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Channel Carrying: A Novel Handoff Scheme for Mobile Cellular Networks ¹

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Abstract

We present a new scheme that addresses the call handoff problem in mobile cellular networks. Efficiently solving the handoff problem is important for guaranteeing Quality of Service (QoS) to already admitted calls in the network. Our scheme is based on a new concept called channel *carrying*: when a mobile user moves from one cell to another, under certain mobility conditions, the user is allowed to carry its current channel into the new cell. We propose a new channel assignment scheme to ensure that this movement of channels will not lead to any extra co-channel interference or channel locking. In our scheme, the mobility of channels relies entirely on localized information, and no global coordination is required. Therefore, this new handoff scheme is simple and can be easily implemented. We further develop a hybrid channel carrying scheme that allows us to maximize performance under various constraints.

We provide numerical results comparing our scheme with the traditional channel reservation types of techniques. We find that our scheme outperforms the reservation scheme over a broad range of traffic parameters.

1 Introduction

The increasing demand for mobile services has generated worldwide interest in wireless communication networks. Coupled with this interest comes the consumer expectation that the wireless systems provide comparable quality of service to their wired counterparts. Studies have shown that one of the most important user concerns is that service not be cut off during an ongoing call. We address this concern by proposing a new scheme to achieve efficient call handoffs in wireless cellular networks.

The use of cellular systems has been a very popular means to enhancing the capacity of wireless communication networks. In such a system, the service area is divided into cells, and *channels* are reused among those cells. In this paper, whenever we refer to a channel, we mean a generic network resource; for example, a frequency band in FDMA, a time-slot in TDMA, or a specific spread spectrum code in CDMA. This definition is consistent with that in [12]. Channels that are used in one cell cannot be used in other cells that are closer than the *minimum reuse distance*. In other words, if the minimum reuse distance is r , then there must be at least $r - 1$ cells between two cells using the same channel. Handoff occurs when a mobile subscriber moves from one cell to another. A handoff call may be blocked if there is no free channel in the new cell. However, since blocking a handoff call is less desirable than blocking a new call, specific schemes have been developed to prioritize handoff calls. Two prioritization schemes have been commonly studied in the literature [1, 2]. They are:

- *Channel reservation schemes*: In this type of schemes, a number of channels are reserved solely for the use of handoff, allowing both handoff and new calls to compete for the remaining channels [3, 4, 7, 6, 13]. Specifically, in each cell a threshold is set, and if the number of channels currently used in the cell is below that threshold, both new and handoff calls are accepted. However, if the number of channels used exceeds this threshold, an incoming new call is blocked and only handoff calls are admitted.
- *Queueing schemes*: In this type of schemes handoff requests are queued, and may be later admitted into the network in case a channel frees up [5, 6, 7].

The above two schemes can also be integrated together to improve the handoff blocking probability and the overall channel utilization. The scheme we propose in this paper is also

readily integrated with the queueing schemes. Therefore, we shall concentrate on comparing our scheme only with the reservation scheme.

Our method for treating the handoff problem stems from the following simple idea. A user requesting a handoff always occupies a channel in its current cell. *Therefore, if that channel could be carried into the new cell, the handoff request would not be blocked.* From a practical point of view this is not difficult to achieve. For example, in an FDMA based system, suppose a user requesting handoff to some cell *A* communicates over a frequency band *x* that cell *A* is not allowed to use. Now, if normal handoff is not possible the user (or its current base-station) could signal cell *A* giving it permission to communicate over channel *x* with it. In a similar way, channels can be carried in CDMA and TDMA systems.

However, when a channel is allowed to move into another cell, it shortens the reuse distance and may violate the minimum reuse distance requirement [1, 8]. To solve this problem, we propose a new channel assignment method that allows channels to be "carried" into a neighboring cell. Furthermore, with an *a priori* agreement on channel movement, channel coordination can be achieved locally. This helps to significantly simplify the implementation. The new handoff scheme proposed in this paper is called *channel carrying*.

In this paper, we first describe how the channels are assigned for the channel carrying scheme, and then present our basic handoff algorithm. We analyze this algorithm and show that it provides substantially lower new call blocking and handoff call blocking probabilities than the channel reservation scheme. We then introduce a refinement of our channel carrying scheme, called the *hybrid channel carrying scheme*, which provides a useful design parameter that can be varied to satisfy various QoS constraints. We also provide numerical results that show that this hybrid scheme significantly outperforms the channel reservation technique over a large range of parameters.

2 Channel Assignment

For simplicity, we describe our channel carrying scheme using a *linear cellular system* model. In this system, cells (or base stations) are arranged in a linear configuration, as shown in Figure 1.¹ Let *N* denote the total number of distinct channels that are available in the

¹Since our algorithm relies only on reuse distance measured in cells, it is easily generalizable to any topology.

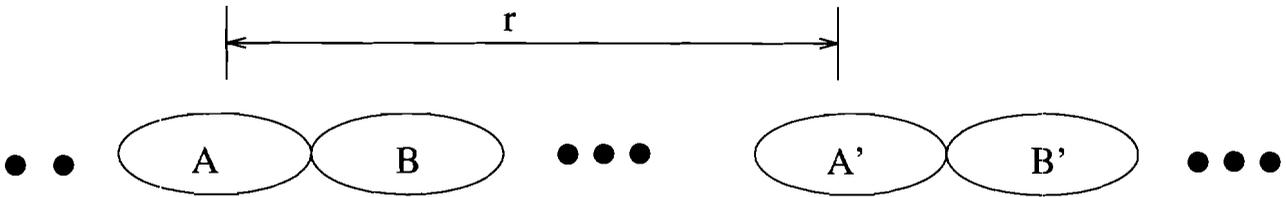
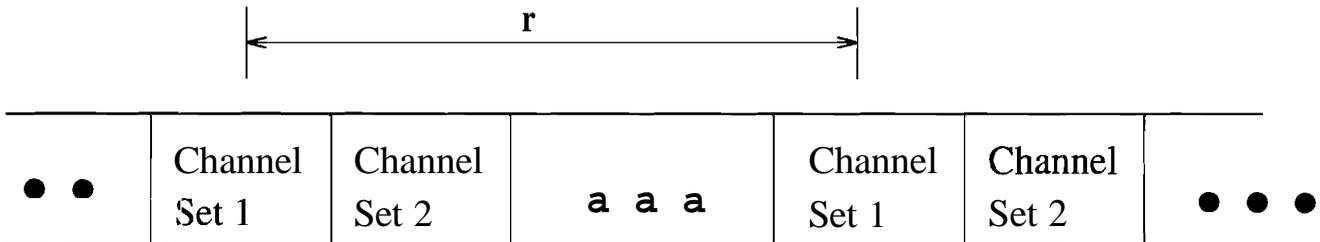


Figure 1: Linear Cellular System

Figure 2: r -Channel Assignment

cellular system. Two cells can use the same set of channels as long as they are at least r cells apart. This distance r is called the minimum reuse distance or reuse factor. In the conventional fixed channel assignment scheme, the channels are assigned such that the same channels are reused exactly r cells apart, as shown in Figure 2. Therefore, the total number of distinct channels available to each cell is N/r . We refer to this channel assignment as r -channel *assignment*.

In our channel carrying scheme, we alleviate blocking due to handoff by allowing calls to "carry" channels from one cell to another. However, using r -channel assignment, a call that carries a channel to an adjacent cell may violate the minimum reuse distance requirement. For example, in Figure 1, cells **A** and **A'** use the same set of channels. Suppose a call in cell **A** uses a channel y , and carries it to cell **B**. Now, if a user arrives in cell **A'** and uses channel y , then the two y channels are only a distance of $r - 1$ cells apart, thus violating the minimum reuse distance requirement. One way to overcome this problem is to have global coordination algorithms that use channel locking [8] to ensure that such situations do not occur. For example, in Figure 1, knowing that channel y has been carried from cell **A** to cell **B**, we do not allow channel y to be used in cell **A'**. However, such schemes are computationally

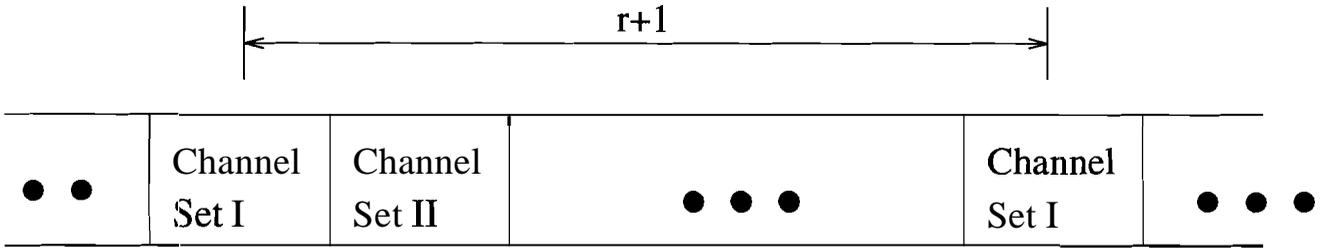


Figure 3: $(r + 1)$ -Channel Assignment

expensive and therefore difficult to implement [8]. Moreover, channel locking also degrades efficiency.

To ensure that the minimum reuse distance requirement is not violated, we use an $(r + 1)$ -channel assignment scheme. In other words, the same channels are reused exactly $r + 1$ cells apart, as shown in Figure 3. In this case, the total number of distinct channels available to each cell is $N/(r + 1)$. To ensure that the same channels do not get closer than r cells apart (due to channel carrying), we restrict the channel movement in the following way. Each channel is allowed to be carried in only one direction, left or right. This restriction thus divides the channels assigned to each cell into two types. Further, as shown in Figure 4, exactly the same division is used in cells that are a distance $r + 1$ apart. Using this $(r + 1)$ -channel assignment scheme, and the channel carrying algorithm described in the next section, we ensure that there is no co-channel interference due to channel movement, while avoiding the need for global coordination.

3 Handoff Algorithm

3.1 Algorithm Description

To describe our handoff algorithm, we first focus our attention on a particular (arbitrary) cell, which we call the local cell. The adjacent cells to the left and right of the local cell are called foreign cells. The channels that have been assigned to the local cell are called local channels, and are divided into two types: local-left (LL) and local-right (LR) channels as shown in Figure 4. An LL (LR) channel is one that can be carried to the left (right) cell

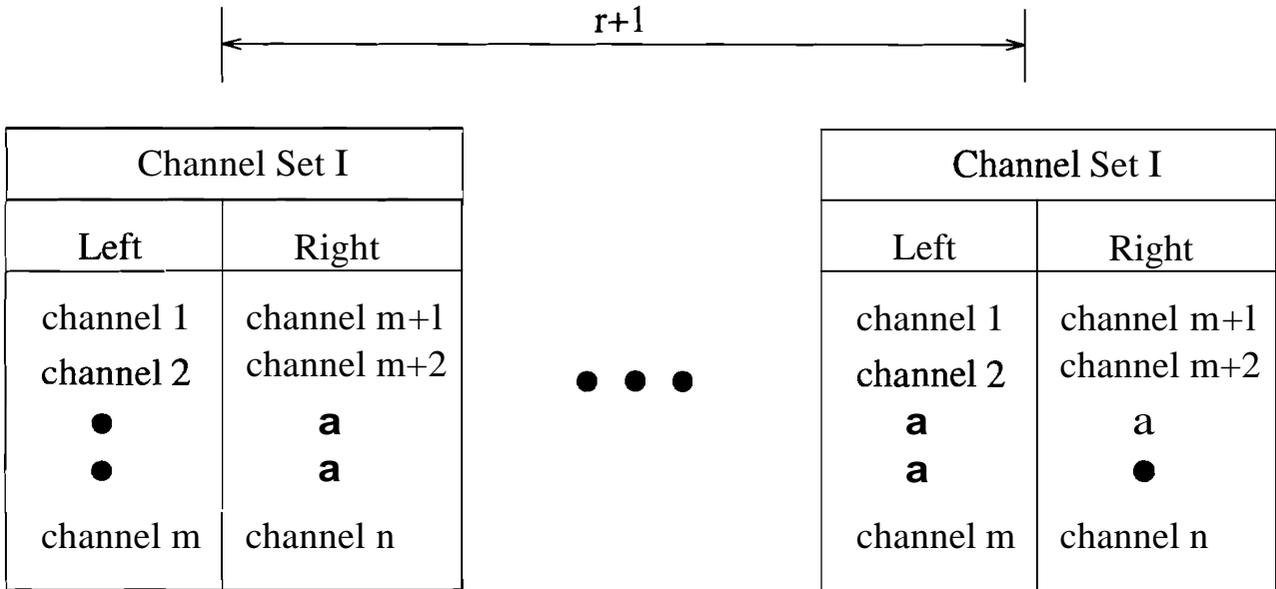


Figure 4: Channel Division in $(r+1)$ -Channel Assignment

during handoff. In other words, an LL (LR) channel can be used by a call in the local cell as well as in the foreign cell to the left (right). A channel from a foreign cell that is being used in the local cell is called a *foreign channel*. Foreign channels from the left cell are called *foreign-left* (FL) channels and foreign channels from the right cell are called *foreign-right* (FR) channels.

Our algorithm can be described in five main parts, corresponding to five different possible scenarios: *arrival of a new call*, *handoff from a foreign cell*, *handoff to a foreign cell*, *termination of a call*, and *when a local channel becomes idle*.

3.1.1 Arrival of a new call

The protocol for handling the arrival of a new call is shown in Figure 5. When a new call arrives, we check if there are any idle (unused) local channels. If there are, the new call is accepted and assigned the idle channel; otherwise, the call is rejected (blocked).

3.1.2 Handoff request from a foreign cell

Figure 6 illustrates the protocol for handoff requests. When a handoff call request is received from a foreign (left or right) cell, we check if there are any idle local channels available. If

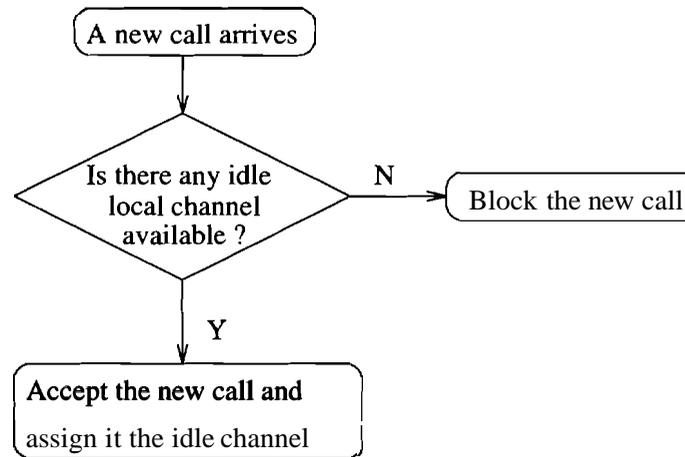


Figure 5: Flow Chart for *Processing A New Arrival*

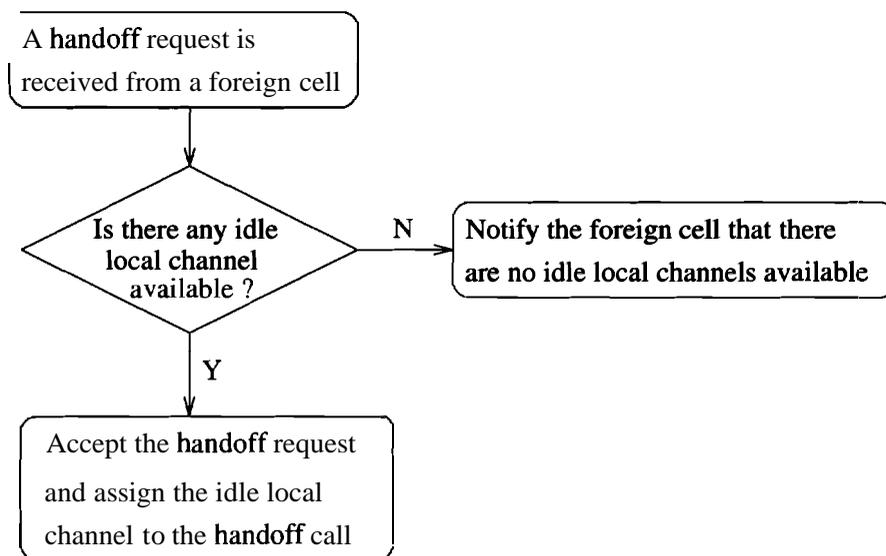


Figure 6: Flow Chart for *Processing A Handoff Request from Neighboring Cells*

there are, the handoff call is accepted and assigned the idle channel; otherwise, the foreign cell is notified that there are no idle local channels.

3.1.3 Handoff to a foreign cell

The protocol for handoff to a foreign cell is depicted in Figure 7. For simplicity, suppose a user U in the local cell wants to move to the *left* foreign cell. The handoff operation is attempted according to the following order:

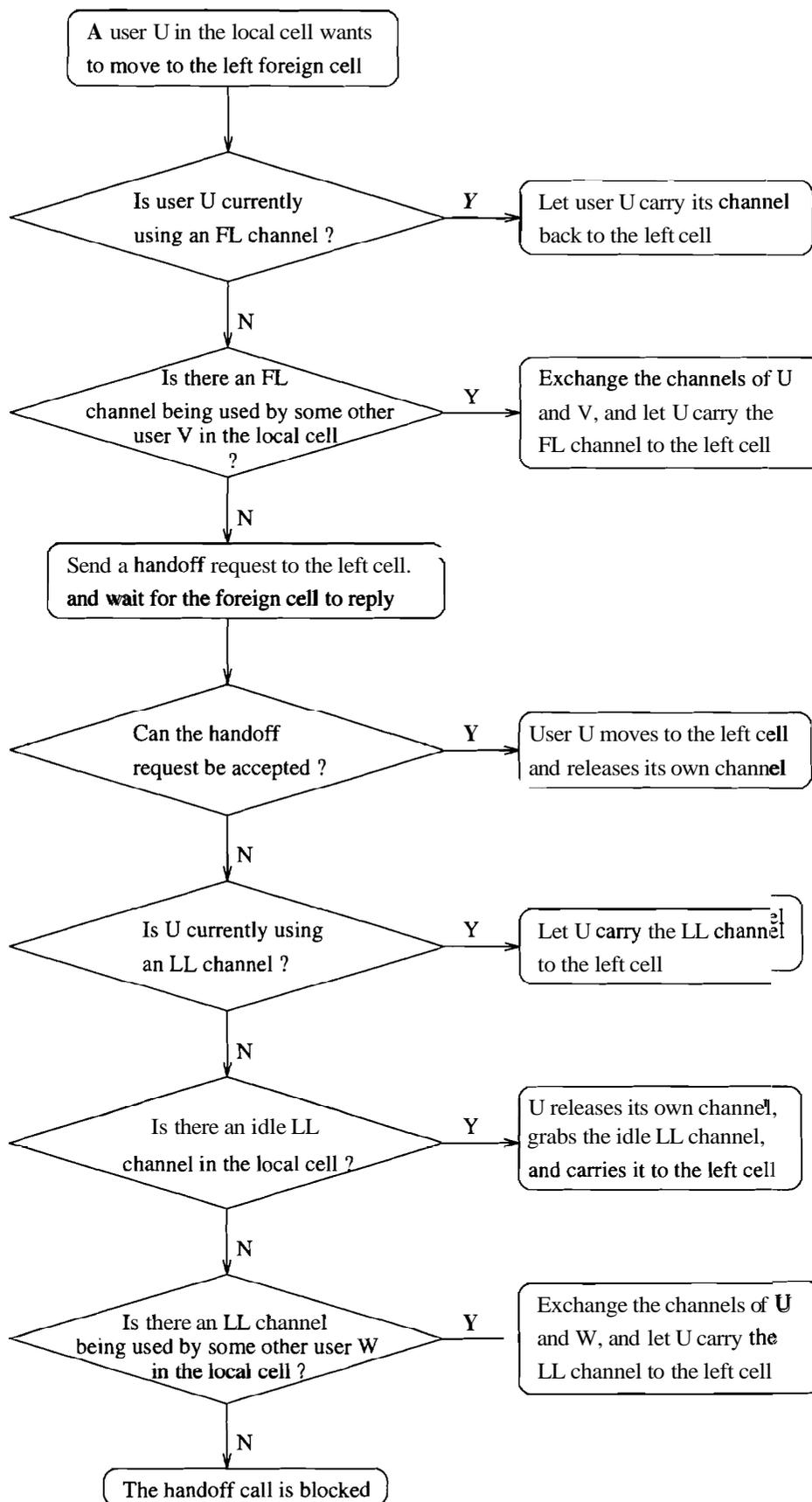


Figure 7: Flow Chart for *Processing A Handoff Request from the Local Cell*. For simplicity we show the flow chart only for a user *U* wanting to move to the left foreign cell.

1. If user U is currently using a foreign-left (FL) channel, then it simply carries it back to the left cell; otherwise, step 2 is initiated.
2. We check if there is an FL channel being used by some other user V in the local cell. If so, user U exchanges its channel with user V and then executes step 1 above; if not, we perform step 3.
3. We send a handoff request to the left foreign cell. The foreign cell then executes the procedure in Section 3.1.2. If the handoff is accepted, user U moves to the left cell and releases its own channel; if not, step 4 is initiated.
4. If user: U is currently using a local-left (LL) channel, then it carries it to the left cell; otherwise, step 5 is initiated.
5. We check if there is an idle LL channel currently in the local cell. If so, U releases its own channel, grabs the idle LL channel, and carries it to the left cell; otherwise step 6 is initiated.
6. We check if there is an LL channel being used by some other user W in the local cell. If so, user U exchanges its channel with user W , and executes step 4 above.
7. If all the above conditions do not hold, then the handoff cannot be accomplished. Normally, this would result in the handoff call being blocked.

A similar procedure would be applied if a user in the local cell wanted to move to the right foreign cell.

3.1.4 Termination of a call

The protocol for terminating a call in the local cell is illustrated in Figure 8. When a call U is terminated (either due to the normal end of the call, or due to handoff blocking), we first check if the channel being used by U is a foreign channel. If so, we release the foreign channel and return it to its originally assigned cell. Otherwise, U is using a local channel—the call is then terminated and the channel becomes idle.

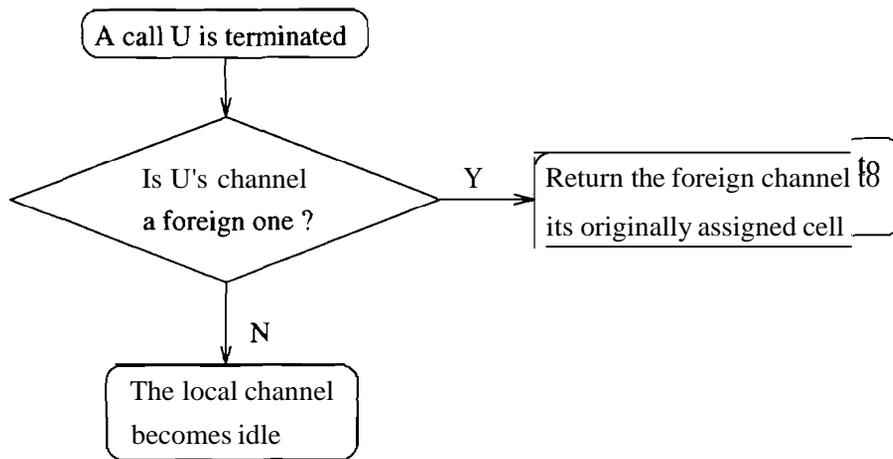


Figure 8: Flow Chart for *Processing A Terminated Call*

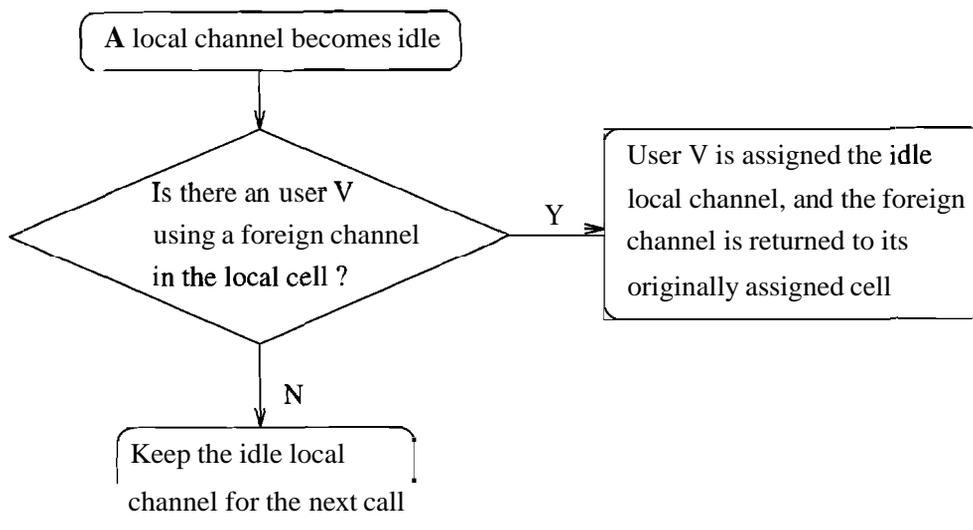


Figure 9: Flow Chart for *Processing An Idle Channel*

3.1.5 Local channel becomes idle

In Figure 9, we depict the protocol for handling the scenario when a local channel becomes idle. This scenario arises in the following situations:

1. Termination of a call in the local cell.
2. Handoff from the local cell to a foreign cell without carrying.
3. Return of an idle local channel from a foreign cell (when a local channel is released in the foreign cell and returned to the local cell).

When a local channel becomes newly idle, we check if there is a user V using a foreign channel in the local cell. If so, user V is assigned the newly idle local channel, and the foreign channel is released and returned to its originally assigned cell.

3.2 Salient Features of the Handoff Algorithm

The following are some of the significant features of our algorithm. Again, for simplicity, we focus only on handoff from the local cell to the *left* foreign cell.

- An important feature of our algorithm is that no global coordination is necessary, thus facilitating implementation. At the same time, the algorithm ensures that there is no co-channel interference due to channel movement.
- In our algorithm, handoff calls have access to a larger portion of the system capacity than new incoming calls. To see this, note that a new call is blocked if and only if there is no idle (local) channel in the local cell. On the other hand, a handoff request to the (left) foreign cell is *blocked if and only if all the left-local (LL) channels are being used in the foreign cell*. This occurrence is relatively rare because it requires that all three of the following conditions are simultaneously true:
 1. All the FL channels are being used by users in the left foreign cell.
 2. All the channels in the left foreign cell are being used.
 3. All the LL channels have been previously carried to the left foreign cell.

It is therefore apparent that in our channel carrying scheme, handoff call requests are favored over new call requests. At the same time, we do not require channels to be reserved *a priori* for handoff calls. This helps increase the efficiency of our scheme compared to reservation schemes, as demonstrated in Sections 4.3 and 5.2.

- In our algorithm, we prefer to use local channels whenever possible. We refer to this policy as a *return-as-soon-as-possible* policy. For example, whenever a channel becomes idle, we always return the foreign channel (if any) instead of keeping that idle channel waiting for a potential call in the local cell. The policy serves to protect potential handoff

calls, because the accumulation of foreign channels may block further handoff requests from the foreign cell.

4 Performance Analysis using the Two-Cell Model

4.1 Model for the Channel Carrying Scheme

In this section we develop a Markov chain model to analyze the performance of our handoff algorithm. The QoS measures that we are interested in are:

- P_{bN} the steady state probability of blocking a new call; and
- P_{bH} the steady state probability of blocking a handoff call.

The system that we are interested in modeling is the linear cellular system shown in Figure 10(a). The traffic is assumed to be symmetrically distributed over all the cells, for example, the new call arrival rate at every cell is A . The handoff rates between cells is assumed to be directly proportional to the number of users in that cell, so if a cell has i users the handoff rate to its neighboring cell is $i\lambda_H$, as shown in Figure 10(a). Analysis of this entire system is computationally infeasible. Therefore, the performance analysis of call handoff schemes in wireless systems is typically done by focusing on a single cell which results in a one dimensional Markov chain [4]. However, the one-cell model does not accurately capture the essence of our algorithm. For example, suppose that a user in the local cell wants to move to the left foreign cell. Whether or not it carries a channel during handoff depends not only on the availability of FL and LL channels in the local cell but also on whether there is an idle channel in the left foreign cell. Hence, the availability of channels in adjacent cells is coupled.

To alleviate difficulties with a one-cell model we consider a two-cell model, as shown in Figure 10(b). We assume that in each cell **A** and **B**, new call requests arrive according to Poisson processes with rate A . The time it takes for each call in a cell to request a handoff to the other cell is assumed to be exponentially distributed with mean $1/\lambda_H$. Call handoffs arrive from outside the two-cell subsystem according to a Poisson process with rate λ_h . The time

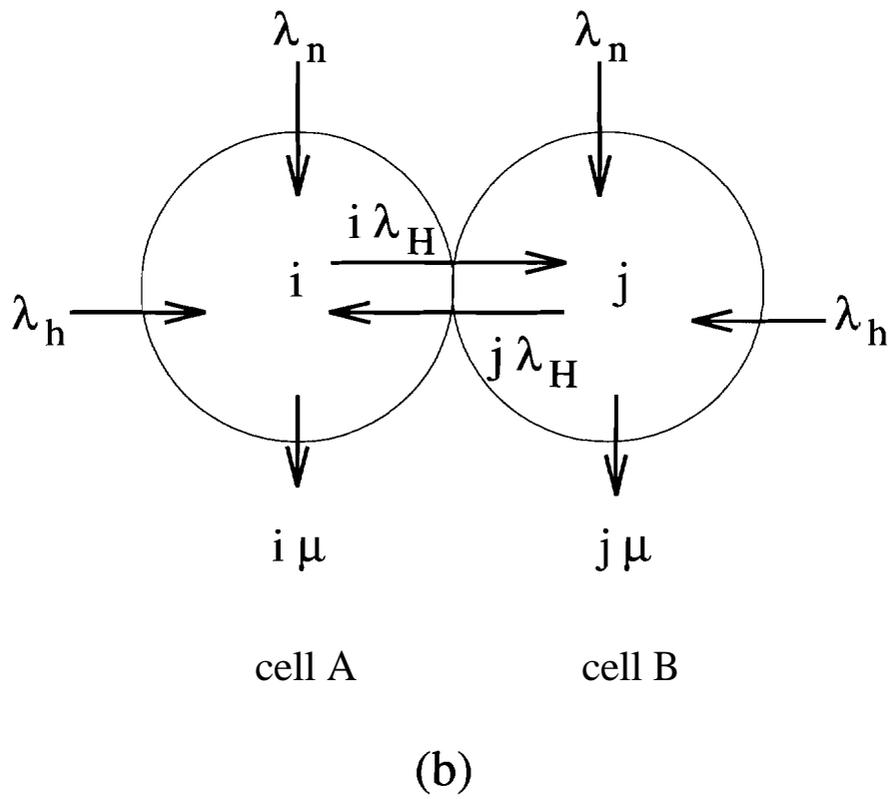
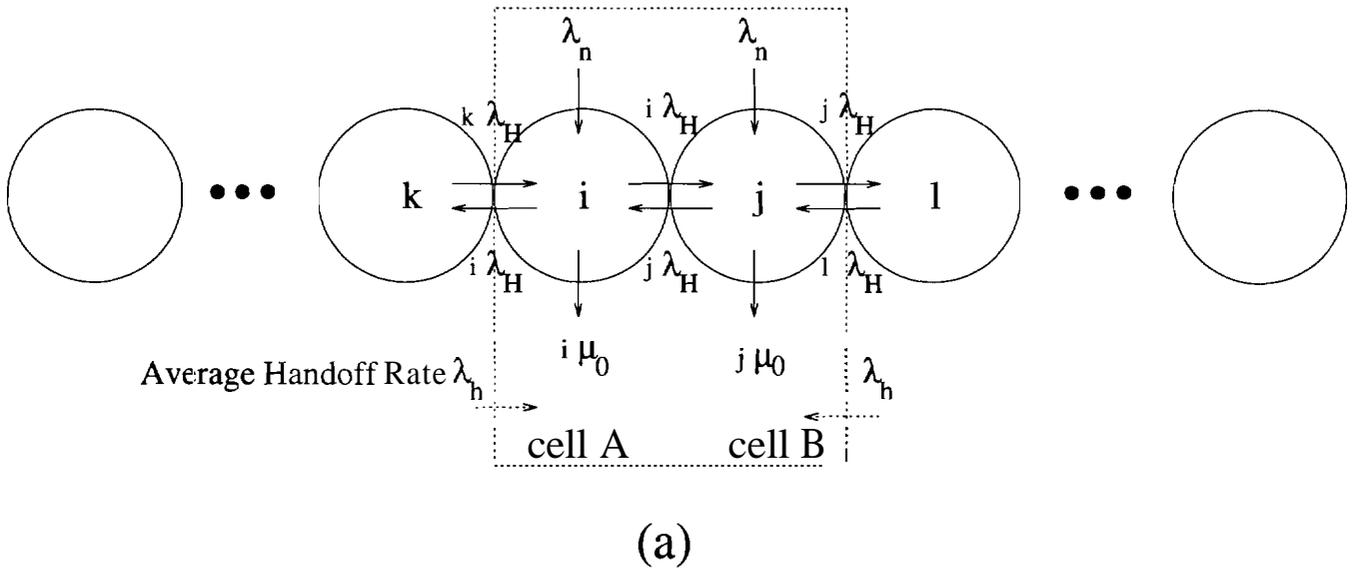


Figure 10: (a) Linear Cellular system with various traffic parameters. (b) Two-Cell model with the corresponding traffic parameters.

until a call terminates is assumed to be exponentially distributed with mean $1/\mu_0$. Therefore the time until a call leaves the two-cell system (either due to handoff or call termination) is exponentially distributed with mean $1/\mu = 1/(\mu_0 + \lambda_H)$. Now, assuming that all of the above mentioned operations (new arrival, call handoff request, and call termination) are mutually independent, we can analyze our two-cell system using a Markov Chain.

Recall that the total number of local channels in each cell is $M = N/(r + 1)$. To further simplify the model, we assume that the total number of local channels, M , is divided into an equal number, $m = M/2$, of local left (LL) and local right (LR) channels.

Our Markov chain model is shown in Figure 11. To describe the model, let $N_A \in \{0, \dots, M\}$ and $N_B \in \{0, \dots, M\}$ represent the number of idle local channels in cell A and cell B, respectively. Next, let $N_{B \rightarrow A} \in \{-\frac{M}{2}, \dots, 0, \dots, \frac{M}{2}\}$ represent the following. If $N_{B \rightarrow A} \geq 0$, it denotes the number of foreign channels from cell B that are being used in cell A. On the other hand, if $N_{B \rightarrow A} \leq 0$, it denotes the number of foreign channels from cell A that are being used in cell B. Hence, $N_{B \rightarrow A}(t)$ can take values from $-\frac{M}{2}$ to $\frac{M}{2}$. The triple $(N_A, N_B, N_{B \rightarrow A})$ represents the state of the Markov chain. Although there are three components in each state, the state transition diagram of the Markov chain can be represented in a planar fashion. To see this, recall that a foreign channel will move into a cell only when there is no idle local channel in that cell. Also, whenever service is terminated, the foreign channel within the local cell will be returned immediately. Thus, if we neglect the additional time it would take to return or carry a channel, it follows that

$$N_{B \rightarrow A} > 0 \Rightarrow N_A = 0 \quad (1)$$

$$N_{B \rightarrow A} < 0 \Rightarrow N_B = 0. \quad (2)$$

The above equations help restrict one degree of freedom thereby resulting in the planar or two-dimensional Markov chain shown in Figure 11. Note that, because of the symmetric nature of the Markov chain, i.e., $P\{N_A = i, N_B = j, N_{B \rightarrow A} = k\} = P\{N_A = j, N_B = i, N_{B \rightarrow A} = -k\}$, only half of the Markov chain is shown in the figure. Let $P_{i,j,k} = P\{N_A = i, N_B = j, N_{B \rightarrow A} = k\}$ denote the steady state probability of the state $\{N_A = i, N_B = j, N_{B \rightarrow A} = k\}$. We obtain these probabilities by exploiting the above mentioned symmetry and by applying standard numerical Markov chain techniques.

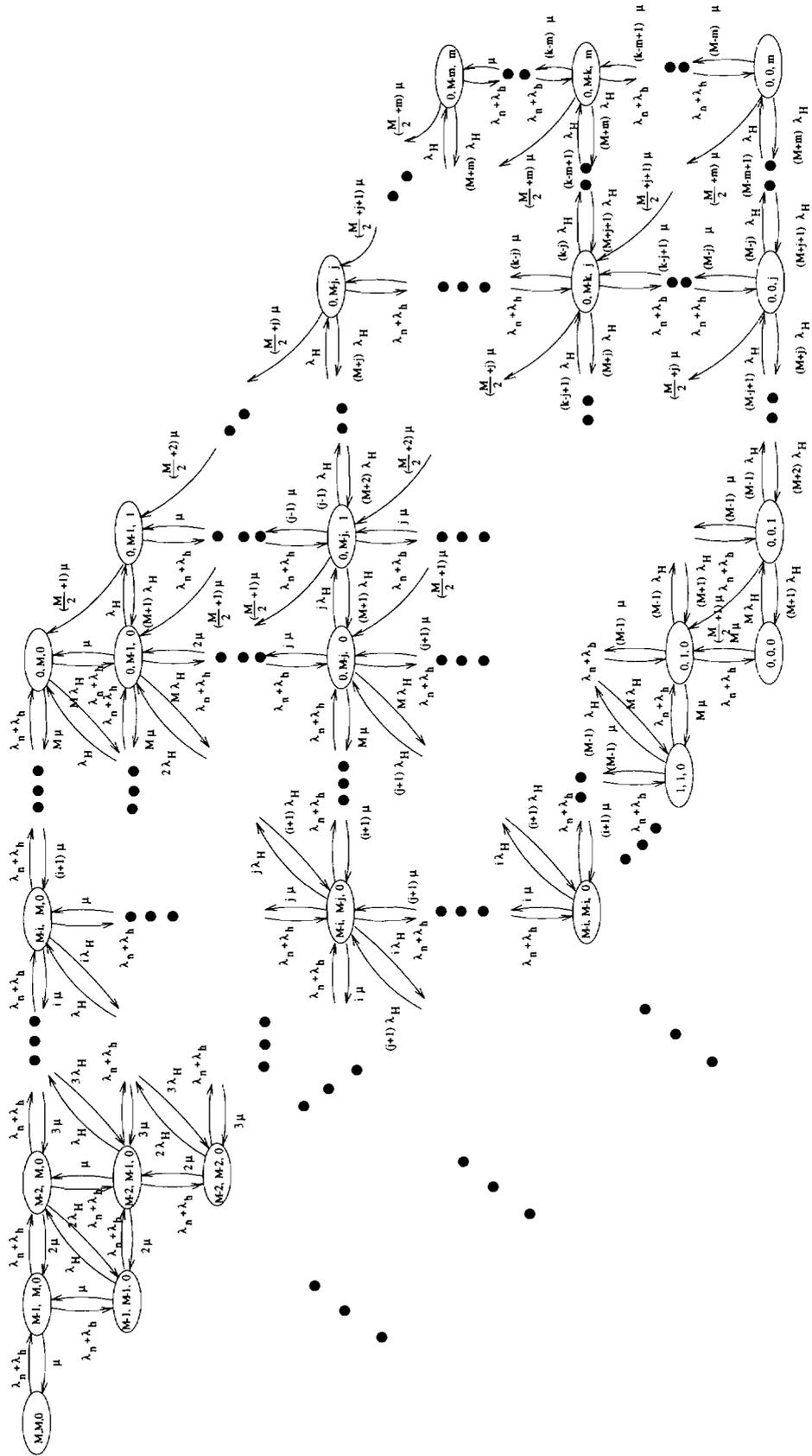


Figure 11: Markov Chain for the Channel Carrying Scheme using the Two-Cell model. Note that $m = M/2$, and $M = N/(r + 1)$.

Now observe Figures 10(a) and 10(b) again. In Figure 10(b) we have focussed only on cells **A** and **B** of Figure 10(a). Let the cells to the right of cell **B** and to the left of cell **A** be called *external* cells. The handoff rate λ_h in the two-cell model of Figure 10(a) is actually the average of the state dependent handoff rate from their neighboring external cells. Averaging over all the states, λ_h is given by

$$\lambda_h = \sum_{i=0}^M (M-i) \lambda_H \sum_{j=0}^M \sum_{k=-m}^m P_{i,j,k}, \quad (3)$$

where $m = M/2$. Since λ_h depends on $P_{i,j,k}$, we iteratively solve the Markov chain. The iteration procedure described below stops when both the absolute and relative errors are less than 10^{-3} .

1. *Initialization:* $\lambda_h = \frac{1}{M} \sum_{i=0}^M i \lambda_H$. (The initial value of λ_h is calculated by taking an unweighted average).
2. Solve for $P_{i,j,k}$ using the Markov Chain in Figure 11 and then determine A_h^{new} , a new value of λ_h using Equation (3).
3. If $\left| \frac{\lambda_h^{new} - \lambda_h}{\lambda_h} \right| \geq 10^{-3}$, or $|\lambda_h^{new} - \lambda_h| \geq 10^{-3}$, set $\lambda_h = A_h^{new}$ and return to Step 2.
4. Set $\lambda_h = A_h^{new}$ and solve for $P_{i,j,k}$.

Having determined $P_{i,j,k}$, we calculate P_{bN} , the steady state probability of blocking a new call, and P_{bH} , the steady state probability of blocking a handoff call by summing over the appropriate states in Figure 11. Therefore,

$$P_{bN} = \sum_{k=0}^m \sum_{j=0}^{M-k} P_{0,j,k} \quad (4)$$

$$P_{bH} = \sum_{j=0}^{M-m-1} P_{0,j,m}, \quad (5)$$

where $m = M/2$, as before.

4.2 Model for the Channel Reservation Scheme

In this section we develop a Markov chain model, shown in Figure 12, to analyze the system performance using the traditional channel reservation scheme. As in the channel carrying scheme, we focus on the two-cell model shown in Figure 10. The parameters λ_h , λ_n , λ_H , and μ are defined as before. Since no channel movement is allowed, the pair (N_A, N_B) , $N_A \in \{0, \dots, M'\}$, $N_B \in \{0, \dots, M'\}$, suffices to characterize the state of the two-cell system. Here, $M' = N/r$ is the total number of distinct channels available to each cell, and N_A (N_B) is the total number of idle channels in cell A (cell B). The resulting Markov chain is shown in Figure 12. Again, because of the symmetric nature of the Markov chain, i.e., $P\{N_A = i, N_B = j\} = P\{N_A = j, N_B = i\}$, only half of the Markov chain is shown in Figure 12. Let $P_{ij} \triangleq P\{N_A = i, N_B = j\}$ denote the steady state probability of the state $\{N_A = i, N_B = j\}$. Then, as in the channel carrying scheme, λ_h , the average external handoff arrival rate, is given by:

$$\lambda_h = \sum_{i=0}^{M'} (M' - i) \lambda_H \sum_{j=0}^{M'} P_{i,j}. \quad (6)$$

Since λ_h depends on $P_{i,j}$, we iteratively solve the Markov chain in Figure 12. The iteration procedure, which is almost identical to the channel carrying case, is given below.

1. Initialization: $\lambda_h = \frac{1}{M'} \sum_{i=0}^{M'} i \lambda_H$.
2. Solve for P_{ij} using the Markov Chain in Figure 12 and then determine A_h^{new} , a new value of λ_h using Equation (6).
3. If $\left| \frac{\lambda_h^{\text{new}} - \lambda_h}{\lambda_h} \right| \geq 10^{-3}$ or $|A_h^{\text{new}} - \lambda_h| \geq 10^{-3}$, set $\lambda_h = A_h^{\text{new}}$ and repeat step 2.
4. Set $\lambda_h = A_h^{\text{new}}$ and solve for P_{ij} .

After determining P_{ij} , we solve for P_{bN} , the steady state probability of blocking a new call, and P_{bH} , the steady state probability of blocking a handoff call by summing over the appropriate states, i.e.,

$$P_{bN} = \sum_{i=0}^{M'-K} \sum_{j=0}^{M'} P_{i,j} \quad (7)$$

$$P_{bH} = \sum_{j=0}^{M'} P_{0,j} \quad (8)$$

It is instructive to compare the state transition diagrams in Figures 11 and 12. There are two main differences in these two figures. First, because of the r -channel assignment, the number of local channels in each cell is M' in Figure 11 instead of M in Figure 12, where $M' = N/r$. The difference d is given by

$$d \triangleq M' - M = \frac{N}{r(r+1)}, \quad (9)$$

which is the cost we pay for channel mobility. Clearly, when the reuse factor r is large, this difference is marginal. Second, because of channel reservation, new calls have to be blocked when the number of occupied local channels exceeds a threshold K in Figure 12. Then, the arrival rate is reduced from $\Lambda + \lambda_h$ to λ_h , which is a disadvantage of the reservation scheme compared to the channel carrying scheme.

4.3 Numerical Results

In this section, we provide numerical results to compare the performance of the channel carrying scheme and the reservation scheme.

To obtain the analytical results we use the two-cell model of Figure 10(b). We then obtain values for P_{bN} , the new call blocking probability and P_{bH} , the handoff blocking probability, under various traffic parameters, using the analytical method outlined in Sections 4.1–4.2.

In addition to computing the performance measures using our Markov chain model, we also simulate the system under the carrying and reservation schemes. Our simulation consists of a 120 cell linear cellular system, such as the one shown in Figure 10(a). Since we are interested in the performance of a typical cell, the statistics are averaged over all cells. Throughout the paper, we find that our simulation results match the analytical results quite well, which indicates that the two-cell model works well in characterizing the behavior of the algorithm in a linear cellular system.

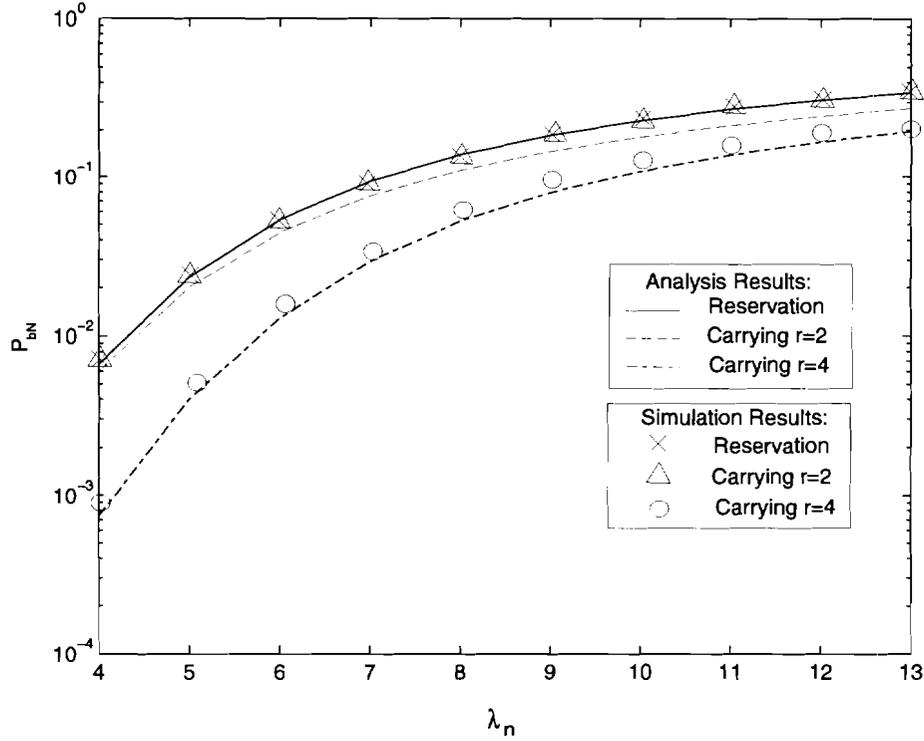


Figure 13: Plot of P_{bN} versus λ_n . The parameters used in this figure are $N/r = 15$, $K = 10$, $\lambda_H = 1$, $\mu_0 = 1$.

In Figure 13 we plot P_{bN} , and in Figure 14, we plot P_{bH} for both the channel carrying and the reservation scheme under different traffic loads λ_n , ranging from 4 calls to 13 calls per unit time. The call handoff rate is $\lambda_H = 1$ call per unit time, and the call termination rate is $\mu_0 = 1$ call per unit time.

For the channel carrying case, two values for the reuse distance are considered: $r = 2$, the minimum possible reuse distance, and $r = 4$, a more typical value for the reuse distance. Further, in both figures, $M' \triangleq N/r = 15$; hence, $N = 30$ when $r = 2$, and $N = 60$ when $r = 4$.

Note, that in the channel reservation scheme, for a given arrival rate, we can vary the threshold K to give us different values of P_{bN} and P_{bH} . We find that if we choose $K = M \triangleq N/(r + 1)$, then the values of P_{bN} for the reservation scheme are close to those for the carrying scheme. The reason for this is that if the number of occupied local channels in a cell reaches K (or M), any new call in the reservation (or carrying, respectively) scheme is now blocked. For $r = 2$, we choose $K = M = 10$, and we can observe in Figure 13 that the new call blocking probability (P_{bN}) curves for the reservation and carrying schemes are in fact

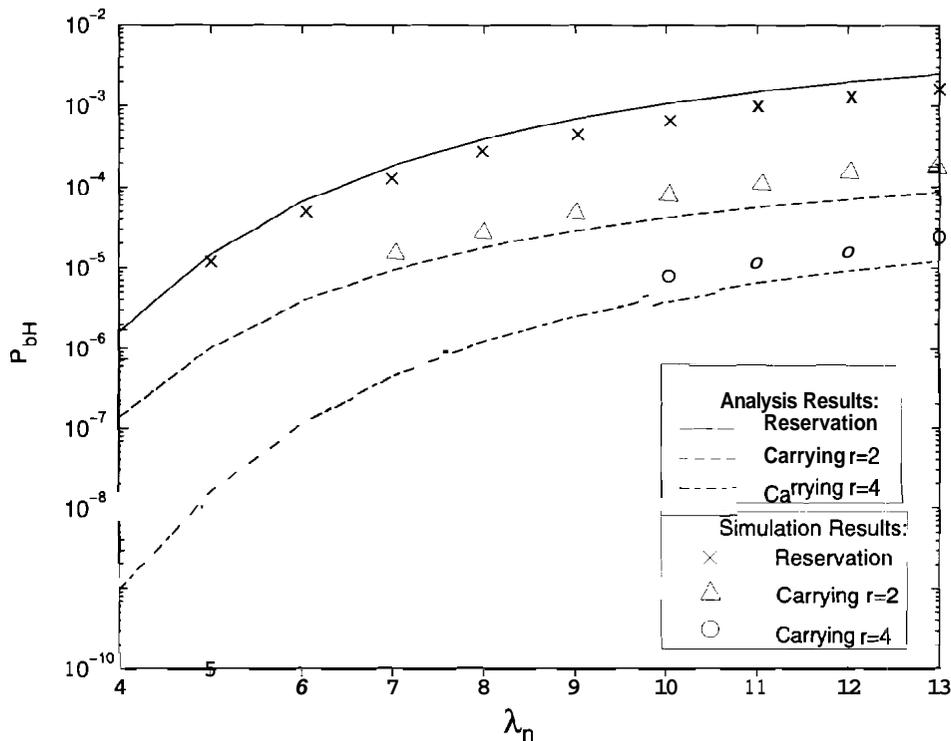


Figure 14: Plot of P_{bH} versus λ_n . The parameters used in this figure are $N/r = 15$, $K = 10$, $\lambda_H = 1$, $\mu_0 = 1$.

very close. However, for the same parameters, the call handoff blocking probability (P_{bH}) as shown in Figure 14 is at least about one order of magnitude lower in the carrying scheme than in the reservation scheme. When the value of the reuse distance is increased to $r = 4$, and we set $K = 10$, the carrying scheme significantly outperforms the reservation scheme in terms of both P_{bN} and P_{bH} . This result can be observed in Figure 13, where the P_{bN} curve in the carrying case is up to one order of magnitude lower than in the reservation scheme, and in Figure 14, where the P_{bH} curve in the carrying scheme is up to three orders of magnitude lower than in the reservation scheme. The reason the carrying scheme provides a lower P_{bN} curve for $r = 4$ is that $M = 12 > K$, in this case. However, if we choose $K = M$, then, although the P_{bN} curves will be closer, the difference in the P_{bH} curves will be even larger.

We next develop a hybrid channel carrying scheme which attempts to maximize performance, under various constraints, by allowing us to vary the number of channels that can be carried.

5 Hybrid Channel Carrying Scheme

5.1 Description

In the numerical examples of the previous section, we observe that the channel carrying scheme results in a large difference between the values of P_{bH} and P_{bN} . In particular, when the load is high, the value of P_{bN} is much higher than that of P_{bH} . For example, for $\lambda_n = 13$ and $r = 4$, the value of P_{bH} is only about 10^{-5} while that of P_{bN} is greater than 10^{-1} . This observation suggests that our channel carrying scheme excessively favors handoff requests over new calls. In the following, we present a hybrid scheme that allows trading off potential handoff blocking for availability of idle channels for new calls.

Recall that in the $(r+1)$ -channel assignment scheme, the number of channels assigned to each cell is $M = N/(r+1)$, and every channel can be carried either to the left or to the right. On the other hand, in the r -channel assignment scheme, the number of channels assigned to each cell is N/r , but none of the channels can be carried to foreign cells. In our hybrid scheme, we divide the total number of channels N into two distinct groups of size N_1 and N_2 , such that

$$N = N_1 + N_2. \quad (10)$$

The N_1 channels are assigned according to the r -channel assignment scheme, and cannot be carried to foreign channels. The N_2 channels, however, are assigned according to the $(r+1)$ -channel assignment scheme, and can be carried either to the left or to the right, just as in the previous channel carrying scheme. Therefore, in the hybrid scheme, each cell is assigned

$$M_{hybrid} = \frac{N_1}{r} + \frac{N_2}{r+1} \quad (11)$$

channels, where the two terms in the sum corresponds to the two groups of channels. As before, the $N_2/(r+1)$ channels of the second type are themselves divided into two types: left and right.

The hybrid scheme above defines a family of channel assignments that encompasses both the pure r - and $(r+1)$ -channel assignment schemes. Specifically, $N_1 = 0$ corresponds to the $(r+1)$ -channel assignment scheme, while $N_2 = 0$ leads to the r -channel assignment scheme. The N_2 channels allow us to trade off the ability to carry (and hence avoid handoff blocking)

with a reduced number of channels available to each cell. In particular, the number of channels that we sacrifice in using $(r+1)$ -channel assignment instead of r -channels assignment is

$$d_{hybrid} = \frac{N_2}{r} - \frac{N_2}{r+1} = \frac{1}{r} \left(\frac{N_2}{r+1} \right). \quad (12)$$

Thus, d_{hybrid} serves as a design parameter that we can adjust to balance the requirements of the performance measures P_{bN} and P_{bH} , analogous to the threshold parameter K in the channel reservation scheme. The larger the value of d_{hybrid} in the hybrid scheme, the more we favor handoff calls because there are more movable channels. Hence, as d_{hybrid} increases, we expect P_{bH} to decrease and P_{bN} to increase. A similar observation holds for the design parameter K in the reservation scheme. Also note that, as in the original channel carrying case, for a fixed number of channels N_2 that are allowed to move, the price we pay for the $(r+1)$ -channel assignment scheme (in terms of d_{hybrid}) decreases with increasing r .

In the next section we provide numerical results comparing the carrying scheme with the reservation scheme for various performance measures.

5.2 Numerical Results

For the purpose of performance evaluation, we adopt the two-cell model and make the same assumptions here as we did in Section 4.3. The resulting Markov chain has exactly the same structure as in Figure 11, the only difference being that we substitute $m_{hybrid} = \frac{N_2}{2(r+1)}$ in place of m . We can then solve for the steady state probabilities in the Markov chains for the hybrid and reservation schemes, and compute P_{bH} and P_{bN} as before. Also, as in Section 4.3, for our simulation study we use a 120 cell linear cellular system and we plot the results together with those obtained from our Markov chain model.

We now provide plots of P_{bN} under varying load conditions for the hybrid and reservation schemes. The performance measures depend on the parameters d_{hybrid} and K in the hybrid and reservation schemes, respectively. To meaningfully compare our hybrid scheme with the reservation scheme, we determine the optimal values of P_{bN} for the two schemes, given a constraint on P_{bH} . Therefore, in the hybrid scheme, to appropriately choose d_{hybrid} , we consider the following optimization problem:

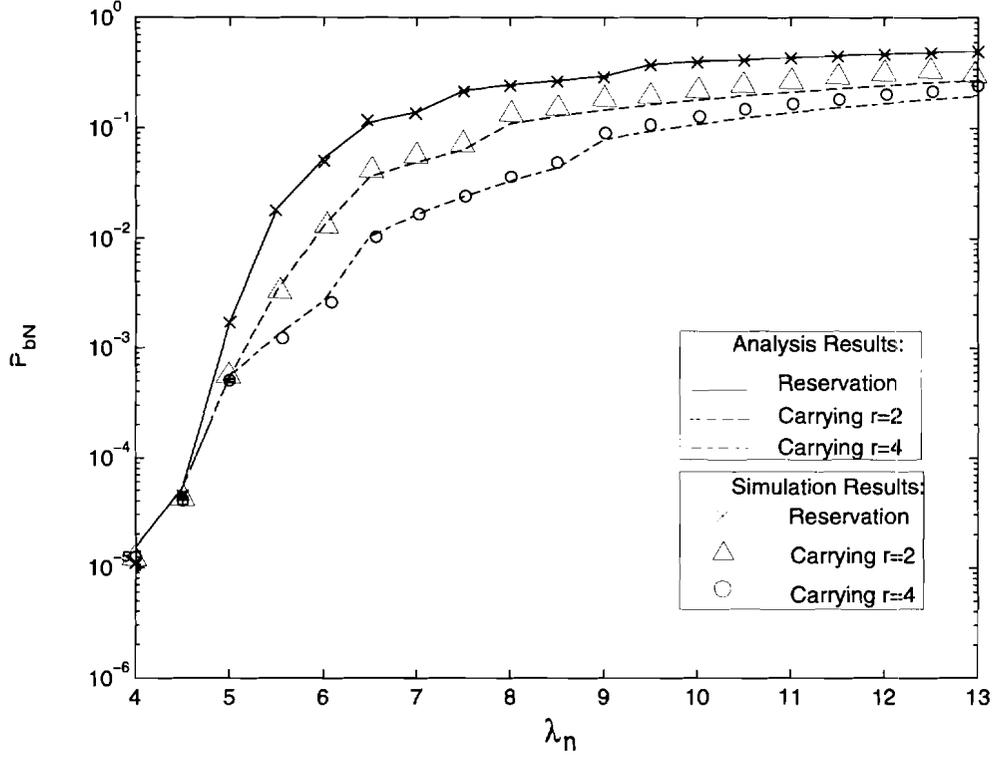


Figure 15: Plot of optimal P_{bN} versus A , for the problem defined in Equation (13). The parameters used in this plot are: $N/r = 15$, $\lambda_H = 1$, $\mu_0 = 1$, $H_{max} = 10^{-4}$.

$$\begin{aligned}
 & \underset{d_{hybrid}}{\text{minimize}} && P_{bN} \\
 & \text{subject to} && P_{bH} \leq H_{max}
 \end{aligned} \tag{13}$$

where H_{max} denotes a prespecified maximum level for P_{bH} . A similar optimization problem can be defined for the reservation scheme, where the decision variable d_{hybrid} above is replaced with the threshold parameter K . For a fair comparison of our hybrid scheme with the reservation scheme, we calculate the optimal values of P_{bN} for the two schemes, given the same H_{max} . The optimal values can be computed numerically using the Markov chains in Figures 11 and 12.

Figure 15 shows plots of the optimal values of P_{bN} for the reservation and hybrid schemes under varying A . For this figure we have used the following parameters: $\lambda_H = 1$, $\mu_0 = 1$, $M' = 15$. Therefore, $N = 30$ for $r = 2$, and $N = 60$ for $r = 4$. For the constraint on P_{bH} , we

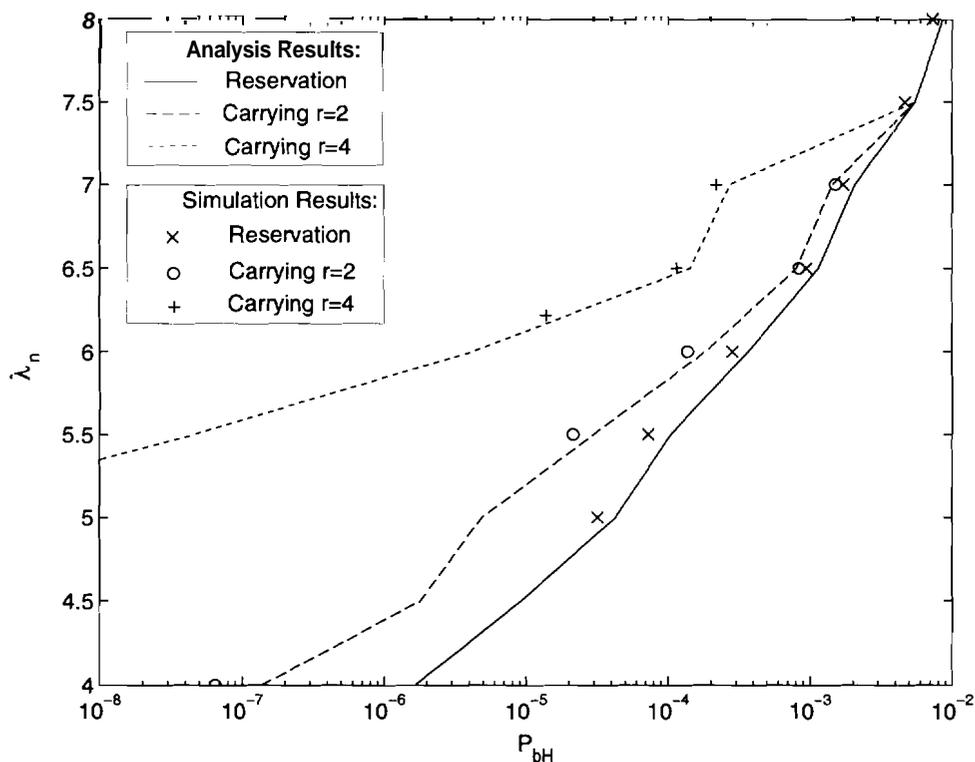


Figure 16: Plot of optimal λ_n versus P_{bH} for the problem defined in Equation (14). The parameters in this figure are: $N/r = 15$, $\lambda_H = 1$, $\mu_0 = 1$, $N_{max} = 10^{-2}$.

used $H_{max} = 10^{-4}$, a typically desirable constraint for the handoff blocking probability. We can see that, the hybrid scheme achieves uniformly lower values of P_{bN} than the reservation scheme. As expected, increasing the value of the minimum reuse distance further decreases P_{bN} in the channel carrying case.

Next, in Figure 16, we plot a graph in which we compare the maximum new call arrival rate λ_n that can be admitted by the carrying scheme and the reservation scheme for various handoff blocking probabilities P_{bH} . More precisely we define the following optimization problem for the channel carrying scheme.

$$\begin{aligned}
 & \underset{d_{hybrid}}{\text{maximize}} && \lambda_n \\
 & \text{subject to} && P_{bN} \leq N_{max} \\
 & && P_{bH} = H
 \end{aligned} \tag{14}$$

Here the constraint H for P_{bH} is varied between 10^{-8} and 10^{-2} and the corresponding maximum value of A , is obtained. A similar optimization problem is defined for the reservation scheme by replacing d_{hybrid} by K . In Figure 16 we plot the optimal values of A , versus P_{bH} for the reservation scheme and the channel carrying scheme with $r = 2$ and $r = 4$. For this figure we use the following parameters: $\lambda_H = 1$, $\mu_0 = 1$, $M' = 15$, $N_{max} = 10^{-2}$. From Figure 16 one can observe that the hybrid carrying scheme allows a higher new call rate than the reservation scheme over all values of P_{bH} . For large values of P_{bH} all the schemes perform essentially the same since it corresponds to the case when no carrying is necessary in the hybrid case ($N_2 = 0$) and no reservation is necessary ($K = N/r$) in the reservation scheme. However, for a typical value of $P_{bH} = 10^{-4}$, the hybrid scheme with $r = 4$ can admit approximately 20% more calls into the network than the reservation scheme. As is shown in the figure, for lower handoff probability constraints, this difference is even larger. This results in increased revenue for the network provider.

From a network provider's point of view, a more useful parameter of interest is the normalized channel utilization, γ , defined as

$$\gamma = \frac{\text{average number of users in one cell}}{\text{total number of available channels in one cell}}$$

where the total number of available channels in one cell is $M' = N/r$. The parameter γ is directly related to the revenue of a cellular network because it incorporates both new and handoff call;. To compute γ for the hybrid scheme we use the equation

$$\gamma = \frac{1}{M'} \sum_{i=0}^{M_{hybrid}} \sum_{j=0}^{M_{hybrid}} \sum_{k=-m_{hybrid}}^{m_{hybrid}} \frac{1}{2} [(M_{hybrid} - i) + (M_{hybrid} - j)] P_{i,j,k} \quad (15)$$

and for the reservation scheme,

$$\gamma = \frac{1}{M'} \sum_{i=0}^{M'} \sum_{j=0}^{M'} \frac{1}{2} [(M' - i) + (M' - j)] P_{i,j}. \quad (16)$$

To plot the values of γ under varying loads for the hybrid scheme, we define the optimization problem

$$\begin{aligned} & \underset{d_{hybrid}}{\text{maximize}} && \gamma \\ & \text{subject to} && P_{bH} \leq H_{max}. \end{aligned} \quad (17)$$

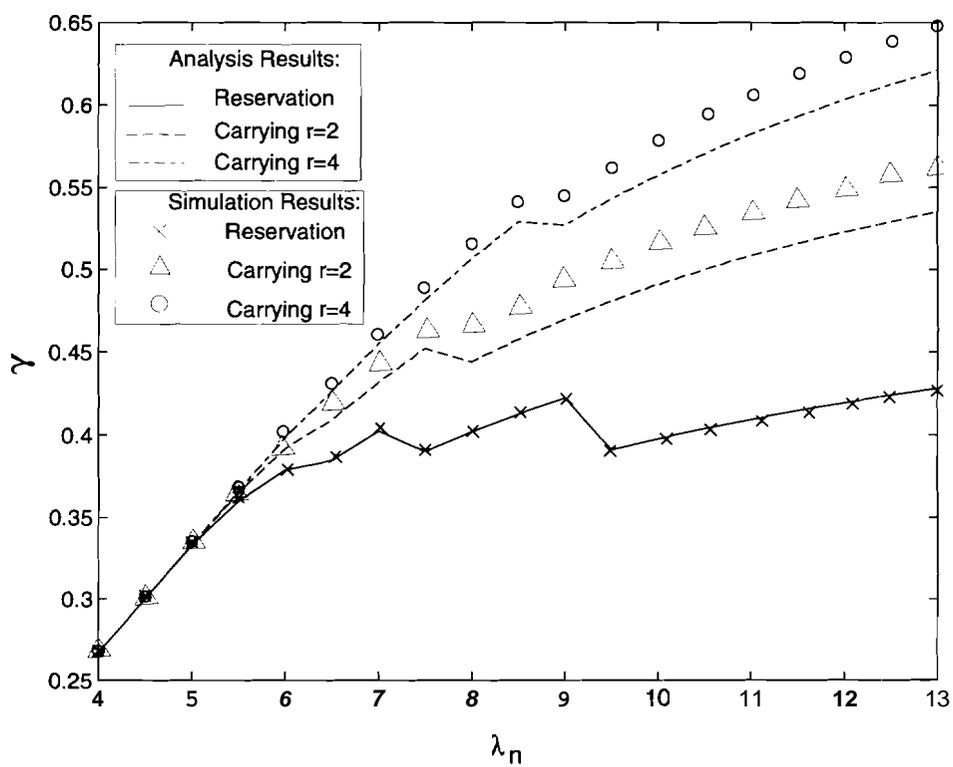


Figure 17: Plot of optimal γ versus λ_n for the problem defined in Equation (17). The parameters used in this figure are: $N/r = 15$, $\lambda_H = 1$, $\mu_0 = 1$, $H_{max} = 10^{-4}$.

Once again, we define a similar optimization problem for the reservation scheme by replacing the decision variable d_{hybrid} by K .

In Figure 17 we plot values of y under varying A_n . The parameters used for this figure are: $\lambda_H = 1$, $\mu_0 = 1$, $M' = 15$, $H_{max} = 10^{-4}$. The hybrid scheme achieves uniformly higher values of y under various loads. The difference between the hybrid and reservation schemes is most apparent at high loads. At such loads, a low value of K is required in the reservation scheme to maintain the QoS constraint on P_{bH} , thus resulting in a low value of y . On the other hand, due to the mobility of channels in the hybrid scheme, the sacrifice in the number of local channels to maintain the QoS constraint on P_{bH} is not as great. When $r = 4$, the channel utilization for the channel carrying scheme at high loads is over 50% more than the reservation scheme. Further, this advantage will be even more significant as r increases. An interesting observation made in Figure 17 is that y does not monotonically increase with A_n . The reason is that the tuning parameter K for the reservation scheme and d_{hybrid} for the carrying scheme can take on only discrete values. For example, for a particular value of K and A_n , the maximum utilization y may be achieved at a blocking probability P_{bH} which is much less than the constraint 10^{-4} . Then, when we increase A_n , this constraint is still met without K being changed, and therefore the utilization y is increased. However, eventually when A_n is large enough, K will have to be decremented to satisfy the constraint, thus resulting in a lowered capacity for new calls and a drop in the utilization.

To study the effect of changing the value of r , in Figure 18 we plot the optimal values of y versus λ_n for various values of r : 4, 8, and ∞ . The traffic parameters we use here are: $M' = 30$, $\lambda_H = 1$, $\mu_0 = 1$. The constraint $H_{max} = 10^{-4}$. For comparison, we also include a plot for the reservation scheme in Figure 18. Note that, as expected, the channel utilization is highest when $r = \infty$, in which case the optimal value of d_{hybrid} is 0. We observe that even for moderate values of r (e.g., $r = 8$), the utilization levels achieved are close to the maximum value (achieved with $r = \infty$), while the utilization levels achieved by the reservation scheme are significantly lower.

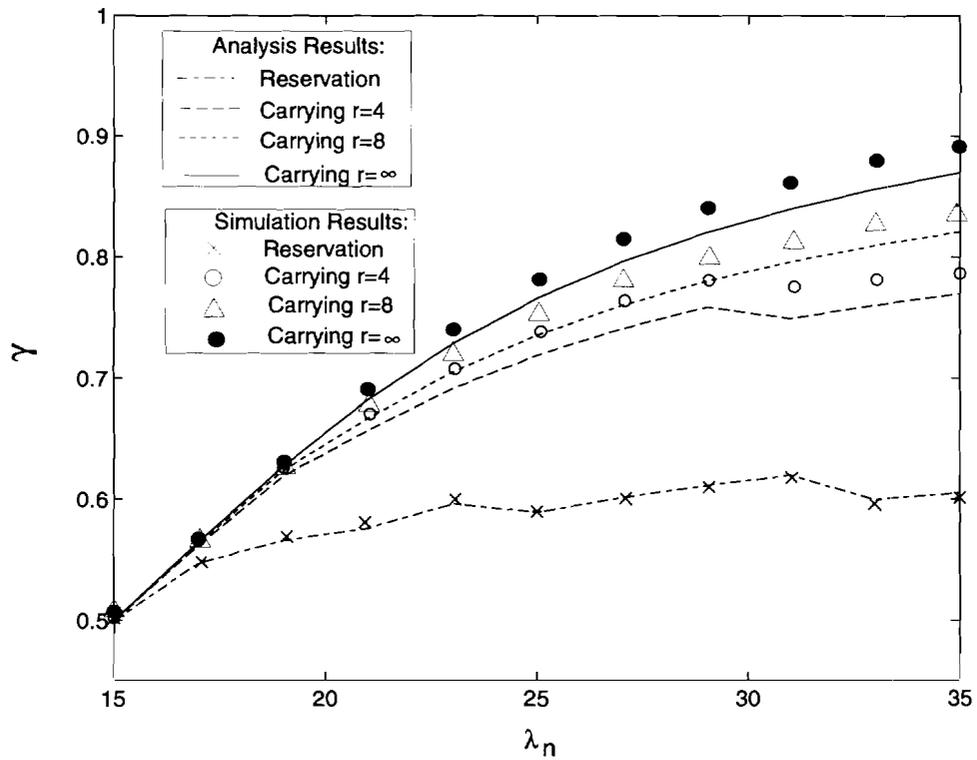


Figure 18: Plot of optimal γ versus λ_n for the problem defined in Equation (17), for various values of r . The parameters used in this figure are: $N/r = 30$, $\lambda_H = 1$, $\mu_0 = 1$, $H_{max} = 10^{-4}$.

6 Conclusion

We have presented a novel channel carrying scheme to address the problem of handoffs in mobile cellular systems. Our basic idea is to allow mobile users to carry their current channels into new cells under certain conditions. In order to avoid co-channel interference, due to channel movement, we use the $(r + 1)$ -channel assignment scheme. This affords us channel mobility at the expense of some capacity. An attractive feature of the channel carrying scheme is that it does not require complex power control techniques or global channel coordination, which simplifies its implementation.

We develop a two-cell model to analyze our channel carrying scheme and the traditional channel reservation technique. We find through numerical results that even in the case of the minimum possible reuse distance, $r = 2$, the channel carrying scheme outperforms the reservation technique.

We further consider a refinement to the channel carrying scheme, which provides a useful design parameter d_{hybrid} that allows us to optimize various parameters of interest. We again find that our scheme uniformly and significantly improves the system performance, in some cases resulting in over 50% better network utilization than the channel reservation scheme.

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