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An Efficient Scheme to Reduce Handoff Dropping in LEO Satellite Systems *

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Abstract. The problem of handoffs in cellular networks is compounded in a low earth orbit (LEO) satellite-based cellular network due to the relative motion of the satellites with respect to a stationary observer on earth. Typically, the velocity of motion of mobiles can be ignored when compared to the very high velocity of the footprints of satellites. We exploit this property of LEO satellite systems and propose a handoff scheme based on a channel sharing approach that results in a substantial decrease in handoff dropping. For the same handoff dropping performance, our scheme has significantly lower new call blocking probability than the conventional reservation scheme. We also present an analytical approximation that is in very good accord with simulation results.

Keywords: satellite networks, handoffs, simulation, analytical approximation, channel reservation

1. Introduction

Low earth orbit (LEO) satellite systems can provide users with low-cost and truly global wireless services, regardless of user locations. Hence, there has been a lot of recent interest in developing efficient schemes for channel allocation and handoff in such systems [1,3,10,15]. LEO satellite systems have certain unique features not found in other satellite and ground-based wireless communication systems. We list some of them here.

While geo-synchronous satellites orbit earth at an altitude of about 36,000 km, LEO satellites orbit earth in the 500–2000 km altitude range. Besides reducing the propagation delay suffered by signals, the lower orbital altitude also means a lower power requirement at the hand-held terminals, thus improving the portability of the terminal. LEO satellite systems can provide communication services even to those areas that do not have a terrestrial wired network in place. In areas where there is a ground-based wireless network in operation, the satellite network can be used either in conjunction with the ground-based network for handling overflow traffic, or in isolation. Because LEO satellites are smaller and lighter than geo-synchronous satellites, they are easily launched.

A large number of satellites will be required to ensure that there is always at least one satellite in view for every location on earth. For example, the IRIDIUM system uses a 66-satellite network to provide global coverage. A typical LEO satellite system will consist of a number of low-earth orbits with a fixed number of satellites traversing each orbit. The footprint of each satellite is divided into several cells with each cell being served by a "spot-beam". As in terrestrial cellular systems, a channel that is used in a given cell cannot be used in another cell if it is at a distance smaller than the *minimum reuse distance*.

Another unique feature of LEO satellites relates to the fact that these satellites are not in geo-synchronous orbit, and hence will not appear stationary to a stationary observer on earth. Instead, the satellites move at a constant velocity relative to a stationary observer on earth. Thus, in addition to the mobile users' random motion we have to handle the deterministic motion of the footprint of the satellite on earth. Fortunately, this does not pose a problem because the velocity of motion of the footprints is of the order of km/s. For example, a typical value for the velocity of the footprint is 7.39 km/s. Hence, it is appropriate (and commonly done) to make the simplifying assumption that the velocity of the mobile can be ignored when compared to the high velocity of the footprint (see [2,12]).

Some areas on earth will have overlapping coverage from different satellites. We will be able to make use of this macrodiversity advantage to reduce erroneous transmission due to channel noise. Additionally, the presence of a large number of satellites ensures survivable communications, since the malfunctioning of a single satellite will not adversely affect the operation of the network.

Our objective in this paper is to improve the handoff dropping performance of LEO satellite systems by exploiting the fact that the relative motion of the mobile is almost deterministic. This paper is organized as follows. In section 2, we discuss the importance of efficiently handling handoffs, and delineate the most important source of handoff call dropping in non-geostationary satellite systems. In section 3, we describe our technique, based on the channel sharing scheme of [6–8], to reduce the incidence of handoff call dropping. We show that our technique is ideally suited to handle the handoff problem because the allocation of channels is done with the knowledge of the direction of the mobile's relative motion. In section 5, we provide an analytical approximation to obtain the performance of our handoff technique. In section 5, we compare our handoff scheme to the fixed chan-

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nel assignment (FCA) scheme with channel reservation, and present numerical results. In section 6, we describe a hybrid channel sharing handoff scheme that has a tunable parameter using which the system can be made to achieve any desired handoff dropping performance.

2. Problem description

We are interested in two different quality-of-service (QoS) measures: *new call blocking probability* and *handoff call dropping probability*. Handoff calls are those calls that have already been admitted in some cell and later try to move to a different cell. If the new cell to which the call is moving does not have an idle channel to allocate to this call, the call is dropped. This is known as *handoff call dropping*. When a cell is unable to allocate an idle channel to a new call, *new call blocking* occurs. Handoff call dropping has the undesirable effect of the user being cut off in the middle of a call. Thus, it is important to reduce handoff call dropping even at the expense of increased new call blocking. A popular approach proposed in terrestrial cellular systems to reduce handoff dropping is the reservation policy (sometimes called the guard channel policy) [11]. Other approaches include queueing of handoff attempts [4] and queueing of handoff attempts based on measured SIR values [14].

As we have already observed, ensuring successful handoffs becomes more complicated in the LEO satellite scenario due to the motion of the satellites relative to any stationary observer on earth. With the assumption that the mobile's velocity is negligible compared to the velocity of the footprint on earth, the motion of the mobile relative to a satellite becomes totally deterministic. Our view is that we can use this knowledge about the motion to reduce handoff dropping substantially while, at the same time, not adversely affecting the new call blocking probability.

The following are the assumptions we make in our analysis:

1. All cells are identical with length L, and the relative motion of the mobile is along the length of the cells.

2. The *call holding time* (or the call duration), t_d, is exponentially distributed with mean $1/\mu$.

3. The velocity of motion of mobiles can be neglected in comparison to the velocity of motion of the footprint on earth, V. Equivalently, we assume that the mobiles are moving with a velocity of V relative to the stationary satellite footprint.

4. The distance new calls have to travel before their first handoff attempt is uniformly distributed between 0 and L. This assumption is reasonable because mobiles are equally likely to begin their call from any location in the cell. Thereafter, the mobile's deterministic relative velocity requires a handoff to be made after the remaining distance in the cell is traversed.

As in [2], we call the cell of origination of a call its "source cell" and the cell to which a call has handed off as its "transit cell". A mobile in its source cell has to travel a distance that is uniformly distributed between 0 and L before its first handoff. A mobile in a transit cell has to travel a fixed distance of L before its next handoff, unless it finishes service before its next handoff. Let Y denote the random variable that represents the distance a mobile has to travel in its source cell before it makes a handoff. Then the probability that a mobile in its source cell will give rise to a handoff, P_{h1}, is

$$P_{h1} = \int_0^L P\left\{t_d > \frac{y}{V}\right\} f_Y(y)\,dy,$$

where

$$f_Y(y) = \begin{cases} \dfrac{1}{L} & \text{if } 0 \leqslant y < L, \\ 0 & \text{otherwise.} \end{cases}$$

Thus,

$$P_{h1} = \frac{1 - e^{-\mu L/V}}{\mu L/V}.$$

In the following, we let $x \triangleq \mu L/V$. Similarly, a call entering a transit cell will give rise to another handoff with probability

$$P_{h2} = e^{-\mu L/V} = e^{-x}. \tag{1}$$

We denote the new call blocking probability by P_{bn} and the handoff call dropping probability by P_{bh}. From the point of view of the mobile user, a quantity that is often more relevant than the handoff call dropping probability is the probability that the call gets eventually dropped due to a handoff failure. We let P_{drop} denote this quantity. Under the above assumptions, it has been shown in [2] that

$$P_{drop} = \frac{P_{h1} P_{bh}}{1 - P_{h2}(1 - P_{bh})},$$

where

$$P_{h1} = \frac{1 - e^{-\mu L/V}}{\mu L/V}$$

is the probability that a call in its cell of origin makes a handoff attempt, and $P_{h2} = e^{-\mu L/V}$ is the probability that a call entering a transit cell makes another handoff attempt.

In figure 1, we plot the *eventual call dropping probability* (P_{drop}) against the handoff call dropping probability (P_{bh}) for some typical values of x and for the most interesting range of P_{bh}. We find that P_{drop} is higher than P_{bh} in this range. This is due to the high number of handoffs that a call is likely to make due to the high relative velocity of the mobile. Therefore, it is important to handle handoffs efficiently in LEO satellite systems. The values of x in figure 1 are typical of the values that are obtained in a practical LEO satellite system [2]. For example, $x = 0.1917$ corresponds to $1/\mu = 180$ s, $L = 425$ km, and $V = 7.39$ km/s.

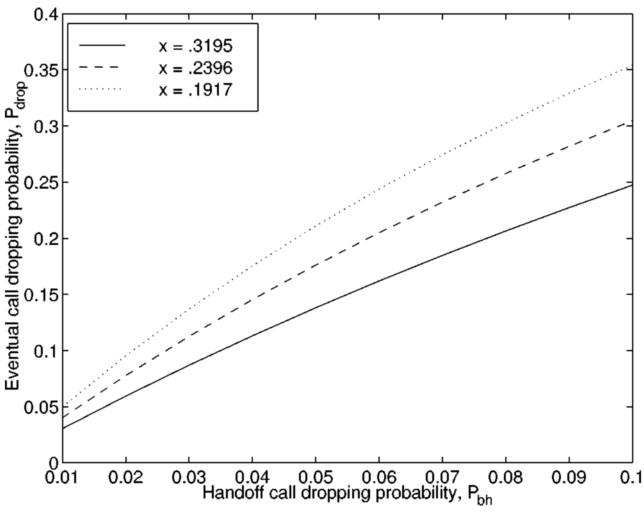

Figure 1. Comparison of P_{bh} and P_{drop} for a few typical values of x.

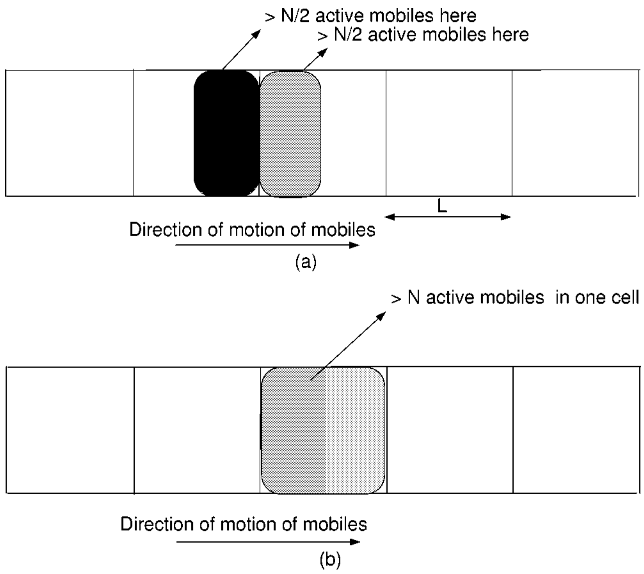

Figure 2. A typical case where handoff dropping occurs.

We next delineate a primary cause for handoff dropping in LEO satellite networks. In figure 2, we illustrate a typical case where handoff dropping occurs. We assume that each cell shown in the figure is allocated N channels and is capable of handling no more than N simultaneous calls. Because the velocities of the mobiles are deterministic and identical, the reason for handoff call dropping is the random initial location of the mobile. Figure 2(a) illustrates such a scenario. The worst situation will be when there are exactly N active mobiles in the two shaded areas in figure 2(a). Since all the mobiles move with the same velocity, we will have as many as N dropped handoff calls, if there are no natural call terminations in the meantime.

In the next section, we propose a scheme to reduce handoff dropping based on the channel sharing scheme in [6–8]. This scheme, as we will see, anticipates the motion of the mobiles and allocates channels accordingly.

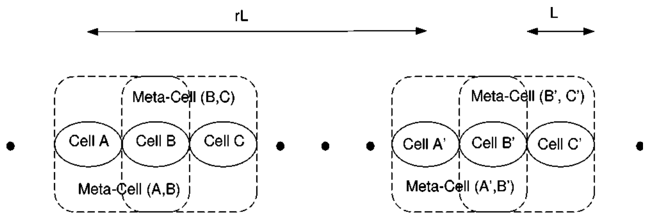

Figure 3. Linear cellular system.

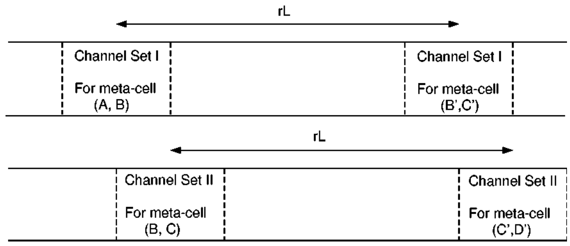

Figure 4. The same set of channels can be used in meta-cells (A, B) and (B', C') and in meta-cells (B, C) and (C', D').

3. Channel sharing handoff scheme

We adopt the channel allocation scheme proposed in [6–8], called the *channel sharing scheme*, to handle handoffs in LEO satellite systems. We first describe this scheme briefly. The sharing scheme allows channels to be shared between neighboring cells. For illustration, we consider a linear cellular network. To facilitate the description, we need some terminology. A *meta-cell* is a pair of neighboring cells. The two adjacent cells that form a meta-cell are called the *component cells* of the meta-cell. The channel sharing scheme allows channels to be shared between neighboring cells (namely, component cells belonging to the same meta-cell).

For example, figure 3 shows a family of meta-cells in a linear cellular system, each comprising two adjacent cells. For this simple linear cellular system, the distance measure $d(X, Y)$ between two cells X and Y is typically given as $d(X, Y) = |c_X - c_Y|$, where c_X and c_Y denote the positions of the centers of cells X and Y, respectively. Suppose that the minimum reuse distance is $\Delta = rL$, where L is the length of a single cell and r is an integer. Cells that are assigned the same set of channels are called *co-channel cells*. In the conventional scheme for fixed channel allocation, each channel is assigned to cells that are exactly a distance Δ apart. We refer to this scheme as the *tightest fixed channel assignment scheme*, in which co-channel cells are exactly r cells apart. For example, in figure 3, cells A and A' are co-channel cells. Let T denote the total number of distinct channels that are available in this linear cellular system. Thus, the total number of distinct channels available for each cell is T/r (i.e., the reuse factor is r).

A meta-cell can be designated by the pair of its component cells. For example, in figure 3, cells A and B are components of meta-cell (A, B). To assign channels to meta-cells, we define a distance measure $d((X, Y), (X', Y'))$ between two meta-cells (X, Y) and (X', Y'). Recall that in the sharing scheme, when a channel is assigned to a meta-cell, it can be used by a mobile user in any cell belonging to that meta-cell. Thus, we have to ensure that the distance between any component cells of two meta-cells assigned the same set of channels complies with the minimum reuse distance requirement. Consequently, we define $d((X, Y), (X', Y'))$ as the minimum of the distance measures between the component cells of meta-cells (X, Y) and (X', Y'), i.e.,

$$d\big((X, Y), (X', Y')\big) = \min\big\{d(X, X'), d(X, Y'), d(Y, X'), d(Y, Y')\big\}. \quad (2)$$

For example, in figure 3, the distance measure between meta-cells (A, B) and (A', B') is given by $(r - 1)L$, which is the distance between cells B and A'. We call meta-cells that are assigned the same set of channels *co-channel meta-cells*. To allocate a maximum number of channels to each meta-cell, co-channel meta-cells must be deployed as close as possible. Therefore, we assign the same set of channels to meta-cells that are exactly the minimum reuse distance apart, i.e., rL in this case.

It then follows that in the channel sharing scheme, each meta-cell is assigned $T/(r + 1)$ distinct channels. In other words, the reuse factor of the channel sharing scheme is $r' = r + 1$. However, in the tightest fixed channel assignment scheme, the number of channels assigned to each meta-cell is T/r, so the cost we pay for allowing channels to be "shared" is $T/r - T/r' = T/r(r + 1)$. Nevertheless, by increasing the reuse distance in this fashion we facilitate a simple way for channels to be shared between cells with little increase in complexity over fixed channel allocation techniques.

Our handoff handling scheme assumes that the channel sharing scheme is chosen as the method of channel allocation. We now describe how our handoff scheme works assuming that the channel sharing scheme has been implemented. We observe that it is reasonable to assume a linear array of cells for the LEO satellite system. This is because handoffs take place in only one direction if we ignore the overlapping region where a mobile could potentially handoff to a cell diagonally across. Without loss of generality, we also assume that the relative motion of mobiles is such that they move towards higher numbered cells. Thus, all mobiles in cell 1 move towards cell 2, those in cell 2 move towards cell 3, and so on. Whenever there is a new call in cell n, it is allocated a channel only if there are idle channels belonging to meta-cell $(n, n + 1)$. Otherwise, the new call is blocked. This procedure is shown schematically in figure 5. By doing the allocation in this manner we can allow the mobiles to "carry" their channel to cell $(n + 1)$ during handoff. Handoff calls arriving in cell n are allocated a channel belonging to meta-cell $(n, n + 1)$ if there is an idle channel available. Otherwise, if the call was using a channel belonging to meta-cell $(n - 1, n)$, it is allowed to carry the same channel over to cell n and is queued for channels belonging to meta-cell $(n, n+1)$. But, at the time of handoff, if the call was using a channel belonging to meta-cell $(n - 2, n - 1)$, then the call is dropped. The flowchart for processing a handoff call arrival is given in figure 6. Each time a channel belonging to meta-cell $(n, n + 1)$ becomes free (either due to a handoff or due to a call termination) the channel is allocated to the first call in the queue waiting for channels belonging to meta-cell $(n, n+1)$. If the queue is empty, the channel is idle and ready to accommodate future new calls or handoff calls. Figure 7 is a schematic representation of the procedure for handling a freed channel.

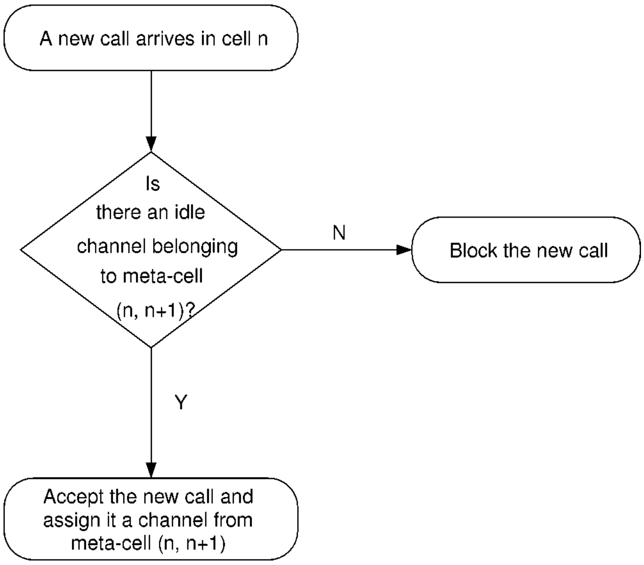

Figure 5. Flow chart for processing a new call.

Our handoff scheme exploits the deterministic nature of the relative velocity of the mobile in a LEO satellite system. Using the knowledge that a new call arriving in cell n will next handoff to cell $(n + 1)$, an attempt is made to allocate the call a channel belonging to meta-cell $(n, n + 1)$. This enables the call to "carry" the same channel to cell $(n+1)$, if an immediate idle channel were to be unavailable in that cell. Similarly, a handoff call in cell $(n+1)$ that is using a channel from meta-cell $(n, n + 1)$ is always looking for a channel from meta-cell $(n + 1, n + 2)$. Thus, a mobile can travel one complete cell-length and look for a free channel during this time. This reduces handoff dropping significantly.

We next note that it is possible to achieve the same handoff dropping performance with the conventional FCA scheme by using channel reservation (but at the cost of increased new call blocking probability). The channel reservation scheme, which seeks to give preferential treatment to handoff calls by reserving channels for them, works as follows. Suppose there are N channels assigned to each cell. Then new calls are admitted in a cell only if the total number of active calls is less than some threshold, P, where $P \leqslant N$. Handoff calls, on the other hand, are admitted as long as there are idle channels. By tuning the parameter P the channel reservation scheme can be made to achieve the same handoff dropping performance as our handoff scheme. But, as we will see in sections 5 and 6, our handoff scheme offers a significantly lower new call blocking probability for

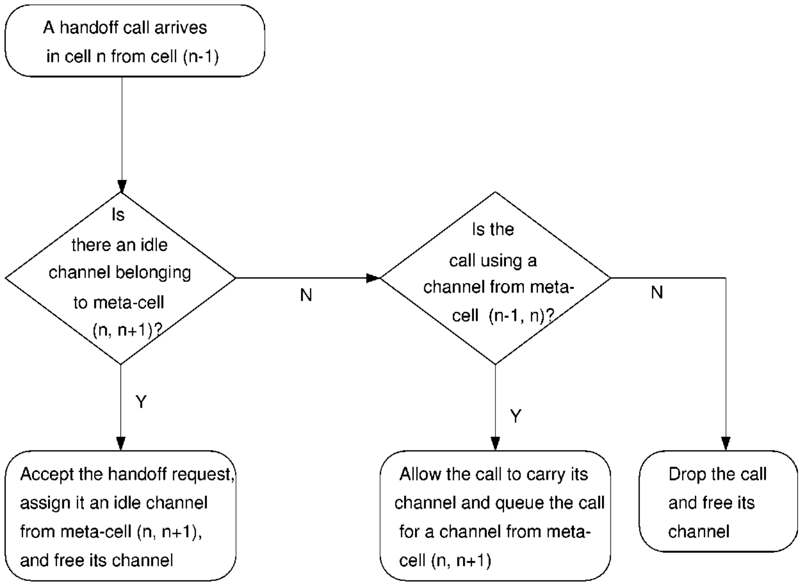

Figure 6. Flow chart for processing a handoff call.

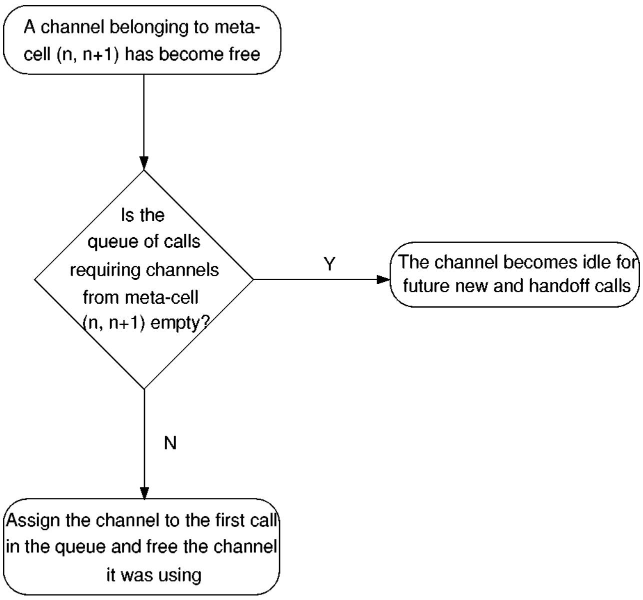

Figure 7. Flow chart for processing a freed channel.

the same handoff dropping performance as FCA with channel reservation.

4. Performance analysis

In this section, we study the performance of our handoff scheme by applying a simple analytical technique called the *two-cell approximation* [13]. We apply the same technique to analyze the FCA scheme with channel reservation. Another approximation, called the *single-cell approximation*, has been used in several studies for performance analysis in LEO systems (e.g., [2,12]). The single cell approximation assumes that the handoff calls arrive into a cell according to a Poisson process and is independent of the new call arrivals [4]. This approximation is used for analytical tractability. Although the single cell approximation could be used to analyze the channel reservation scheme, it is not suited for the analysis of our channel sharing handoff scheme, as discussed below. Hence, for a fair comparison, we use the two-cell approximation for both the channel reservation scheme, and our channel sharing handoff scheme.

As mentioned earlier, the single-cell approximation does not adequately capture the essence of our channel sharing handoff scheme. For example, the number of idle channels in a given cell, say n, not only depends on the number of active calls in that cell but also on the number of channels belonging to meta-cell $(n, n+1)$ that are in use in cell $(n+1)$. Therefore, we use the following two-cell approximation to obtain the quantities of interest for our handoff scheme. In such approximations, we isolate a group of cells and approximate the handoff traffic into the group from outside the group by a Poisson process, but make no such assumption about the handoff traffic originating from within the group [13]. Then we choose the statistics of that cell from among the group whose statistics will closely approximate the actual P_{bn} and P_{bh}. For the analysis to be tractable the number of cells within the group must not be too large. We choose a group of two cells and carry out an approximate analysis.

The reference scenario is shown in figure 8, where i and j refer to the number of active mobiles in cells 1 and 2, respectively. The following are the assumptions in this section:

1. Each cell has independent Poisson new call arrivals at a rate of λ calls/s.

2. The *call holding time* (or the call duration), t_{d}, is exponentially distributed with mean $1/\mu$.

3. The *cell residence time* (the time for which a call resides in a given cell) is exponentially distributed with mean $1/\gamma = L/V$, where L is the length of a cell and V is

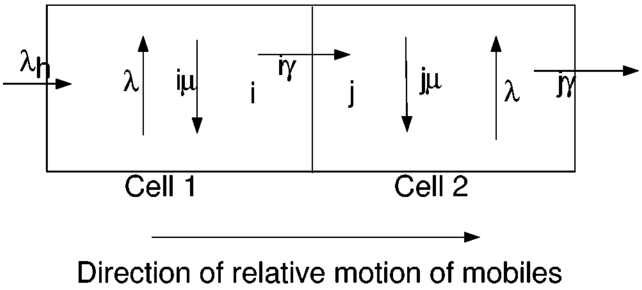

Figure 8. Reference scenario for the two-cell approximation.

the relative velocity of the mobile. We make this approximation for analytical tractability (see [2] for a similar assumption). We validate this approximation using simulation results that are discussed in sections 5 and 6. In the simulations, we do not make the exponential cell residence time assumption, and the results indicate that the approximation is reasonable.

4. Handoff arrival from outside the group into cell 1 is Poisson with rate λ_h. We compute λ_h as follows. The average rate at which new calls are accepted in each cell is $\lambda(1 - P_{bn})$. The probability that a new call will attempt a first handoff is $P_{h1} = (1 - e^{-x})/x$, where $x = \mu L/V$. Thus, the average rate at which calls that are making their first handoff arrive in each cell is $\lambda(1 - P_{bn})P_{h1}$. The average rate at which calls that are making their second handoff arrive in each cell is $\lambda(1 - P_{bn})P_{h1}(1 - P_{bh})P_{h2}$. Thus,

$$\lambda_h = \lambda(1 - P_{bn})P_{h1}\sum_{i=0}^{\infty}(1 - P_{bh})^i P_{h2}^i = \frac{\lambda(1 - P_{bn})P_{h1}}{1 - (1 - P_{bh})P_{h2}}. \quad (3)$$

The above model can be described as a two-dimensional continuous-time Markov chain because new call arrivals in either cell and handoff call arrivals to cell 1 are independent Poisson processes. Additionally, the duration of a call and the cell residence time are exponentially distributed and all the above mentioned parameters are independent of each other. We will now use the two-cell approximation to obtain the quantities of interest for the channel sharing handoff scheme and the FCA scheme with channel reservation.

4.1. Channel sharing handoff scheme

In the channel sharing handoff scheme each meta-cell is allocated $k = Nr/(r + 1)$ channels, where N is the number of channels allocated to each cell in the FCA scheme. For the reference scenario in figure 8, new calls are accepted in cell 1 only if there are unused channels belonging to meta-cell $(1, 2)$. The state of the system is denoted by (i, j), where i denotes the number of active mobiles in cell 1, and j denotes the number of active mobiles in cell 2. Apart from the obvious restriction that $0 \leqslant i,\ j \leqslant 2k$, we also have the additional constraint that $0 \leqslant i + j \leqslant 3k$. This is because the two cells together have access to a maximum of $3k$ channels. The set of all feasible states, $S(k)$, can be defined as follows:

$$S(k) = \{(i, j){:}\ 0 \leqslant i, j \leqslant 2k;\ 0 \leqslant i + j \leqslant 3k\}.$$

Let $P(i, j)$, $(i, j) \in S(k)$ be the stationary probability of the system being in state (i, j). The state transition diagram of the two-cell approximation for the channel sharing handoff scheme is given in figure 9. We define the following notation to write the balance equations:

$$\delta^{(i)} = \begin{cases} 0 & \text{if } i = 0, \\ 1 & \text{otherwise,} \end{cases} \qquad \omega^{(i)} = \begin{cases} 1 & \text{if } i < 2k, \\ 0 & \text{otherwise,} \end{cases} \qquad \kappa^{(i)} = \begin{cases} 1 & \text{if } i < k, \\ 0 & \text{otherwise,} \end{cases} \qquad \theta^{(i,j)} = \begin{cases} 1 & \text{if } i + j < 2k, \\ 0 & \text{otherwise.} \end{cases} \quad (4)$$

With these definitions the balance equations are:

$$\begin{aligned} &P(i, j)\lambda\big(\kappa^{(j)} + \kappa^{(i)}\theta^{(i,j)}\big) \\ &\quad + P(i, j)\big\{\lambda_h\omega^{(i)}\theta^{(i,j-k)} + (i + j)(\mu + \gamma)\big\} \\ &= P(i, j - 1)\lambda\kappa^{(j-1)}\delta^{(j)} \\ &\quad + P(i + 1, j - 1)(i + 1)\gamma\delta^{(j)}\omega^{(i)} \\ &\quad + P(i - 1, j)\big\{\lambda_h\delta^{(i)} + \lambda\kappa^{(i-1)}\delta^{(i)}\theta^{(i-1,j)}\big\} \\ &\quad + P(i + 1, j)\big\{(i + 1)\big(\mu\omega^{(i)}\theta^{(i,j-k)} \\ &\qquad + \gamma\big(1 - \omega^{(j)}\big)\kappa^{(i)}\big)\big\} \\ &\quad + P(i, j + 1)(j + 1)(\mu + \gamma)\omega^{(j)}\theta^{(i,j-k)} \end{aligned} \quad (5)$$

for all $(i, j) \in S(k)$.

On the left-hand side of the above equation is the rate of leaving state (i, j), and on the right-hand side we have the rate of entering state (i, j). We note that whenever cell 1 has more than k active mobiles it is unlikely that handoff calls from cell 1 to cell 2 can be dropped. This is because we have at least one channel from meta-cell $(1, 2)$ in use in cell 1, and we assume that the queueing discipline ensures that this channel gets used for the handoff from cell 1 to cell 2. Besides satisfying the balance equations, the stationary probabilities have to satisfy the following normalization condition:

$$\sum_{(i,j)\in S(k)} P(i, j) = 1. \quad (6)$$

The new call and handoff call dropping probabilities are given as follows:

$$P_{bn} = \sum_{i=0}^{2k}\ \sum_{j\in S_i(k),\ j\geqslant k} P(i, j), \quad (7)$$

$$P_{bh} = \frac{\sum_{i=0}^{k} i P(i, 2k)}{\sum_{(i,j)\in S(k)} i P(i, j)}, \quad (8)$$

where $S_i(k) = \{j{:}\ (i, j) \in S(k)\}$.

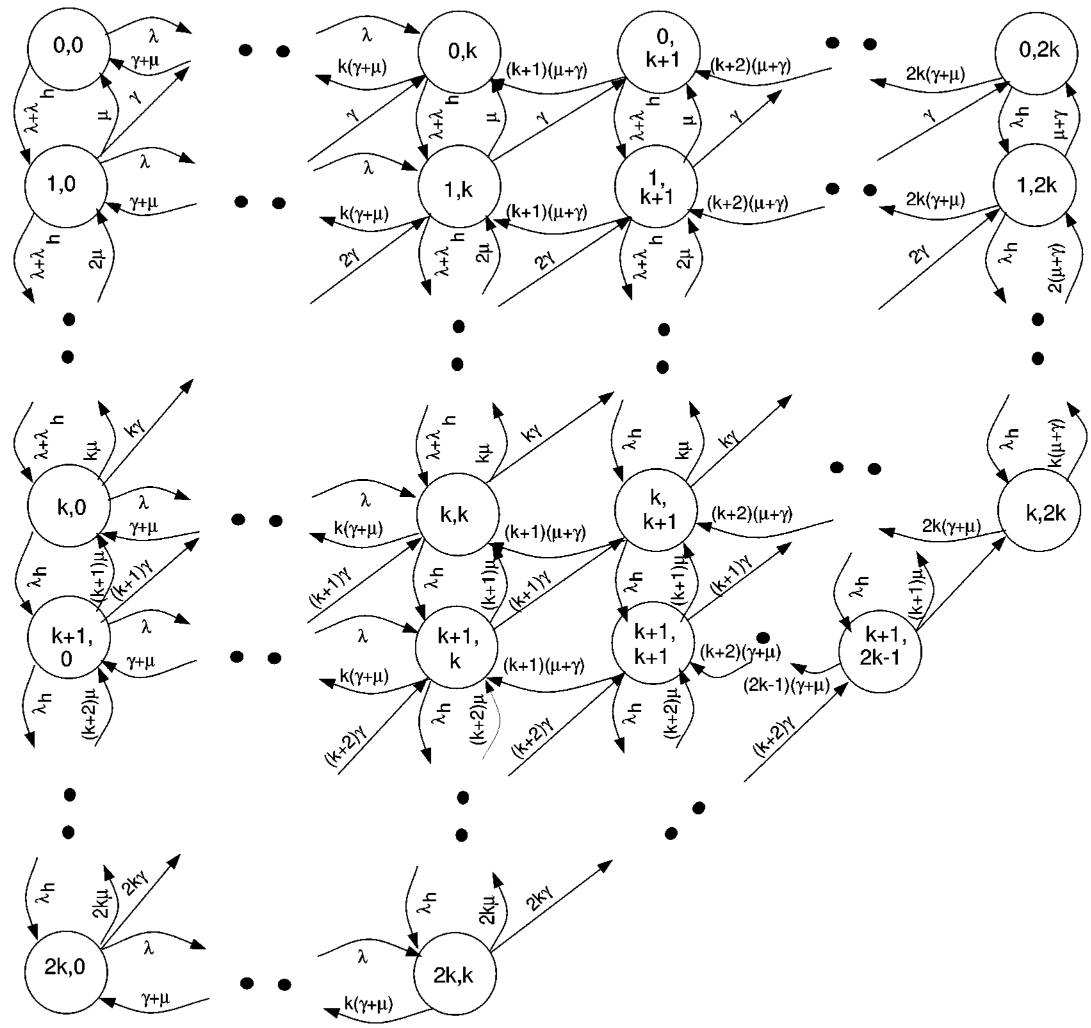

Figure 9. Continuous-time Markov chain of the two-cell approximation for channel sharing handoff scheme.

Equation (7) is the new call blocking probability experienced by calls originating in cell 2. We note that this is a good approximation of the actual new call dropping probability. Equation (8) is derived by taking the ratio of the number of unsuccessful handoffs to the total number of handoff attempts arriving in cell 2. A recursive procedure using equations (3), (5)–(8) has to be followed to compute P_{bh} and P_{bn}. To facilitate comparison with the channel reservation scheme, we now describe the two-cell approximation for the channel reservation scheme.

4.2. FCA with $N - P$ guard channels

Each cell is assigned N channels with $N - P$ channels reserved for handoff calls. New call arrivals are admitted only if there are fewer than P active mobiles in the cell, while handoff calls are accepted as long as there are idle channels. We denote states of the two-dimensional Markov chain by (i, j), where i refers to the number of active mobiles in cell 1 and j refers to the number of active mobiles in cell 2. Let $P(i, j)$, $0 \leqslant i, j \leqslant N$, be the stationary probabilities of the system being in state (i, j).

The state transition diagram is shown in figure 10. To write the balance equations, we define the following notation:

$$\beta^{(i)} = \begin{cases} 1 & \text{if } i < N, \\ 0 & \text{if } i = N, \end{cases} \qquad \eta^{(i)} = \begin{cases} 1 & \text{if } i < P, \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

We can now write the balance equations as follows:

$$\begin{aligned} P(i, j)\bigl\{\lambda\eta^{(i)} + \lambda\eta^{(j)} + \lambda_h\beta^{(i)} + (i+j)\mu + (i+j)\gamma\bigr\} \\ = P(i, j-1)\lambda\delta^{(j)}\eta^{(j-1)} \\ + P(i, j+1)(j+1)(\gamma+\mu)\beta^{(j)} \\ + P(i-1, j)\bigl\{\lambda_h\delta^{(i)} + \lambda\delta^{(i)}\eta^{(i-1)}\bigr\} \\ + P(i+1, j)\bigl\{(i+1)\mu\beta^{(i)} + (i+1)\gamma\beta^{(i)}(1-\beta^{(j)})\bigr\} \\ + P(i+1, j-1)(i+1)\gamma\delta^{(j)}\beta^{(i)} \end{aligned} \tag{10}$$

for all $0 \leqslant i, j \leqslant N$, where the definition of $\delta^{(i)}$ is the same as in equation (4). On the left-hand side of equation (10), we have the rate of leaving state (i, j), and on the right-hand side is the rate with which we enter state (i, j). Moreover,

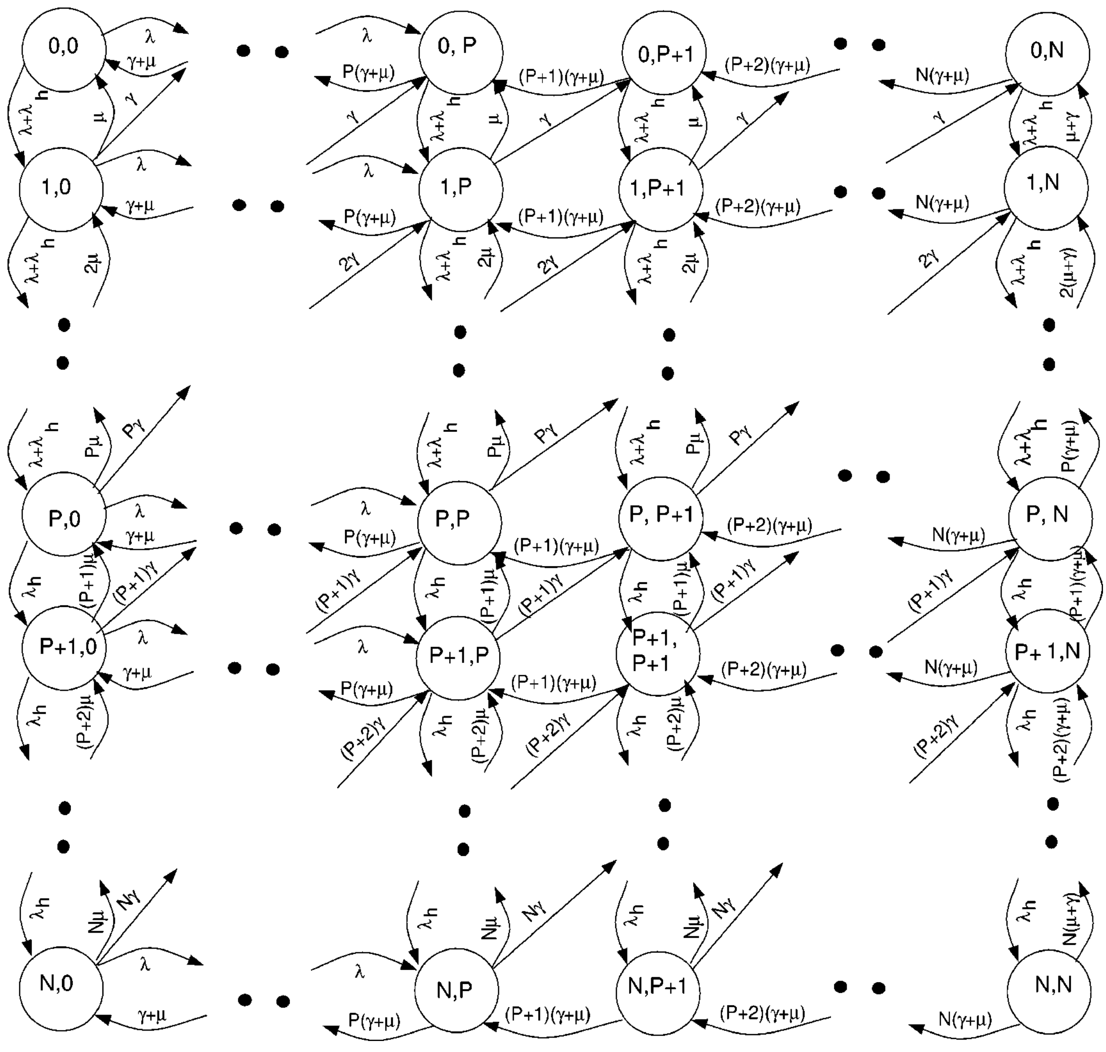

Figure 10. Continuous-time Markov chain of the two-cell approximation for fixed channel allocation with $N - P$ guard channels.

the stationary probabilities have to satisfy the normalization condition in the following equation:

$$\sum_{i=0}^{N} \sum_{i=0}^{N} P(i, j) = 1. \tag{11}$$

For the FCA scheme with $N - P$ guard channels, the new call blocking probability can be derived as

$$P_{\text{bn}} = \sum_{i=0}^{N} \sum_{j=P}^{N} P(i, j), \tag{12}$$

and the handoff call dropping probability can be obtained from

$$P_{\text{bh}} = \frac{\sum_{i=0}^{N} i\, P(i, N)}{\sum_{i=0}^{N} \sum_{j=0}^{N} i\, P(i, j)}. \tag{13}$$

Equation (12) is the new call blocking probability experienced by calls originating in cell 2. Equation (13) is derived by taking the ratio of the number of unsuccessful handoffs to the total number of handoff attempts arriving in cell 2. A recursive method using equations (3), (10)–(13) has to be employed to evaluate P_{bn} and P_{bh}.

5. Numerical results

In this section, we provide numerical results to compare our handoff scheme and the conventional FCA scheme with channel reservation. We use both simulation and the analytical technique presented in the last section to perform the comparison.

The following is the reference scenario for the simulation:

1. We have a linear array of 30 cells, with the end cells being connected to each other.
2. The new call arrival, λ, is the same in all the cells.
3. Each cell is allocated 12 channels in the fixed channel allocation scheme; that is, $N = 12$. The number of channels allocated per meta-cell for the channel sharing handoff scheme is $Nr/(r + 1)$, where r is the reuse factor.
4. The length L of each cell is assumed to be 425 km.

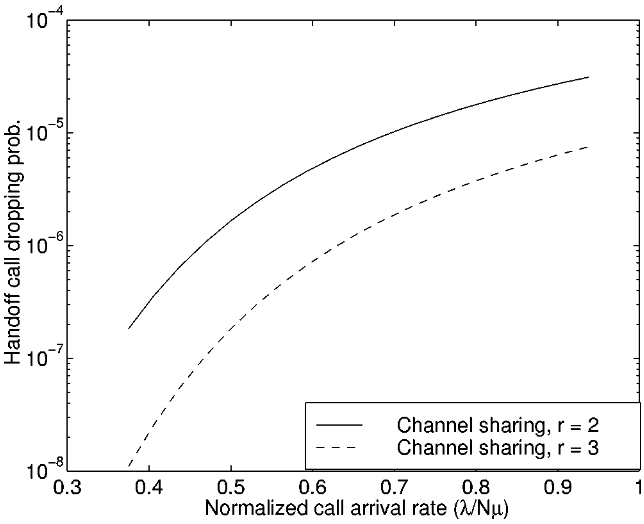

Figure 11. Comparison of two-cell approximations of handoff dropping probabilities for the channel sharing handoff scheme for reuse factors $r = 2$ and 3.

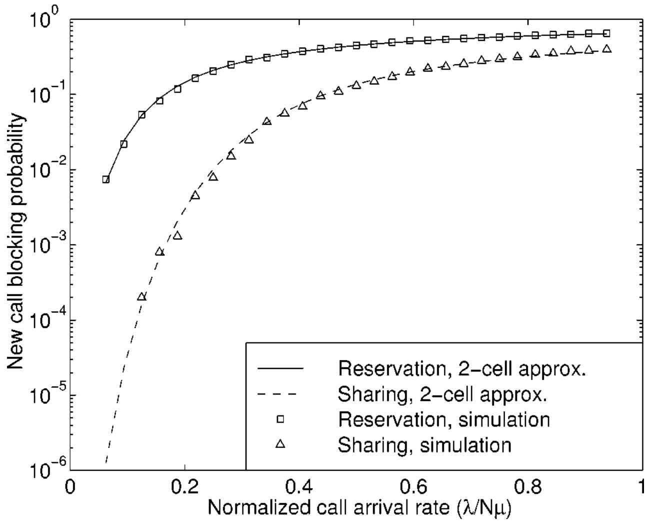

Figure 12. Comparison of new call blocking probabilities for the channel sharing handoff scheme and the channel reservation scheme (reuse factor $r = 2$).

5. The relative velocity V of the mobiles is 26,600 km/h.
6. The mean call holding time, $1/\mu$, is 3 min.

For the analytical results the same values of L, μ, and V are used. The simulation scenario does not make the assumptions made in the analytical model and serves to validate the assumptions made in the analytical model. More specifically, the simulation example does not make the assumption that the cell residence time is exponentially distributed, nor does it make the assumption that the handoff call arrivals into a cell is a Poisson process. Instead, in the simulation example, calls reside for a duration that is uniformly distributed between 0 and L/V in their source cells and a fixed duration of L/V in their transit cells before their next handoff. In both the simulation and analytical examples, we make the assumption that new calls arrive into a cell according to a Poisson process and that call holding times are exponentially distributed. In all the results presented here, we use the normalized call arrival rate as a parameter. The normalized call arrival rate is obtained by dividing the actual call arrival rate by $N\mu$.

The handoff dropping probability for our handoff scheme is too low to obtain reliable estimates using simulation. Therefore, we use the two-cell approximation to obtain estimates of the handoff dropping probabilities. In figure 11, we plot the handoff call dropping probabilities of our handoff scheme for reuse factors 2 and 3.

To do a fair comparison between the channel reservation scheme and our channel sharing handoff scheme, we choose the parameter P in the channel reservation scheme such that its handoff dropping probability closely approximates the handoff dropping probability obtained from our handoff scheme. We choose the parameter P of the channel reservation scheme as follows:

$$P_r^* = \min\left\{P\colon\ P_{\mathrm{bh}}^{\mathrm{res}}(N-P) \geqslant P_{\mathrm{bh}}^{\mathrm{sh}}(r) \text{ for } \frac{\lambda}{N\mu} = 0.5625\right\},$$

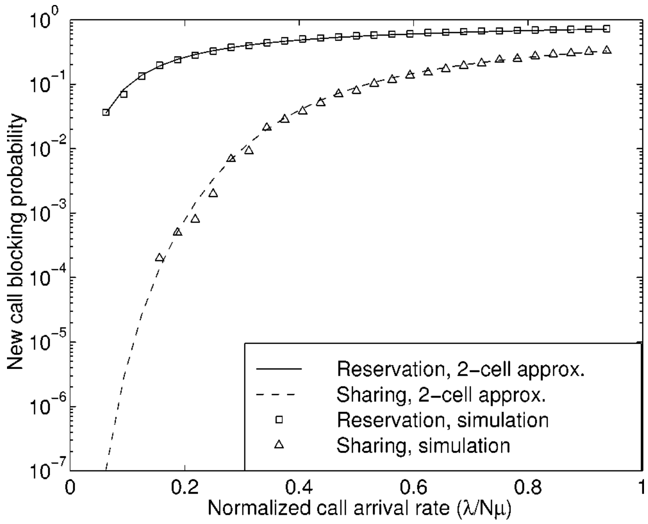

Figure 13. Comparison of new call blocking probabilities for the channel sharing handoff scheme and the channel reservation scheme (reuse factor $r = 3$).

where $P_{\mathrm{bh}}^{\mathrm{res}}(N-P)$ is the handoff dropping probability of the reservation scheme with $N - P$ guard channels, and $P_{\mathrm{bh}}^{\mathrm{sh}}(r)$ is the handoff dropping probability of the channel sharing handoff scheme for a reuse factor of r. The choice of λ in the above equation was arbitrary.

In figure 12, we compare the new call blocking probabilities of the FCA scheme with $N - P_2^*$ guard channels and our handoff scheme (for reuse factor $r = 2$). Similarly, in figure 13, we compare our handoff scheme (for $r = 3$) with the channel reservation scheme with $N - P_3^*$ guard channels. We see that we obtain several orders of magnitude improvement. Intuitively, such an improvement can be explained as follows. For the channel reservation scheme to obtain the same performance as our scheme, the number of guard channels should be as many as the number of channels allowed to be carried in our scheme. While these channels are idle most of the time in the channel reservation scheme, in the channel sharing handoff scheme the channels can be used in adjacent cells to reduce the new call blocking probability. Figures 12 and 13 also show that the analytical results from the two-cell approximation are in very good agreement with the simulation results.

6. Hybrid channel sharing handoff scheme

Our channel sharing handoff scheme shows a significant reduction in the new call blocking probability for similar handoff dropping performance as shown in section 5. But the scheme, as described in section 3, cannot be tuned to achieve the handoff dropping performance desired by the system operator. In this section, we describe a hybrid channel sharing handoff scheme that the system operator can appropriately tune to obtain the desired handoff dropping or new call blocking performance [9]. We also compare the performance of such a hybrid scheme with the channel reservation scheme.

In the hybrid scheme, the entire set of available channels T is not allocated according to the channel sharing scheme. Instead, only a smaller set T_1 ($\leqslant T$) of channels are allocated according to the channel sharing scheme. The remaining $T - T_1$ channels are allocated according to the FCA scheme. Note that the hybrid scheme includes the FCA scheme and the pure channel sharing scheme of section 3 as special cases.

Once channels are allocated in this manner, our hybrid handoff scheme works as follows. A new call arriving in cell n is allocated a channel only if there are idle channels available from those allocated exclusively to cell n (according to the FCA scheme) or those belonging to meta-cell $(n, n+1)$. Handoff call arrivals that cannot find an idle channel are allowed to carry their channel to cell n if they were using a channel belonging to meta-cell $(n-1, n)$. By setting the value of T_1 the system operator can tune the system to perform as desired. We observe that increasing the value of T_1 increases handoff dropping probability but decreases the new call blocking probability.

The performance of our hybrid handoff scheme can be analyzed by the two-cell approximation described in section 4. The balance equations in equation (5) can be appropriately modified for this purpose. To compare the performance of our hybrid handoff scheme with the reservation scheme, we consider the following optimization problem:

$$\min_{T_1} \; P_{\mathrm{bn}}$$
$$\text{subject to } P_{\mathrm{bh}} \leqslant H,$$

where H is a predetermined handoff dropping probability threshold. The above optimization problem is for the channel sharing handoff scheme, and a similar problem can be formulated for the reservation scheme with P as the decision variable.

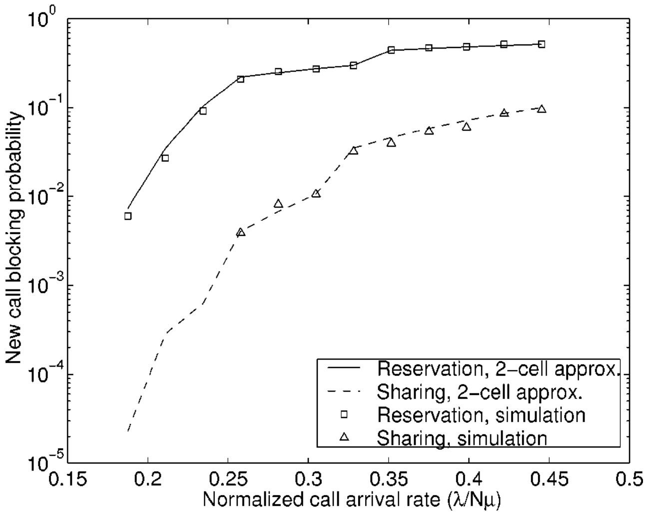

Figure 14. Comparison of new call blocking probabilities for the hybrid channel sharing handoff scheme and the channel reservation scheme (reuse factor $r = 2$). The handoff dropping probability threshold is set at 10^{-6}.

In figure 14, we compare the performance of the hybrid scheme and the reservation scheme with the handoff dropping probability threshold H set at 10^{-6}. We find that the new call blocking performance obtained using our channel sharing handoff scheme is significantly better than that obtained with the reservation scheme. Note that due to the discrete nature of the optimization problem we do not obtain smooth curves. Figure 14 also shows that the simulation results are in very good agreement with the analytical results. The parameters used in the simulation are identical to those in section 5.

7. Conclusions

We have developed a handoff scheme based on the channel sharing scheme in [6–8] for LEO satellite-based cellular networks. We obtained a significant reduction in handoff dropping probability. The conventional FCA scheme can obtain such a reduction in handoff dropping probability only by making a significant compromise in the new call blocking probability. We compared the new call blocking probabilities of our channel sharing handoff scheme to that of the reservation scheme under similar performance with handoff dropping probabilities. Our handoff scheme performs significantly better. We also developed an analytical approximation that is in very good agreement with the simulation results. Finally, we extended our scheme so that it can be tuned to achieve any desired handoff dropping performance.

We considered the channel sharing scheme in the context of a circuit-switched mode of operation. But the channel sharing scheme has wider applicability, and it has been shown that it achieves good performance even in packet-switched networks in [5]. Although [5] is set in the context of terrestrial cellular systems, we believe that it can be modified for LEO satellite networks that use packet-switched technology.

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