

$$U_i = \begin{bmatrix} \eta & & & & \\ & 2\eta & & & \\ & & \ddots & & \\ & & & (L_i - 2)\eta & \\ & & & & (L_i - 1)\eta \end{bmatrix}. \quad (5)$$

Let us assume that $x = [x_0, x_1, \ldots, x_C]$ is the steady-state probability vector for the CTMC Q in (1) which satisfies $xQ = \mathbf{0}^T$ and $x\mathbf{1} = 1$. Here, $\mathbf{0}$ and $\mathbf{1}$ are column vectors of zeros and ones, respectively. On the other hand, x_i ($0 \leq i \leq C$) is a row vector having L_i scalar elements. $x_i = [x_{i,0}, x_{i,1}, \ldots, x_{i,L_i-1}]$, where $x_{i,j}$ represents the steady-state probability of having i ongoing calls in cell 1 and j ongoing calls in cell 2. If we let $\prod_{i=1}^{n} \beta_i = \beta_1, \beta_2, \ldots, \beta_n$ for matrices $\beta_1, \beta_2, \ldots, \beta_n$, we can find the steady-state probability vector x_i ($1 \leq i \leq C$) using the technique of Gaver et al. [34] in the following way:

$$x_i = x_0 \prod_{k=1}^{i} \left(U_{k-1} \left(-E_k \right)^{-1} \right) \quad (1 \leq i \leq C), \quad (6)$$

where x_0 satisfies $x_0 E_0 = \mathbf{0}^T$, and

$$x_0 \left(I + \sum_{i=1}^{C} \prod_{k=1}^{i} \left(U_{k-1} \left(-E_k \right)^{-1} \right) \right) \mathbf{1} = 1. \quad (7)$$

E_k ($0 \leq k \leq C$) is recursively determined by $E_C = B_C$, and

$$E_k = B_k + U_k \left(-E_{k+1} \right)^{-1} D_{k+1} \quad (0 \leq k \leq C - 1). \quad (8)$$

In our two-cell system, we capture handoff call arrivals to cells 1 and 2 as subdiagonal of U_i ($0 \leq i \leq C - 1$) and super-diagonal of D_i ($1 \leq i \leq C$) matrices, respectively. The handoff rate due to an individual user from a cell to the neighboring cell is η. For l ($1 \leq l \leq C$) users in a cell, the handoff rate to the neighboring cell is $l\eta$ and this l varies with the number of users in that cell (i.e., with the state of the Markov chain). On the other hand, for exponentially distributed interarrival time or Poisson distributed arrival process the transition to another state occurs with a fixed rate. However, the handoff arrival process from and to a cell in our two-cell system does not remain fixed. For hyperexponential distribution, the change from one state to another state can occur with any rate of the fixed number of exponential distributions that constitute the hyperexponential distribution. However, the change between handoff generation rates is correlated for our two-cell system. The handoff generation rate can switch from $l\eta$ to $(l - 1)\eta$ but not to the rate $(l - 2)\eta$ (for $l \geq 2$) directly. Similarly, the handoff generation rate cannot change directly from $l\eta$ to $(l + 2)\eta$ (for $l + 1 < C$). Therefore, the handoff interarrival time from and to a cell is neither exponentially nor hyperexponentially distributed. Hence, the assumption of Poisson distributed handoff arrival process or exponentially distributed handoff interarrival time is not justified.

The handoff generation process from cell 1 to cell 2 occurs with rate $i\eta$ ($0 \leq i \leq C$), and the handoff generation rate from cell 2 to cell 1 occurs with rate $j\eta$ ($0 \leq j \leq C$). As both the cells are identical, the mean handoff arrival rate $\bar{\lambda}_{h_1}$ from cell 2 to cell 1 and the mean handoff arrival rate $\bar{\lambda}_{h_2}$

TABLE 1: Structure of B_i in cutoff priority guard-channel handoff scheme for two-cell system.

B_i $(0 \le i \le K-1)$ has the following structure:

$$B_i = \begin{bmatrix} B_i(0,0) & B_i(0,1) \\ B_i(1,0) & B_i(1,1) & B_i(1,2) \\ & B_i(2,1) & B_i(2,2) & B_i(2,3) \\ & \ddots & \ddots & \ddots \\ & & B_i(K-1,K-2) & B_i(K-1,K-1) & B_i(K-1,K) \\ & & & B_i(K,K-1) & B_i(K,K) \\ & & & & \ddots & \ddots \\ & & & & & B_i(C-1,C-2) & B_i(C-1,C-1) \\ & & & & & & B_i(C,C-1) & B_i(C,C) \end{bmatrix},$$

where $B_i(j,j) = -(2\lambda_n + (i+j)\mu_c)$ for $(0 \le j \le K-1)$, $B_i(j,j) = -(\lambda_n + (i+j)\mu_c)$ for $(K \le j \le C)$, $B_i(j,j+1) = \lambda_n$ for $(0 \le j \le K-1)$, and $B_i(j,j-1) = j\mu$ for $(1 \le j \le C)$.

B_i $(K \le i \le C)$ has the following structure:

$$B_i = \begin{bmatrix} B_i(0,0) & B_i(0,1) \\ B_i(1,0) & B_i(1,1) & B_i(1,2) \\ & B_i(2,1) & B_i(2,2) & B_i(2,3) \\ & \ddots & \ddots & \ddots \\ & & B_i(K-1,K-2) & B_i(K-1,K-1) & B_i(K-1,K) \\ & & & B_i(K,K-1) & B_i(K,K) \\ & & & & \ddots & \ddots \\ & & & & & B_i(L_i-2,L_i-3) & B_i(L_i-2,L_i-2) \\ & & & & & & B_i(L_i-1,L_i-2) & B_i(L_i-1,L_i-1) \end{bmatrix},$$

where $B_i(j,j) = -(\lambda_n + (i+j)\mu_c)$ for $(0 \le j \le K-1)$, $B_i(j,j) = -(i+j)\mu_c$ for $(K \le j < L_i)$, $B_i(j,j+1) = \lambda_n$ for $(0 \le j \le K-1)$, $B_i(j,j-1) = j\mu$ for $(K \le i \le C-1, 1 \le j < L_i)$, and $B_C(j,j-1) = j\mu_c$ for $(1 \le j < L_C)$.

from cell 1 to cell 2 are same, that is, the mean handoff arrival rate to a cell is $\bar{\lambda}_h = \bar{\lambda}_{h_1} = \bar{\lambda}_{h_2}$. We can express $\bar{\lambda}_{h_1}$ and $\bar{\lambda}_{h_2}$ as

$$\bar{\lambda}_{h_1} = \sum_{i=0}^{C} \sum_{j=1}^{L_i-1} j\eta x_{i,j},$$

$$\bar{\lambda}_{h_2} = \sum_{i=1}^{C} \sum_{j=0}^{L_i-1} i\eta x_{i,j}. \tag{9}$$

We can compute the handoff failure probabilities in cells 1 and 2 using the approach of Poisson arrivals see time averages (PASTA) [35]. For the duration of time T, an outside observer sees $\sum_{i=1}^{C} i\eta x_i \mathbf{1} T = \sum_{i=1}^{C} \sum_{j=0}^{L_i-1} i\eta x_{i,j} T$ and $\sum_{i=0}^{C} \sum_{j=1}^{L_i-1} j\eta x_{i,j} T$ as average numbers of handoff calls from cell 1 to cell 2 and from cell 2 to cell 1, respectively. The outside observer also notices that $\sum_{j=1}^{L_C-1} j\eta x_{C,j} T$ and $\sum_{i=1}^{K} i\eta x_{i,C} T$ calls are dropped on average in cell 1 and cell 2, respectively, for time T. Therefore, the handoff failure probabilities P_{hf_1} in cell 1 and P_{hf_2} in cell 2 can be expressed as

$$P_{\text{hf}_1} = \frac{\sum_{j=1}^{L_C-1} j x_{C,j}}{\sum_{i=0}^{C} \sum_{j=1}^{L_i-1} j x_{i,j}},$$

$$P_{\text{hf}_2} = \frac{\sum_{i=1}^{K} i x_{i,C}}{\sum_{i=1}^{C} \sum_{j=0}^{L_i-1} i x_{i,j}}. \tag{10}$$

Similarly, the new call blocking probabilities P_{b_1} of cell 1 and P_{b_2} of cell 2 can be expressed as

$$P_{b_1} = \sum_{i=K}^{C} \sum_{j=0}^{L_i-1} x_{i,j},$$

$$P_{b_2} = \sum_{i=0}^{C} \sum_{j=K}^{L_i-1} x_{i,j}. \tag{11}$$

The two cells are identical with respect to total number of channels, number of guard channels, new call arrival rate, cell residence time, and call holding duration. Hence, they have the same handoff failure probabilities and the same new call blocking probabilities which we can be written as $P_{\text{hf}_1} = P_{\text{hf}_2} = P_{\text{hf}}$, and $P_{b_1} = P_{b_2} = P_b$.

We now have the expressions for new call blocking and handoff failure probabilities. We can now compute the optimum number of guard channels g that we require to keep the new call blocking probability minimum and the handoff call failure probability within a threshold. We can write this optimization problem as

$$\begin{aligned} &\text{compute } g \text{ which} \\ &\text{minimizes } P_b \\ &\text{subject to } P_{\text{hf}} \le P_{\text{th}}. \end{aligned} \tag{12}$$

Enumeration technique can be used to solve the above optimization problem to obtain the optimum value of g.

We can find the mean number of calls in a cell for the two-cell system with guard channel scheme. The mean number of calls in cell 1 is $\overline{N_1} = \sum_{i=1}^{C} \sum_{j=0}^{L_i-1} i x_{i,j}$, and the mean number of calls in cell 2 is $\overline{N_2} = \sum_{i=0}^{C} \sum_{j=1}^{L_i-1} j x_{i,j}$. As both the cells are identical, the mean number of calls in both the cells are same which we can write as $\overline{N} = \overline{N_1} = \overline{N_2}$. On the other hand, the expected channel utilization for the two-cell system with the guard channel scheme is $\overline{N}/C$.

Nonprioritized handoff scheme for the two-cell system is a special case of guard channel scheme with no guard channels, that is, $g = 0$, $L_i = C + 1$ ($0 \leq i \leq C$), and $K = C$. Distribution of average number of calls, new call blocking probability, handoff failure probability, distribution of handoff call arrival process, and average handoff call arrival rate for nonprioritized handoff scheme can be computed in the same fashion like the guard channel scheme.

3. AN ADAPTIVE CALL ADMISSION CONTROL SCHEME FOR TWO-CELL AND MULTIPLE-CELL SYSTEMS

In this section, we first develop an adaptive call admission control scheme for the two-cell system. In our adaptive scheme, we try to ensure, with some probability, that if a call is considered for acceptance in a cell then the call gets a handoff channel in the neighboring cell if it needs one. Moreover, we guarantee, with some probability, that the acceptance of the new call in the target cell will not have adverse effect on calls seeking handoff to the target cell. We propose a set of constraints for acceptance of calls in the two cells of our system which implicitly prioritizes handoff calls over new calls. If we assume that i and j represent total number of calls in cells 1 and 2, respectively, then a new call is accepted in cell 1 with this set of rules when the following constraints are satisfied.

(i) There is at least one free channel in cell 1 for accepting the new call, that is, $i < C$.

(ii) We can guarantee with at least probability P_E that the call will get a free channel in cell 2 if it needs to handoff.

We can compute the probability of a call getting a free channel in the neighboring cell if it needs to handoff. We can perform the transient analysis to compute the average probability $\overline{P}_E(T)$ of dropping a candidate call in cell 2 in T time ahead when it comes to cell 1 for acceptance. If the candidate call is accepted in cell 1, then we have to consider the remaining $C - 1$ channels of cell 1 and C channels of cell 2. We can consider a CTMC for both cells as in Section 2. The state-space of this CTMC for the adaptive scheme has $C(C + 1)$ elements. The state space of this CTMC can be represented as $\{(\hat{i}, \hat{j}) : 0 \leq \hat{i} \leq C - 1, 0 \leq \hat{j} \leq C\}$, where $\hat{i}$ represents total number of calls in the $C - 1$ channels of cell 1, and $\hat{j}$ represents total number of calls in C channels of cell

2. An example of the CTMC and all possible transitions in the CTMC are shown in [33]. The generator matrix of the CTMC is shown in the following equation:

$$\tilde{Q} = \begin{bmatrix} \tilde{B}_0 & \tilde{U}_0 & & & & \\ \tilde{D}_1 & \tilde{B}_1 & \tilde{U}_1 & & & \\ & \tilde{D}_2 & \tilde{B}_2 & \tilde{U}_2 & & \\ & & \ddots & \ddots & \ddots & \\ & & & \tilde{D}_{C-2} & \tilde{B}_{C-2} & \tilde{U}_{C-2} \\ & & & & \tilde{D}_{C-1} & \tilde{B}_{C-1} \end{bmatrix}. \quad (13)$$

Here, $\tilde{B}_{\hat{i}}$, $\tilde{U}_{\hat{i}}$, and $\tilde{D}_{\hat{i}}$ represent, respectively, no change, an increase by one, and a decrease by one in the number of ongoing calls in $(C - 1)$ channels of cell 1 when the number of ongoing calls in $(C - 1)$ channels of cell 1 is $\hat{i}$. $\tilde{B}_{\hat{i}}$ ($0 \leq \hat{i} \leq C - 1$), $\tilde{U}_{\hat{i}}$ ($0 \leq \hat{i} \leq C - 2$), and $\tilde{D}_{\hat{i}}$ ($1 \leq \hat{i} \leq C - 1$) are $(C + 1) \times (C + 1)$ matrices. $\tilde{B}_{\hat{i}}$ has nonzero elements in the diagonal, subdiagonal, and super diagonal. The diagonal elements of $\tilde{B}_i$ represent the rate of no change in the number of ongoing calls in both cells 1 and 2. The super-diagonal elements of $\tilde{B}_{\hat{i}}$ represent the rate of a new call connection in cell 2. The subdiagonal elements of $\tilde{B}_{\hat{i}}$ show the rate of completion of an ongoing call in cell 2. $\tilde{U}_{\hat{i}}$ has nonzero elements in the diagonal and subdiagonal. The diagonal of $\tilde{U}_{\hat{i}}$ indicates the rate of a new call connection in cell 1. The subdiagonal elements of $\tilde{U}_{\hat{i}}$ represent the rate of a successful handoff call from cell 2 to cell 1. $\tilde{D}_{\hat{i}}$ has nonzero elements in the diagonal and super diagonal. The diagonal elements of $\tilde{D}_{\hat{i}}$ show the rate of a call completion in cell 1. The super diagonal elements of $\tilde{D}_{\hat{i}}$ represent the rate of a successful handoff call from cell 1 to cell 2.

The structure of $\tilde{B}_{\hat{i}}$ ($0 \leq \hat{i} \leq C - 1$) is shown in Table 2. $\tilde{D}_{\hat{i}}$ ($1 \leq \hat{i} \leq C - 1$) has the following structure:

$$\tilde{D}_{\hat{i}} = \begin{bmatrix} \hat{i}\mu & \hat{i}\eta & & & & \\ & \hat{i}\mu & \hat{i}\eta & & & \\ & & \hat{i}\mu & \hat{i}\eta & & \\ & & & \ddots & \ddots & \\ & & & & \hat{i}\mu & \hat{i}\eta \\ & & & & & \hat{i}\mu_c \end{bmatrix}. \quad (14)$$

$\tilde{U}_{\hat{i}}$ ($0 \leq \hat{i} \leq C - 2$) has the following structure:

$$\tilde{U}_{\hat{i}} = \begin{bmatrix} \lambda_n & & & & & \\ \eta & \lambda_n & & & & \\ & 2\eta & \lambda_n & & & \\ & & \ddots & \ddots & & \\ & & & (C-1)\eta & \lambda_n & \\ & & & & C\eta & \lambda_n \end{bmatrix}. \quad (15)$$

Let $\tilde{x}(0)$ and $\tilde{x}(t)$ be $1 \times C(C + 1)$ row-vectors representing the state of the two-cell system at time 0 and t, respectively, for $(C - 1)$ channels in cell 1 and C channels for cell 2. In the model for admission control, we can express

TABLE 2: Structure of $\widetilde{B}_{\hat{i}}$ in adaptive call admission control scheme for two-cell system.

$\widetilde{B}_{\hat{i}}$ $(0 \leq \hat{i} \leq C - 1)$ has the following structure:

$$
\widetilde{B}_{\hat{i}} = \begin{bmatrix}
\widetilde{B}_{\hat{i}}(0,0) & \widetilde{B}_{\hat{i}}(0,1) & & & & & \\
\widetilde{B}_{\hat{i}}(1,0) & \widetilde{B}_{\hat{i}}(1,1) & \widetilde{B}_{\hat{i}}(1,2) & & & & \\
& \widetilde{B}_{\hat{i}}(2,1) & \widetilde{B}_{\hat{i}}(2,2) & \widetilde{B}_{\hat{i}}(2,3) & & & \\
& \ddots & \ddots & \ddots & & & \\
& & \widetilde{B}_{\hat{i}}(\hat{j}-1,\hat{j}-2) & \widetilde{B}_{\hat{i}}(\hat{j}-1,\hat{j}-1) & \widetilde{B}_{\hat{i}}(\hat{j}-1,\hat{j}) & & \\
& & & \widetilde{B}_{\hat{i}}(\hat{j},\hat{j}-1) & \widetilde{B}_{\hat{i}}(\hat{j},\hat{j}) & \widetilde{B}_{\hat{i}}(\hat{j},\hat{j}+1) & \\
& & & & \ddots & \ddots & \ddots \\
& & & & \widetilde{B}_{\hat{i}}(C-1,C-2) & \widetilde{B}_{\hat{i}}(C-1,C-1) & \widetilde{B}_{\hat{i}}(C-1,C) \\
& & & & & \widetilde{B}_{\hat{i}}(C,C-1) & \widetilde{B}_{\hat{i}}(C,C)
\end{bmatrix},
$$

where $\widetilde{B}_{\hat{i}}(\hat{j},\hat{j}) = -(2\lambda_n + (\hat{i} + \hat{j})\mu_c)$ for $(0 \leq \hat{i} \leq C - 2)$ and $(0 \leq \hat{j} \leq C - 1)$, $\widetilde{B}_{\hat{i}}(C,C) = -(\lambda_n + (\hat{i} + C)\mu_c)$ for $(0 \leq \hat{i} \leq C - 2)$, $\widetilde{B}_{C-1}(\hat{j},\hat{j}) = -(\lambda_n + (\hat{j} + C - 1)\mu_c)$ for $(0 \leq \hat{j} \leq C - 1)$, $\widetilde{B}_{C-1}(C,C) = -(2C - 1)\mu_c$, $\widetilde{B}_{\hat{i}}(\hat{j},\hat{j} + 1) = \lambda_n$ for $(0 \leq \hat{i} \leq C - 1, 0 \leq \hat{j} \leq C - 1)$, $\widetilde{B}_{\hat{i}}(\hat{j},\hat{j} - 1) = \hat{j}\mu$ for $(0 \leq \hat{i} \leq C - 2, 1 \leq \hat{j} \leq C)$, and $\widetilde{B}_{C-1}(\hat{j},\hat{j} - 1) = \hat{j}\mu_c$ for $(1 \leq \hat{j} \leq C)$.

$\widetilde{x}_{(r_0 \to r)}(0,t) = \Pr\{\widetilde{x}(t) = r \mid \widetilde{x}(0) = r_0\}$ as the probability that the system is in state r at time t given the initial state r_0 at time zero. If we consider the system at time t, we have $\widetilde{x}_{(r)}(t) = \Pr\{\widetilde{x}(t) = r\}$ which is conditioned on the initial state. These transient probabilities are the elements of $\widetilde{x}(t) = [\widetilde{x}_0(t), \widetilde{x}_1(t), \ldots, \widetilde{x}_{C-1}(t)]$, where $\widetilde{x}_{\hat{i}}(t)$ $(0 \leq \hat{i} \leq C - 1)$ is a $(C + 1)$-element row vector representing the probability vector for total $\hat{i}$ calls in the $C - 1$ channels of cell 1 at time t. $\widetilde{x}_{\hat{i}}(t)$ can be represented as $\widetilde{x}_{\hat{i}}(t) = [\widetilde{x}_{\hat{i},0}(t), \widetilde{x}_{\hat{i},1}(t), \widetilde{x}_{\hat{i},2}(t), \ldots, \widetilde{x}_{\hat{i},C}(t)]$. Here, $\widetilde{x}_{\hat{i},\hat{j}}(t)$ denotes the probability of seeing $\hat{i}$ customers in $C - 1$ channels of cell 1 and $\hat{j}$ customers in C channels of cell 2 at time t. To calculate $\widetilde{x}(t)$, we have to solve the Kolmogorov-forward equations which can be expressed in the matrix form as follows:

$$
\frac{d\widetilde{x}(t)}{dt} = \widetilde{x}(t)\widetilde{Q}. \tag{16}
$$

If we solve (16), we get

$$
\widetilde{x}(t) = \widetilde{x}(0)e^{\widetilde{Q}t}. \tag{17}
$$

If the candidate call at time 0 sees $\hat{i}$ and $\hat{j}$ calls in cells 1 and 2, respectively, then $(\hat{i}(C + 1) + \hat{j})$th element (with the assumption of counting begins from the starting position as 0th position) of $\widetilde{x}(0)$ is one and all other elements of $\widetilde{x}(0)$ are zero. Now, exploiting the special structure of $\widetilde{x}(0)$ we can determine $\widetilde{x}(t)$ which is the $(\hat{i}(C + 1) + \hat{j})$th row of $e^{\widetilde{Q}t}$. $e^{\widetilde{Q}t}$ is not computed using formula of exponential function which is $e^{\widetilde{Q}t} = I + \sum_{k=1}^{\infty} ((\widetilde{Q}t)^k/k!)$ as $\widetilde{Q}$ has negative elements in the diagonal which makes the computation of $e^{\widetilde{Q}t}$ unstable as this computation involves repeated multiplication and addition of negative and positive quantities. Therefore, uniformization technique of Jensen [36] is used for computing $e^{\widetilde{Q}t}$ which is a general and efficient way to obtain the solution from the above (17) as it does not involve repeated multiplication and addition of negative

and positive quantities. In this technique, the new transition probability matrix P is defined as

$$
P = \frac{\widetilde{Q}}{\Lambda} + I, \tag{18}
$$

where $\Lambda \geq \max(-\widetilde{B}_{\hat{i}}(\hat{j}, \hat{j}), 0 \leq \hat{i} \leq C - 1, 0 \leq \hat{j} \leq C)$. If the arrival rate of new call is greater than the inverse of mean channel holding time (i.e., $\lambda_n > \mu_c$), we use $\Lambda = 2\lambda_n + (2C - 3)\mu_c$. On the other hand, if the arrival rate of new call is less than the inverse of mean channel holding time (i.e., $\lambda_n < \mu_c$) we use $\Lambda = (2C - 1)\mu_c$. Now, using (17) and (18), we get

$$
\begin{aligned}
\widetilde{x}(t) &= \widetilde{x}(0)e^{(P-I)\Lambda t} \\
&= \widetilde{x}(0)e^{P\Lambda t}e^{-\Lambda t} \\
&= \widetilde{x}(0)\sum_{n=0}^{\infty} P^n \frac{(\Lambda t)^n}{n!}e^{-\Lambda t}.
\end{aligned} \tag{19}
$$

The infinite summation in (19) is truncated at some value $n = M$ such that the truncation error remains below ε which can be expressed mathematically as

$$
\widetilde{x}(t) = \widetilde{x}(0)\sum_{n=0}^{M} P^n \frac{(\Lambda t)^n}{n!}e^{-\Lambda t}, \tag{20}
$$

where $\sum_{n=M+1}^{\infty} e^{-\Lambda t}((\Lambda t)^n/n!) < \varepsilon$.

The probability of an accepted user in cell 1 that needs handoff at time t is $(1 - e^{-\eta t})e^{-\mu t}$. Now, the probability of all the channels in cell 2 being occupied at time t is $\sum_{\hat{i}=1}^{C-1} \widetilde{x}_{\hat{i},C}(t)$. Therefore, the candidate call accepted at cell 1 will be dropped at time t if at that moment the call needs to handoff to cell 2 and finds all the channel occupied which occurs with probability $p_e(t) = e^{-\mu t}(1 - e^{-\eta t})\sum_{\hat{i}=1}^{C-1} \widetilde{x}_{\hat{i},C}(t)$. Now, the average probability $\overline{P}_E(T)$ of an accepted call in cell 1 of not finding any empty channel in cell 2 if it requires handoff is

$$
\overline{P}_E(T) = \frac{1}{T}\int_0^T p_e(t)dt. \tag{21}
$$

The integration of (21) is carried out numerically using Simpson's method of numerical integration. In this method, the range $[0, T]$ is divided into r subintervals of equal length $l = T/r$, where r is an even number. The numerical integration can be expressed as

$$\overline{P}_E(T)$$

$$= \frac{l}{3T}(f_0 + 4f_1 + 2f_2 + 4f_3 + 2f_4 + \cdots + 2f_{r-2} + 4f_{r-1} + f_r)$$

$$= \frac{1}{3r}(f_0 + 4f_1 + 2f_2 + 4f_3 + 2f_4 + \cdots + 2f_{r-2} + 4f_{r-1} + f_r),$$

$$(22)$$

where $f_k = p_e(kT/r)$, $0 \leq k \leq r$.

For different $C(C+1)$ values of $\widetilde{x}_0$ we can compute values of $\overline{P}_E(T)$. The threshold value P_E is one of the $C(C+1)$ values for different initial states of x_0. We can determine this threshold value of P_E for accepting a new call by running simulation experiments with the goal of minimizing the new call blocking probability while keeping the handoff failure probability below a prespecified value. The admission controller can keep the table of $\overline{P}_E(T)$ and the threshold values of P_E in memory. Whenever a new call comes to cell 1, then the admission controller needs to check whether the $(\widehat{i}(C + 1) + \widehat{j})$th entry of the table storing values of $\overline{P}_E(T)$ is not more than P_E. If this condition is satisfied the call is accepted in cell 1. On the other hand, when a call comes to cell 2 for admission it needs to check that the $(\widehat{j}(C+1)+\widehat{i})$th entry of the table storing values of $\overline{P}_E(T)$ is not more than P_E. If this condition is satisfied, the call is accepted in cell 2. We conjecture that acceptance of new call in our model guarantees a successful handoff for the accepted call with some probability. Guard channel scheme fails to guarantee this handoff in a cell for different number of calls in the neighboring cells.

The advantage of our model is that we can compute $\overline{P}_E(T)$ in T time ahead for different values of $\widetilde{x}(0)$ and keep these values in a table. Whenever a new call attempt is made in a cell, the CAC algorithm needs to get the value of $\overline{P}_E$ to decide about accepting the call.

3.1. Extension to multiple-cell wireless network

We can extend our adaptive CAC scheme for the two-cell system to multiple-cell wireless network. Here, each cell contains C channels, new call arrival process to each cell is Poisson distributed with mean λ_n, cell residence time in each cell is exponentially distributed with mean $1/\eta$, and call holding duration is exponentially distributed with mean $1/\mu$. In this approximation, let us assume that our target cell F_t has i calls, and the target cell has J immediate neighbors $F_{n_1}, F_{n_2}, \ldots, F_{n_J}$ having $l_{n_1}, l_{n_2}, \ldots, l_{n_J}$ calls, respectively. A new call is blocked if $i = C$. On the other hand, we can use the values in the table for accepting a call in the target cell for $i < C$ and $j = \lceil \sum_{k=1}^{J} l_{n_k}/J \rceil$ using the table which contains values for probability of dropping a candidate call in the target cell if it needs to handoff the neighboring cell. We need to determine the threshold value P_E by carrying out
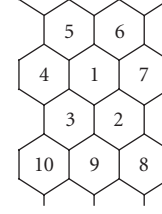
FIGURE 2: Hexagonal structure of cellular wireless network.

simulation to keep the handoff failure probability below that value. When a call comes to the target cell with at least one free channel, we can consider $\widehat{i} = i$ and $\widehat{j} = j$. The admission controller needs to check whether the $(i(C+1)+j)$th entry of the table storing values of $\overline{P}_E(T)$ is not more than P_E. If this condition is satisfied, the call is accepted in the target cell. Otherwise, the new call is blocked. In lower load, the handoff failure probability is very low and needs no prioritization of handoff calls over new calls. As a result, the value of P_E is the highest value of the values of handoff failure probabilities of candidate call in the neighboring cell stored in the table. An example of hexagonal cell structure of cellular wireless network is shown in Figure 2. If a new call comes to cell 1, then cell 1 is the target cell. If there is at least one free channel in cell 1, then i is the value of the number of calls in cell 1 and the value of j is computed as the ceiling of the average number of calls in the immediate neighboring cells 2, 3, 4, 5, 6, and 7. We show the adaptive CAC algorithm for the target cell in the multiple-cell system using Pseudocode 1.

In Section 4, we find that it is not always possible to get the exact desired handoff call failure probability using adaptive algorithm in higher load. We develop another variant of this adaptive algorithm which we call fractional adaptive algorithm using the approach similar to fractional guard channel scheme [4]. In this algorithm, we select the threshold value P_E which is the immediate higher value than the threshold value used in adaptive scheme from the table of the adaptive scheme. In the fractional adaptive scheme, a new call is always accepted in a target cell if the $(i(C + 1) + j)$th entry of the table storing values of $\overline{P}_E(T)$ is less than P_E. On the other hand, a new call is accepted with some probability P_{th} when the $(i(C + 1) + j)$th entry of the table storing values of $\overline{P}_E(T)$ is equal to P_E. We can choose the value of P_{th} by simulation in such a way that the handoff failure probability is approximately equal to the desired handoff failure probability value. Adaptive scheme can be considered as a special case of fractional adaptive scheme, where $P_{th} = 1$, and P_E is chosen in such a way that handoff failure probability is not more than the desired handoff failure probability. We show the fractional adaptive CAC algorithm for target cell in the multiple-cell system using Pseudocode 2.

4. NUMERICAL EXAMPLES

We carry out analytical and discrete event simulation studies on the two-cell system of Figure 1. Simulation studies are also performed on the nineteen-cell wireless system of

```
if (handoff call)
    if (i < C)
        accept the handoff call;
    else /*if (i = C)*/
        reject the call;
else /* if (new call) */
    if (i = C)
        reject the call
    else /* if (i < C)*/
        sum ← 0;
        for k ← 1 to J do
            sum ← sum + l_{n_k};
        j ← ⌈(sum/J)⌉;
        Get (i(C + 1) + j)th entry
        P̄_E(T) from table;
        if (P̄_E(T) ≤ P_E)
            accept the call;
        else /* if (P̄_E(T) > P_E)*/
            reject the call;
```

PSEUDOCODE 1: Adaptive algorithm.
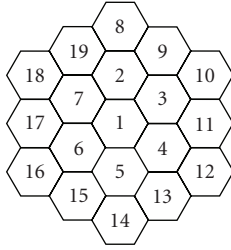
FIGURE 3: Cellular network consisting of nineteen cells with wrap-around structure.

Figure 3 with wrap-around structure. We assume that there are ten channels in each cell. The cell residence time and call holding duration are assumed to be exponentially distributed with means 1.0 unit time and 0.25 unit time, respectively. New call arrival process is assumed to follow Poisson distribution. Mean call arrival rate is varied from 4.0/unit time to 48.0/unit time. We assume that our goal is to minimize the new call blocking probability while keeping handoff call failure probability below 0.015. We use $T = 5.0$ unit time for our adaptive admission control scheme in numerical examples. 100000.0 unit time is chosen as warm-up time for the simulation. Ten independent replications of length 50000.0 unit time are performed in the simulation studies. We discuss numerical examples for two-cell and multiple-cell wireless networks in Sections 4.1 and 4.2, respectively. In the figures, we denote analytical and simulation results for nonpriority handoff scheme as "Guard0 Analytical" and "Guard0 Simulation," respectively. We denote analytical results for guard channel schemes with one and two guard channels as "Guard1 Analytical" and "Guard2 Analytical," respectively. Similarly, we denote simulation results for guard channel schemes with one and two guard channels as

```
if (handoff call)
    if (i < C)
        accept the handoff call;
    else /*if (i = C)*/
        reject the call;
else /* if (new call) */
    if (i = C)
        reject the call
    else /* if (i < C)*/
        sum ← 0;
        for k ← 1 to J do
            sum ← sum + l_{n_k};
        j ← ⌈(sum/J)⌉;
        Get (i(C + 1) + j)th entry
        P̄_E(T) from table;
        if (P̄_E(T) < P_E)
            accept the call;
        else if (P̄_E(T) = P_E)
            u ← rand(0, 1);
            if (u ≤ P_th)
                accept the call;
            else /* if (u > P_th)*/
                reject the call;
        else /* if (P̄_E(T) > P_E)*/
            reject the call;
```

PSEUDOCODE 2: Fractional adaptive algorithm.

"Guard1 Simulation" and "Guard2 Simulation," respectively. The simulation results for adaptive and fractional adaptive scheme are represented as "adaptive simulation" and "fractional adaptive simulation," respectively.

4.1. Numerical result for two-cell system

Analytical studies are carried out on nonpriority handoff scheme and guard channel scheme with one and two guard channels. Simulation studies are performed on nonpriority handoff scheme, guard channel scheme with one and two guard channels, and our adaptive CAC scheme.

Analytical and simulation results of channel utilization, new call blocking probability, and handoff call failure probability are shown in Figures 4, 5, and 6, respectively. We can see that our analytical and simulation results agree well for nonpriority handoff scheme and guard channel scheme with one and two guard channels from these figures.

Figures 4, 5, and 6 show that nonpriority handoff scheme and guard channel scheme with one guard channel fails to keep the handoff failure probability below 0.015 for higher load while they have lower new call blocking probability and higher channel utilization. On the other hand, our adaptive CAC scheme and guard channel scheme with two guard channels succeed to keep the handoff failure probability below the required value 0.015. Moreover, our adaptive call admission control scheme has higher channel utilization and lower new call blocking probability than the guard channel scheme with two guard channels.
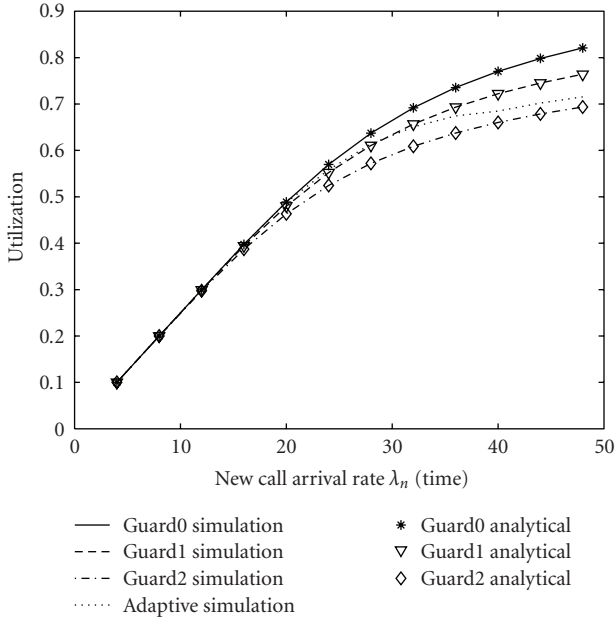
Figure 4: Analytical and simulation results of channel utilization for the two-cell system.
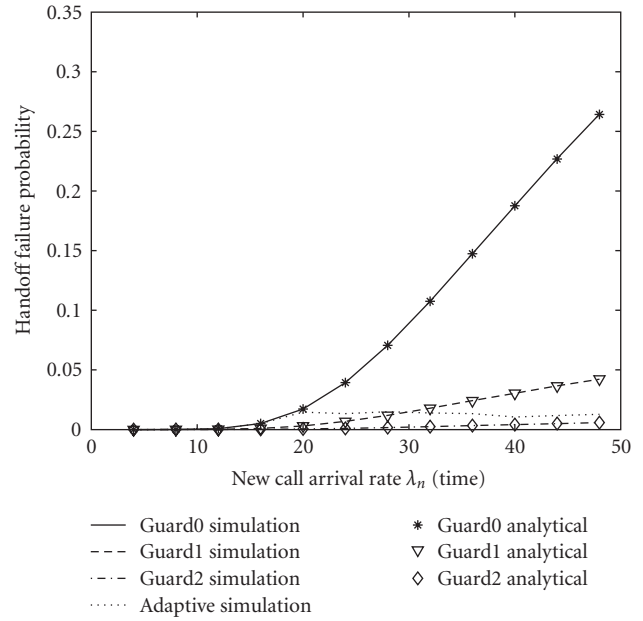
Figure 6: Analytical and simulation results of handoff failure probability for the two-cell system.
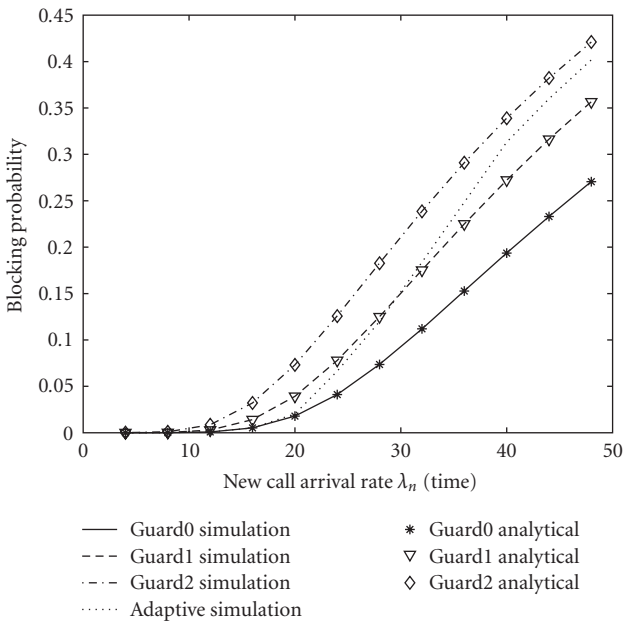

Figure 5: Analytical and simulation results of new call blocking probability for the two-cell system.
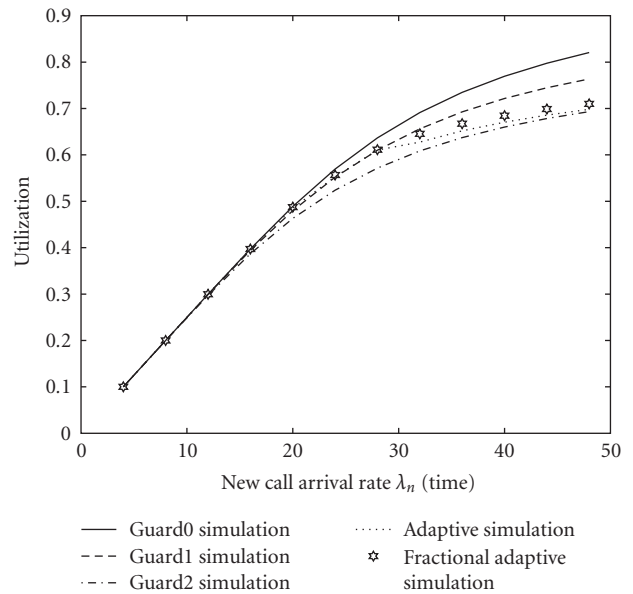

Figure 7: Simulation results of channel utilization for nineteen-cell wrap around structure.

4.2. Numerical result for multiple-cell system

Channel utilization, new call blocking probability, and handoff failure probability are studied using simulation for guard channel scheme. The guard channel schemes are with zero, one, and two guard channels. Simulation is also carried out for adaptive and fractional adaptive CAC schemes for the wrapped around nineteen-cell wireless network of Figure 3 where each cell has six neighbors (e.g., cell 12

has neighboring cells 4, 11, 13, 17, 18, and 19). Results of simulation studies for channel utilization, new call blocking, and handoff failure probabilities are presented in Figures 7, 8, and 9, respectively.

Figures 7 and 8 show that at lower new call arrival rates channel utilization, and new call blocking probabilities are almost the same for the different schemes. At higher new call arrival rates, channel utilization and new call blocking probabilities are largest for nonpriority handoff scheme.
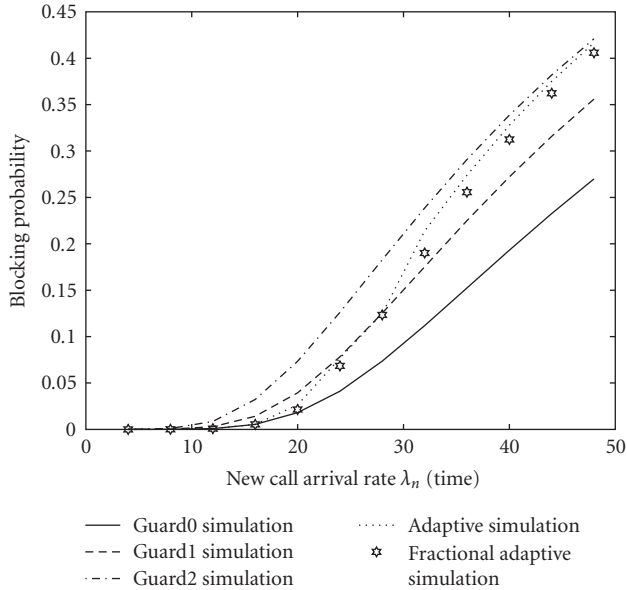
FIGURE 8: Simulation results of new call blocking probability for nineteen-cell wrap around structure.

FIGURE 9: Simulation results of handoff call failure probability for nineteen-cell wrap around structure.

With respect to channel utilization and new call blocking probabilities, the remaining schemes can be ordered in decreasing order as guard channel scheme with one guard channel, fractional adaptive scheme, adaptive scheme, and guard channel scheme with two-guard channels. Figure 9 shows that handoff failure probability is lower than 0.015 for all the schemes in lower loads. However, at higher loads only adaptive, fractional adaptive, and guard channel scheme with two-guard channels can keep the handoff failure probability below 0.015. We can see from Figure 9 that the handoff failure probability can be kept quite close to 0.015 by adaptive scheme at higher loads. On the other hand, fractional adaptive scheme keeps the handoff failure probability almost equal to 0.015. It is clear that at higher loads adaptive and fractional adaptive schemes better control handoff failure probability than the guard channel scheme, and fractional adaptive scheme is better than adaptive scheme in controlling the handoff failure probability to a threshold value.

5. CONCLUSION

In this paper, steady-state analysis of guard channel scheme is performed for two-cell system. It is shown that the assumption of exponentially or hyperexponentially distributed handoff interarrival time is not justified. We propose an adaptive call admission control scheme for the two-cell system which provides a guarantee with some probability that if a user is admitted the call will be completed irrespective of its movement in the two-cell system. The advantage of our scheme is that the computations are performed offline. We extend the adaptive scheme for the two-cell wireless network to develop the adaptive call admission control scheme for multiple-cell wireless network. We develop fractional adaptive scheme for multiple-cell wireless system—a variant of our adaptive scheme for multiple-

cell system. Our adaptive and fractional adaptive schemes are found to better control the handoff failure probability than the guard channel scheme. Our next directions are to develop the adaptive scheme for multiple class traffic. We will also study the sensitivity of adaptive and fractional adaptive schemes to the value of T.
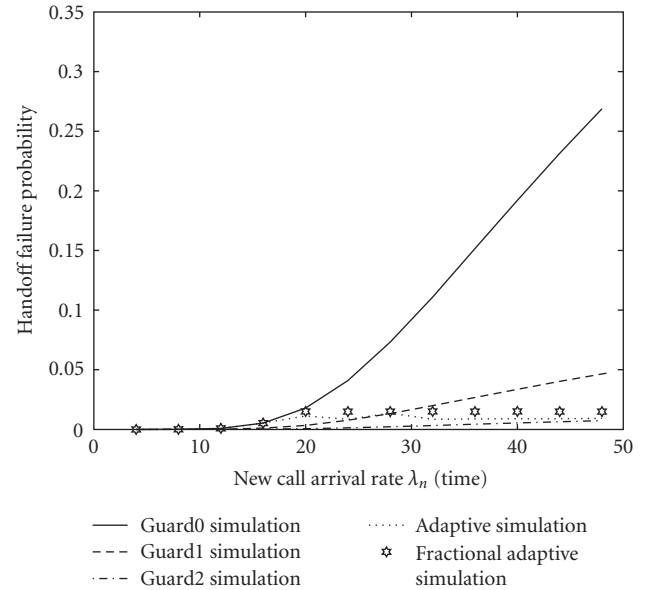
ACKNOWLEDGMENT

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