A new localized channel sharing scheme for cellular networks *

Junyi Li [a], Ness B. Shroff [b] and Edwin K.P. Chong [b]

[a] *Lucent Technologies, Bell Labs Innovations, 101 Crawfords Corner Road, Holmdel, NJ 07733-3030, USA*
[b] *School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907, USA*

Enhancing system capacity while maintaining quality of service is an important issue in wireless cellular networks. In this paper, we present a new localized channel sharing scheme to address this problem. Our basic idea is to allow channels to be shared between adjacent cells. We further propose a fixed channel assignment scheme to maximize channel reuse efficiency while allowing channel sharing. We show that our sharing scheme can also facilitate handoff processing. An important feature of our sharing scheme is that channel management is localized between adjacent cells, and no global coordination or optimization is required, thus making it suitable for implementation. We provide simulation results comparing our scheme with the conventional channel assignment and handoff techniques. We find that our scheme improves system capacity over a broad range of traffic parameters and a variety of quality of service requirements.

1. Introduction

Worldwide focus on wireless networking research has intensified in recent years. Compared to its wired counterpart, wireless spectrum is a much more scarce resource. Thus, enhancing system capacity is of great importance in wireless networks. The use of cellular technology is a common means to this end. In a cellular system, the service area is divided into cells, and the wireless spectrum is reused among those cells. We refer to the unit of wireless spectrum needed to serve a single user as a *channel*. For example, in a TDMA system, a time-slot is viewed as a channel. We consider circuit-switched applications, such as voice communications, where the bandwidth requirement for each connection is fixed.

We adopt the usual assumption that channels used in one cell cannot be used in other cells that are closer than the *minimum reuse distance*. A significant body of research has been conducted on efficiently allocating channels to individual cells under this minimum reuse distance constraint [13,22]. There are, in general, two types of channel allocation schemes:

1. *Fixed Channel Allocation (FCA)*: Channels are allocated permanently to each cell for its exclusive use. Users in a cell can be served only by channels belonging to that cell. To maximize reuse efficiency, the same set of channels is reused in cells exactly a minimum reuse distance apart [15,9]. An attractive feature of FCA lies in its simple implementation, compared to the dynamic channel allocation schemes, described next.
2. *Dynamic Channel Allocation (DCA)*: Channels are not tied to a fixed cell, but allocated dynamically upon each call request. DCA is expected to improve system capacity over FCA by exploiting the traffic fluctuation in different cells. However, in general, implementation complexity is also increased. Specifically, to avoid violating the minimum reuse distance constraint, coordination of channel use within the required reuse distance is necessary. Further, to maximize reuse efficiency, global optimization is typically required. Channel coordination and optimization can be done in a centralized [4,5,24,25] or decentralized fashion [1,2,6,8,14,19], which results in various tradeoffs between performance and complexity.

The use of cellular technology also gives rise to new quality of service (QoS) related problems; i.e., those related to handoffs. A handoff occurs when a mobile user moves from one cell to another. A handoff call is blocked if there is no free channel available in the new cell. The probability of blocking a handoff call is an important QoS measure that needs to be considered in wireless networks. In fact, since blocking a handoff call is less desirable than blocking a new call, specific schemes have to be developed to prioritize handoff calls. The channel reservation scheme is a common prioritization method used in FCA systems [7,18,20,21,23]. 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.

In this paper, we propose a novel localized channel sharing (LCS) scheme to improve system capacity and QoS in wireless cellular networks. While the LCS scheme is motivated by our previous work in [16], it is more general, overcomes the drawbacks of the previous work, and provides significantly better performance. The basic idea in our LCS scheme is to allow channels to be shared between adjacent cells; i.e., channels can be used by any user in

* This research was supported in part by AT&T special purpose grant 670-1285-2569, by the National Science Foundation through grants NCR-9624525, ANI 9805441, CDA-9422250, CDA 96-17388, ECS-9410313, and ECS-9501652, and by the U.S. Army Research Office through grant DAAH04-95-1-0246.

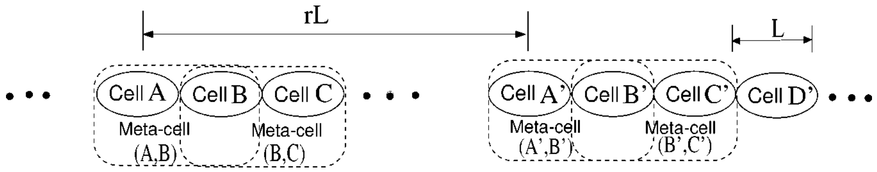

Figure 1. Cells and meta-cells in the linear cellular system.

either cell, without coordinating with other cells for the use of the same channels. In this way, channel management can be localized within adjacent cells. Further, to avoid global optimization, we propose a new fixed channel assignment scheme that attempts to keep the co-channel reuse distance as close as possible while allowing channel sharing. We show that the LCS scheme can also facilitate handoff processing. Moreover, channels are assigned in such a way that each base-station is responsible to transmit over only a portion of the entire channel set, compared with the case in DCA where each base-station may have to transmit over any channel. Therefore, the physical implementation complexity of the LCS scheme is significantly simplified. The above salient features are especially attractive in micro-cellular networks, where handoff occurs more frequently, and, on the other hand, base-station equipment may be inexpensive and not expected to carry out full hardware and software functionality.

We first describe the main idea of the LCS scheme and channel assignment technique in section 2.1, and then illustrate our scheme by considering two commonly used cellular configurations: linear (section 2.2) and 2-D hexagonal (section 2.3). In section 3, we present in detail a protocol to implement the LCS scheme. To make the scheme practically useful, we then introduce two refinements in section 4, which provide useful design parameters to maximize performance under various QoS constraints. Simulation results in section 5 show that our scheme significantly outperforms the FCA and the reservation handoff scheme over a large range of traffic conditions and a variety of QoS requirements. We also quantitatively analyze the implementation complexity associated with the LCS scheme.

2. Localized channel sharing assignment scheme

2.1. Meta-cells

Consider a set of cells in a cellular system. Each cell contains a base station, which communicates with mobile users in that cell. Associated with the cellular system is a set of channels, which are to be allocated to the cells. In each cell, an individual channel can be used by only one mobile user in the cell for communication with the base station. The same channel can be reused in two different cells as long as they (the cells) satisfy a *minimum reuse distance requirement*. To elaborate, we assume that we are given a distance measure d, where $d(X,Y)$ is the distance between cells X and Y. We are also given a parameter Δ that represents the *minimum reuse distance*. Two cells X and Y are said to satisfy the minimum reuse distance requirement if $d(X,Y) \geqslant \Delta$.

In the conventional scheme for fixed channel assignment, each channel is assigned to cells that are exactly a distance Δ apart. Consequently, a maximum number of channels are assigned to each cell while still satisfying the minimum reuse distance requirement. We refer to this scheme as *tightest fixed channel assignment*. To illustrate the scheme, consider a simple linear cellular system, as shown in figure 1. In the figure, each cell is allocated a particular subset of channels, and the same channel set is allocated to cells that are exactly a distance of Δ apart.

In cellular systems using the tightest fixed channel assignment scheme, calls in a cell can only use those channels assigned to that cell. Call blocking results if such a channel is not available. For example, if a call arrives at cell B in figure 1, where all channels are already being used, then this new call is blocked. Channel borrowing is one way to reduce call blocking. Specifically, if at the time the call arrives at cell B, cell A has some idle channels, then cell B may borrow one of the idle channels to serve the new call. To achieve this, however, we need to coordinate the use of channels in the co-channel cells of cell A. For example, to avoid violating the minimum reuse distance requirement, channels that are borrowed by cell B cannot be used in cell A'. Such a global channel coordination is computationally expensive and therefore difficult to implement, and further channel utilization may be decreased at high traffic loads [10].

In our scheme, we attempt to alleviate call blocking by sharing channels between neighboring cells, while localizing the channel coordination. To facilitate the description of our scheme, we first introduce some terminology. A *meta-cell* is a fixed collection of neighboring cells (typically a pair of two adjacent cells). For example, figure 1 shows a family of meta-cells in a linear cellular system, each comprising a pair of two adjacent cells. Each meta-cell is designated by a pair (X,Y), where X and Y are individual cells called the *component cells* of that meta-cell. For example, in figure 1, cells A and B are components of meta-cell (A,B). As before, we assume that we have a distance measure for meta-cells (e.g., based on the distance measure d between cells).

The main idea of our channel assignment scheme is to allocate channels to meta-cells in such a way that a maximum number of channels can be assigned to each meta-cell while any two meta-cells assigned the same channels satisfy the minimum reuse distance requirement, i.e., the distance measure, now with respect to two meta-cells, is no

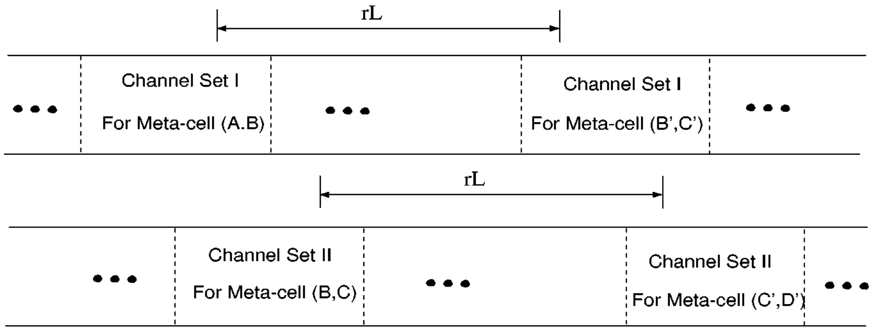

Figure 2. Channel assignment scheme that allows channel sharing in the linear cellular system.

shorter than Δ. For example, figure 2 (described in more detail later) depicts the channel assignment scheme for the two meta-cell groups in the linear cellular system illustrated previously.

Our channel assignment scheme, done at the meta-cell level, is different from the usual channel assignment scheme which is done at the cell level. In particular, channels are assigned not to individual cells but to meta-cells. A user in a given cell can use any channel that is assigned to a meta-cell to which the given cell belongs, with the usual proviso that only one user can use a given channel within a given meta-cell at a given instance.

Our channel allocation scheme allows channels to be shared between neighboring cells (namely, cells belonging to the same meta-cell). We point out two fundamental advantages:

1. First, the sharing of resources between cells leads to more efficient utilization of the resources. In particular, if a new user arrives at a cell and a channel is not being used in a neighboring cell, the user can use that channel (as long as the neighboring cell belongs to the same meta-cell). This feature potentially reduces the probability of blocking a new call.
2. Second, when a user moves from one cell to another, under certain circumstances it may not be necessary to assign another channel to the user. Specifically, if a user in a given cell moves to a neighboring cell which is part of the same meta-cell, and the user is using a channel that is assigned to that meta-cell, the user can move to the neighboring cell without any risk of handoff blocking. This feature potentially reduces the probability of blocking a handoff call.

Note that relative to the usual fixed channel assignment scheme, in the LCS scheme we need to coordinate between cells in a meta-cell. However, since meta-cells consist only of neighboring cells, the scheme should be easy to implement.

The idea of sharing channels among users in adjacent cells has also been explored in [3,12], where the authors proposed to exploit the overlapping coverage of adjacent base-stations naturally arising in many cellular systems, and to allow users in overlapping areas to access channels of two base-stations. However, the performance improvement is limited by the physical area of overlapping coverage and the amount of instantaneous traffic in that area. The LCS scheme proposed in this paper creates logical overlapping coverage (meta-cell), and allocates the channels in such a way that all users in a cell can access channels assigned to the meta-cells covering that cell. Thus, it does not rely on a particular physical overlapping coverage in a given system.

Note that if no channels are available for a new call in the meta-cells in which the given call belongs, it may still be possible to satisfy the channel request, provided there is *some* channel available elsewhere. To see how this can be done, consider the linear cellular configuration shown in figure 1. Suppose a channel is requested at cell A and no channel is available in meta-cell (A, B), but a channel is available in meta-cell (B, C). A user in cell B using a channel assigned to meta-cell (A, B) could then exchange its channel for the unused channel assigned to meta-cell (B, C), thus freeing up its channel, which can then be used to satisfy the channel request at cell A. If, instead, a channel is not available in meta-cell (B, C) but in some other meta-cell further along, a string of exchanges similar to the above can be made to eventually free up a channel in meta-cell (A, B) needed to serve the channel request. Of course, some limit will need to be placed in practice on the maximum number of exchanges allowed to serve any given channel request to limit the complexity of the scheme. Throughout this paper, unless otherwise specified, we assume that such exchanges are not allowed (i.e., for simplicity, we assume that if channels are not available for a cell in the meta cells in which the request occurs, the call is blocked).

In the following, we illustrate our channel assignment scheme for two typical cellular systems: linear and 2-D hexagonal. We develop methods to deploy meta-cells assigned the same channels as tightly as possible, while not violating the minimum reuse distance requirement. We then present a protocol to implement the channel assignment scheme, which maximally exploits the advantages of our framework. We then compare the performance of our scheme with the tightest fixed channel assignment scheme.

2.2. Linear case

Consider again figure 1. 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 width of a single cell and r is an integer. Cells that are assigned the same set of channels are called *co-channel cells*. Therefore, in the tightest fixed channel assignment scheme, co-channel cells are exactly r cells apart. For example, in figure 1, cells A and A' are co-channel cells. Let N 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 N/r. The integer r is called the *reuse factor*, being the ratio of the total number of channels in the system to the number of channels allowed to be used in a single cell.

To assign channels to meta-cells, we next define the *distance measure* $d((X,Y),(X',Y'))$ between two meta-cells (X,Y) and (X',Y'). Recall that in our 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 measure 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 $(X,Y),(X'Y')$, i.e.,

$$d\big((X,Y),\big(X',Y'\big)\big) = \min\big\{d\big(X,X'\big), d\big(X,Y'\big), d\big(Y,X'\big), d\big(Y,Y'\big)\big\}. \quad (2.1)$$

For example, in figure 1, 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 have to be deployed as close as possible to maximize channel reuse efficiency. 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. For example, in figure 2, meta-cells (A,B) and (B',C') are assigned the same set of channels (i.e., they are co-channel meta-cells). Consider a particular channel in this set. Now, when the channel is used simultaneously in meta-cells (A,B) and (B',C'), the shortest possible reuse distance is between cells B and B', which is exactly the minimum reuse distance rL. Thus, the same channel can be independently used in cell A or B and cell B' or C'.

It is easy to show that, using our scheme, each meta-cell is assigned $N/(r+1)$ distinct channels. In other words, the reuse factor of our channel assignment scheme is

$$r' = r + 1. \quad (2.2)$$

This reuse factor is the same as that of the channel assignment scheme in [16].

The linear case described above is important in its own right. For example, it accurately models cellular configuration on highways and rural areas. However, to handle cellular systems in more metropolitan-type environments, we next discuss our channel assignment in the planar case.

2.3. Planar (2-D) case

In the planar or 2-D case, the cellular configuration is usually assumed to be hexagonal. This means that the entire area of interest is covered with equal-sized hexagonal cells, as shown in figure 3. As in the linear case, the distance $d(X,Y)$ between two cells X and Y is typically defined as the distance between their centers. Let N denote the total number of distinct channels available in this hexagonal cellular system. In the tightest fixed channel assignment scheme, co-channel cells are exactly a distance of Δ, the minimum reuse distance, apart. Consequently, each cell is assigned N/R channels, where R is the minimum reuse factor. It has been shown in [9] that R can be determined from Δ by $R = (1/3)(\Delta/\rho)^2$, where ρ is the radius of a single cell. In general, the minimum reuse factor R can be represented by

$$R = p^2 + pq + q^2, \quad (2.3)$$

where p and q are nonnegative integers satisfying $p+q \geqslant 2$. Without loss of generality, we assume that $q \geqslant p$ in the following.

As in the linear case, a meta-cell here consists of two adjacent neighboring cells. To allow for channel sharing, we assign channels to meta-cells, as in the linear case, under the minimum reuse distance constraint in terms of meta-cells. For our purpose, the distance measure between two meta-cells is defined in the same way as in equation (2.1). Again, the main idea of our channel assignment scheme is to deploy co-channel meta-cells as close as possible, under the minimum reuse distance constraint, to maximize channel reuse efficiency. In the remainder of this section, we describe this channel assignment scheme in detail.

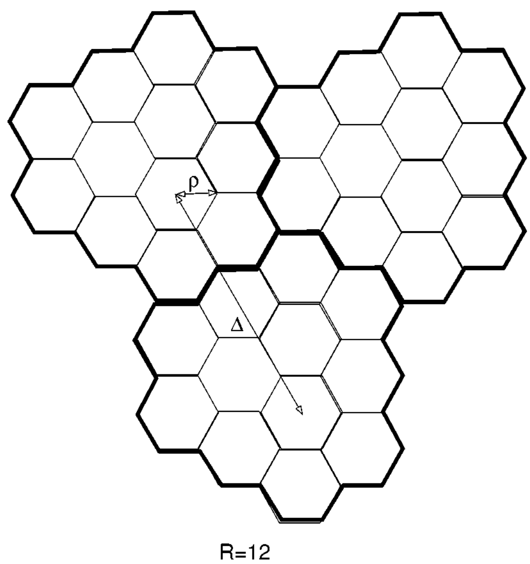

Figure 3. Hexagonal cells in a 2-D system.

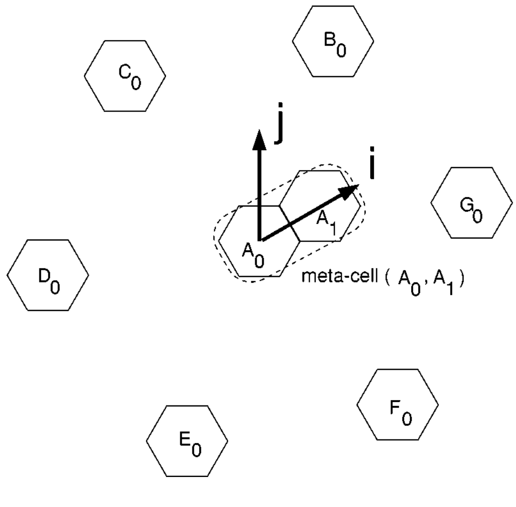

Figure 4. The set of i–j coordinates in a 2-D hexagonal system.

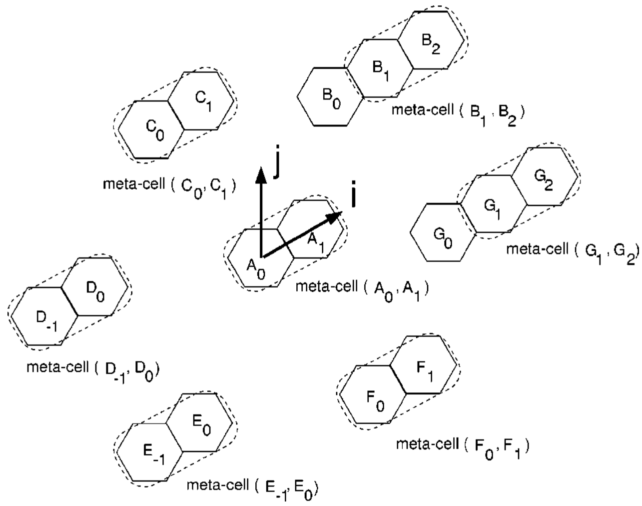

Figure 5. Configuration of co-channel meta-cells in the case of $p+1 \geqslant p$.

Consider an arbitrary cell A_0 in the hexagonal cellular system as shown in figure 4, and establish a set of coordinates i–j originating at the center of cell A_0, where the two axes form a 60^o angle, and the unit distance along the axes is $\sqrt{3}\rho$. Then, the minimum reuse distance Δ is equal to R coordinate units in this set of coordinates. The center of any hexagon Z can be designated by a pair of coordinates (i_Z, j_Z), with i_Z and j_Z integers. Let B_0, C_0, D_0, E_0, F_0, and G_0 denote six hexagons with centers at the coordinates (p, q), $(-q, p+q)$, $(-p-q, p)$, $(-p, -q)$, $(q, -p-q)$, and $(p+q, -p)$, respectively (see figure 4). Note that their distance to cell A_0 (centered at $(0, 0)$) are equal and given by $p^2 + pq + q^2 = R$ units. In the tightest fixed channel assignment scheme, cells B_0, C_0, D_0, E_0, F_0, and G_0 are assigned the same set of channels as cell A_0.

Let A_1 be the adjacent right neighboring cell of A_0 along the i-axis as shown in figure 4, i.e., $(i_{A_1}, j_{A_1}) = (i_{A_0}+1, j_{A_0}) = (1, 0)$. We next focus on meta-cell (A_0, A_1) as the *reference meta-cell*. Note that in the 2-D case, meta-cells may have three distinct orientations (the orientation of a meta-cell is the directional relationship between its two component cells). Each meta-cell may have six neighboring co-channel meta-cells. Consequently, there are many different ways to deploy co-channel meta-cells, including irregular (non-repetitive) deployment patterns. For the sake of simplicity and regularity, in the following we restrict ourselves to deployment methods in which all co-channel meta-cells are of the same orientation. In other words, for any co-channel meta-cell of (A_0, A_1) of interest, two components are adjacent along the i-axis. Therefore, we can identify any co-channel meta-cell of reference meta-cell (A_0, A_1) by its left component (the component cell that is positioned in the left side along the i-axis).

It turns out that for different values of p and q, we need different methods to deploy co-channel meta-cells of reference meta-cell (A_0, A_1), depending on whether $p+1 \geqslant q$. For simplicity, we assume that $p+1 \geqslant q$. (The case where $p+1 < q$ is more involved and is therefore omitted in the interest of space; we refer to our technical report [17] for the details.) The values of R within this category are $3, 7, 12, 19$, etc. It can be shown that in this case, as illustrated in figure 5, the meta-cells whose left components are respectively B_1, C_0, D_{-1}, E_{-1}, F_0, and G_1, can be deployed as co-channel meta-cells of reference meta-cell (A_0, A_1), where the centers of cells B_1, D_{-1}, E_{-1}, and G_1 are given respectively as follows: $(i_{B_1}, j_{B_1}) = (p+1, q)$, $(i_{D_{-1}}, j_{D_{-1}}) = (-p-q-1, p)$, $(i_{E_{-1}}, j_{E_{-1}}) = (-p-1, -q)$, and $(i_{G_1}, j_{G_1}) = (p+q+1, -p)$. Furthermore, we have shown that when assigning channels according to this co-channel meta-cell deployment, the channel reuse factor is

$$R' = R + p + q. \tag{2.4}$$

The detailed proofs and further discussions are provided in [17].

3. Channel sharing protocol

In the previous section, we described our channel assignment scheme, in which channels are assigned to meta-cells instead of cells. Channels assigned to a meta-cell can be shared by any of its component cells. We next develop a channel sharing protocol to exploit this sharing feature of our scheme. Specifically, whenever a new call arrives at a given cell, the protocol determines whether or not the call can be accommodated, and which channel is to be used to serve the call. Here we do not distinguish between new and handoff call requests. We will explicitly address the handoff problem later in section 4.2.

3.1. Protocol description

To describe our channel sharing protocol, we focus our attention on a particular (arbitrary) cell, which we call the *local cell*. Recall from the previous section that using our channel assignment scheme, each cell in the cellular network is always covered by several overlapping meta-cells, called the *covering meta-cells* of that cell. For example, in the linear case, each cell is covered by two meta-cells, while in the 2-D case with a hexagonal configuration, each cell is covered by six meta-cells. We call channels that are assigned to the covering meta-cells of the local cell the *accessible channels*, since users in the local cell may have access to those channels. The entity that manages those accessible channels is called the *channel controller*, which resides in the base-station of the local cell. The channel controller only needs to exchange channel usage information with channel controllers of adjacent cells, as will be described in this section. This exchange of information can be done in a variety of ways, such as via an out-of-band signaling channel (or a wired channel) that connects the base-stations of the local cell and its adjacent cells.

In our channel assignment scheme, each accessible channel is shared between the local cell and one of its adjacent cells. Therefore, for each channel at any given instance, either the local cell or one of the adjacent cells can use the channel. In other words, at any given instance, not all the accessible channels can be used by the local cell. Those channels that can be used by the local cell are called *enabled channels*. To coordinate the use of accessible channels between the local cell and the corresponding sharing cells, the local cell maintains a look-up table, in which each accessible channel occupies one entry consisting of the following two fields. The first field indicates the current state of an associated channel. The state in the first field may be “DISABLED”, “IDLE”, or “BUSY”, described as follows. An accessible channel labeled “DISABLED” is *not enabled* in the local cell. This indicates that the channel is concurrently enabled in the sharing cell associated with that channel. The local cell can use only those accessible channels labeled “BUSY” or “IDLE” (i.e., these channels are the enabled channels in the local cell). In this case the labels further indicate whether channels are currently occupied by mobile users in the local cell. The second field simply records the names of the sharing cells associated with the accessible channels.

Initially, for each accessible channel, the channel controller may arbitrarily set its state in the look-up table of the local cell “IDLE” or “DISABLED”; concurrently, the state in the look-up table of the sharing cell associated with that accessible channel must be inversely set “DISABLED” or “IDLE”, respectively.

Our protocol can be described in three main parts, corresponding to three different possible scenarios: *arrival of a call, sharing a request from a sharing cell,* and *departure of a call.*

3.1.1. Arrival of a call

The protocol for handling the arrival of a call is shown in figure 6. When a call arrives, the channel controller checks if there are any accessible channels labeled “IDLE” in the look-up table of the local cell. If there are, the arriving call is accepted and assigned an idle channel, and the state of that channel is then changed to “BUSY”. Otherwise, the channel controller attempts to obtain an idle

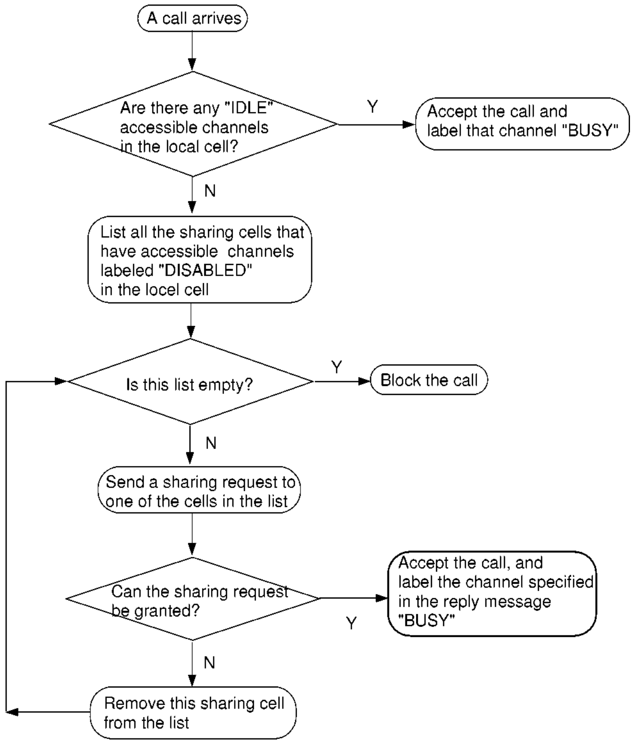

Figure 6. Protocol for handling a call arrival.

accessible channel from some sharing cell, as follows. The channel controller first looks up all accessible channels currently labeled “DISABLED” in the local cell and obtains a list of the sharing cells associated with those “DISABLED” accessible channels. The channel controller then chooses one of the sharing cells on this list and sends it a *sharing request*. The sharing cell, upon receiving the sharing request, then executes the procedure in section 3.1.2. If the sharing request is granted, the channel controller accepts the arriving call by assigning the accessible channel specified in the return message from the sharing cell, and setting the state of that channel “BUSY”. If the request is denied, the channel controller proceeds to send another sharing request to one of the remaining sharing cells on the list. The process is continued until the sharing request is accepted or denied by all sharing cells on the list, in which case the call is rejected (blocked). The way to choose one of the sharing cells for directing a sharing request may be totally random, as done later in this paper for simplicity, or may follow some heuristic rules, such as starting from the one associated with the largest number of accessible channels currently labeled “DISABLED” in the local cell.

3.1.2. Sharing request from a sharing cell

The protocol for handling the sharing request from a sharing cell is illustrated in figure 7. When a sharing request is received from a sharing cell, the channel controller first checks whether there is any accessible channel U, associated with that sharing cell, currently labeled “IDLE” in the local cell. If so, the channel controller grants the sharing request by sending back the identification number

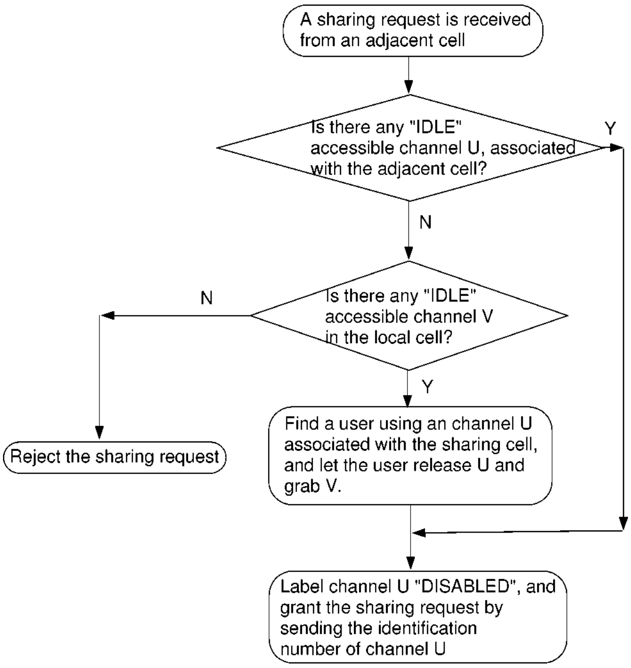

Figure 7. Protocol for handling the sharing request from a sharing cell.

of channel U in the return message, and setting channel U "DISABLED" in the local look-up table. Otherwise, the channel controller attempts to obtain such an idle channel U by *swapping channels* as follows. The channel controller checks whether there is any accessible channel V currently labeled "IDLE" in the local cell. If so, the channel controller finds a user currently using an accessible channel U associated with the sharing cell (we can always find such a user because, from section 3.1.1, a sharing request is directed to the local cell only if in the sharing cell there are sharable channels labeled "DISABLED", which must be either "BUSY" or "IDLE" in the local cell). That user then releases channel U and grabs channel V, so that the channel controller can grant the sharing request by returning the identification number of channel U and setting channel U as "DISABLED" in the local look-up table. If no accessible channels are in the "IDLE" state, the channel controller rejects the sharing request, for simplicity, as illustrated in figure 7.

For example, suppose that in the linear cellular system shown in figure 1, cell A, after receiving a call request, sends a sharing request to cell B. The channel controller in cell B first checks whether there is any idle channel U of set I in cell B (see figure 2). If so, channel U is labeled "DISABLED" in cell B and consequently it can be assigned to that call arrival and labeled "BUSY" in cell A. Otherwise, the channel controller then checks whether there is any idle channel V in cell B, which in this case must belong to channel set II. If so, the channel controller lets a user, who is currently using a channel U of set I in cell B, grab channel V, so that channel U can be released to cell A. Otherwise, the sharing request is rejected, according to the protocol of figure 7.

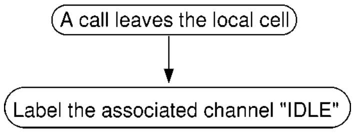

Figure 8. Protocol for handling a call departure.

It should be pointed out, however, that even in the above case, rejecting a sharing request may not be necessary. Instead, the channel controller may further send another sharing request to the sharing cells of the local cell, the same way as in section 3.1.1, so that the channel controller may obtain an idle accessible channel and grant the original sharing request. This process may be repeated from cell to cell (i.e., sharing requests are propagated from one cell to another) until one of the sharing requests can be granted. We will quantitatively investigate the performance improvement when applying this sharing propagation strategy in section 5.3.

3.1.3. Departure of a call

Figure 8 depicts the protocol to handle the scenario when a call leaves the local cell. This scenario arises when a call terminates in the local cell, or when a call migrates to another cell. In this case, the channel controller simply labels the associated channel "IDLE".

Consider again the example in the last section. When channel U, which was granted from cell B to cell A by sharing, is released, it remains "IDLE" and is not immediately returned to cell B (unless there is a sharing request from cell B).

3.2. Salient features of the channel sharing protocol

The following are some of the important features of our channel sharing protocol:

1. *Channel sharing within a meta-cell is localized* between two adjacent cells and can therefore be done in a decentralized fashion. No global coordination is necessary in our protocol, thus facilitating implementation. At the same time, our channel assignment scheme ensures that there is no co-channel interference due to channel movement. The major computational effort in the local cell includes communication with the sharing cells, channel swappings, and simple table look-ups. We will investigate the complexity of our protocol later in section 5.1 by estimating the expected number of inter-cell communication and channel swappings for each call arrival.

2. *Channel utilization is improved* because channels are assigned to meta-cells instead of to individual cells. Clearly, an idle channel can be accessed by calls in either of its component cells, thus effectively reducing the fraction of idle periods of channels. Consequently, *the blocking of handoff requests occurs relatively rarely* in our protocol because it requires all three of the following conditions to be simultaneously true:

(a) All sharable channels between the handoff originating cell and the destination cell are already occupied in the destination cell.

(b) All channels in the destination cell are occupied.

(c) In each of the adjacent cells of the destination cell, either there are no idle channels, or there are no channels sharable with the destination cell.

For example, suppose a user in the local cell desires to move into a neighboring (destination) cell. If there is a channel in the local cell (whether busy or idle) that can be shared with the destination cell, then the user can move to the neighboring cell without experiencing handoff blocking. In this case, the first condition above does not hold.

3. *Handoff processing may be easier* when using our protocol. A special case of the example scenario pointed out above is when a user moves from one cell to another, and the user is using a sharable channel between the two cells. In this case, not only can the user change cells with no risk of handoff blocking, but the processing of the handoff can also be simplified by continuing the service using the same channel during handoff. Moreover, if we model and predict the mobility of a particular user, we can further reduce the incidence of handoff blocking by reassigning (if necessary) to the user a channel that can be shared with the next destination cell. The benefit here is that we effectively have a mechanism for processing handoffs by anticipating the movement of a mobile user, and the time available to do this processing is the time a user spends in a given cell. This is in contrast to the potentially much shorter time available to conventionally process a handoff call, typically only when a user is at the boundary between two cells. This feature is especially important for cellular systems with small-sized cells, such as micro-cellular systems.

4. Refinements

In the previous section, we presented the basic assignment scheme and protocol for our channel sharing strategy. To make our scheme practically useful, we next discuss two refinements.

4.1. Combined scheme

It is instructive to compare the effective channel capacity using the LCS scheme and the tightest fixed channel assignment scheme. In our scheme, the maximum possible channel capacity of each cell is clearly just the total number of distinct accessible channels for each cell. As we pointed out above, in an individual cell, the number of accessible channels in our scheme is generally larger than that of the fixed scheme. Note that, however, this number is an upper bound on the effective channel capacity since it assumes that the statistical sharing advantage can fully be exploited. On the other hand, if we totally ignore the statistical sharing advantage, we may then obtain a lower bound for the channel capacity. To be specific, we equally distribute channels that are assigned to each meta-cell into two component cells and then count the total number of distinct channels now available for each cell. For example, the lower bound capacity in the linear case is N/r' channels. Hence, the effective channel capacity using the LCS scheme is bounded by these two extreme scenarios and depends on the extent to which the statistical sharing advantage is actually obtained.

Next, we present a combined scheme that attempts to maximize the effective channel capacity for each cell. Specifically, we divide all the N channels into two distinct groups of size N_1 and N_2 such that

$$N = N_1 + N_2. \tag{4.1}$$

The first group of N_1 channels is assigned to cells using the tightest fixed channel assignment scheme and thus cannot be shared between adjacent cells. The remaining group of N_2 channels, however, is assigned to meta-cells according to our channel sharing assignment scheme, and can be shared within meta-cells, the same as in the previous sections.

The combined scheme above defines a family of channel assignments that encompasses both the fixed and the basic LCS schemes. At one end of the spectrum, where $N_2 = N$ (corresponding to the basic LCS scheme), the maximum number of channels are assigned to meta-cells. In this case, every channel can be shared by two adjacent cells. Thus, the upper bound of the effective channel capacity is largest, but the lower bound is smallest at the same time. With decreasing N_2, the upper bound is decreased while the lower bound is increased, until $N_2 = 0$ (corresponding to the tightest fixed channel assignment) where there is no channel sharing. In this case, the upper and lower bounds coincide and are equal to the effective channel capacity.

Varying N_2 allows us to maximize the effective channel capacity. Specifically, the parameter N_2 enables us to trade off the potential advantage from statistical sharing with a reduction in the average number of channels for each cell. The larger the value of N_2 in the combined scheme, the more the gain we expect from statistical sharing, but at the same time the higher the price we pay by reducing the average number of channels for each cell. The reduction in this average number, relative to its maximum value when $N_2 = 0$, is given by

$$d = \frac{N_2}{r} - \frac{N_2}{r'} = \frac{N_2}{r(r+1)}$$

in the linear case, or

$$d = \frac{N_2}{R} - \frac{N_2}{R'} = \frac{N_2(R' - R)}{RR'}$$

in the 2-D case, while the number of sharable channels for each cell is $s = N_2/r'$ in the linear case, or $s = N_2/R'$ in the 2-D case. Further, s and d are related by $s/d = r$ in the linear case, or $s/d = R/(R' - R)$ in the 2-D case. Clearly, for the same price we pay in the combined scheme

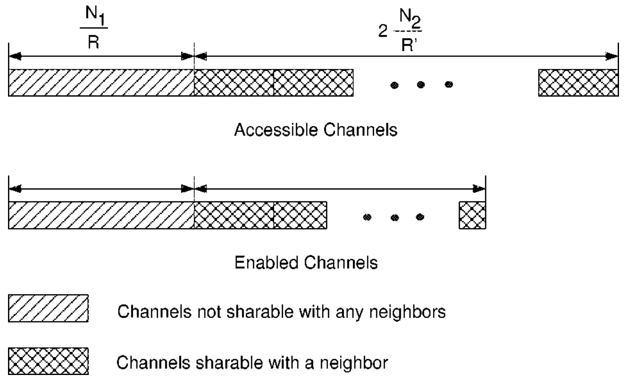

Figure 9. Partition of channels in local cell (for 2-D case).

in terms of d, the number of sharable channels s increases with increasing r in the linear case or $R/(R' - R)$ in the 2-D case.

Figure 9 illustrates the partitioning of accessible channels in a cell into the two groups described above. The number of accessible channels in each of these groups is N_1/R and $2N_2/R'$, respectively (in the 2-D case). Note that the number of enabled channels in the first (N_1/R) group is fixed, whereas the number of enabled channels in the second group can vary between 0 and $2N_2/R'$.

4.2. *Threshold handoff scheme*

In our basic LCS scheme, we do not distinguish between new and handoff call arrivals. However, studies have shown that one of the most important user concerns is that service not be cut off during an on-going call. Therefore, blocking a handoff arrival is even less desirable than blocking a new arrival. Various schemes have been proposed to prioritize handoff calls (e.g., [11]). The *threshold* scheme is particularly well known. Specifically, a number of channels can be reserved solely for the use of handoffs, allowing both handoff and new calls to compete for the remaining channels.

To illustrate the main idea underlying the threshold scheme, we now describe a popular scheme called *channel reservation*. Consider the tightest fixed channel assignment. A threshold K is set in each cell ($K \leqslant N/r$ for the linear case and $K \leqslant N/R$ for the 2-D case). If the number of channels currently used in the cell is below K, both new and handoff calls are accepted. Otherwise, if the number of channels used exceeds this threshold, incoming new calls are blocked and only handoff calls are admitted.

To prioritize handoff calls in our LCS scheme, we apply a threshold idea similar to the channel reservation scheme above. Our threshold scheme is composed of two parts, as described next. Note that the threshold restrictions apply only to new call requests.

4.2.1. K_1 *threshold*

The first part of our threshold scheme is the same as the channel reservation scheme. Specifically, a new call arriving at a cell will be blocked if the number of current users in that cell exceeds a threshold K_1, with $K_1 \leqslant N_1/r + 2N_2/r'$ in the linear case or $K_1 \leqslant N_1/R + 2N_2/R'$ in the 2-D case. As in the case of the channel reservation scheme (for the tightest fixed channel assignment), here also we set the threshold K_1 to avoid overall excessive use of accessible channels by new calls. For example, in some scenarios, accessible channels may be accumulated in one cell because of channel movement. In this case, it is desirable to limit excessive access to those channels by new calls, waiting instead for potential sharing requests from sharing cells. Note that the K_1 threshold takes effect only if the number of enabled channels (as described in section 3.1) is greater than K_1 (otherwise, we apply another threshold, K_2, described in the next section).

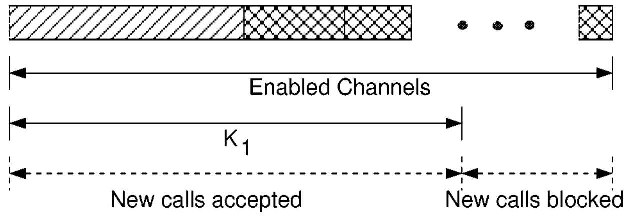

Figure 10. K_1 threshold scheme.

Figure 10 provides an illustration of the K_1 threshold scheme. In the figure, we assume that the number of enabled channels is greater than K_1. As illustrated, if the number of channels being used does not exceed K_1, then new calls are accepted; otherwise, they are blocked.

Note that to achieve a given quality of service requirement for handoff, the threshold K_1 in our scheme may generally be chosen higher than K in the channel reservation scheme because now handoff requests have access to more channel capacity due to sharing. In other words, we need to reserve fewer channels *a priori* for handoff calls. This helps increase the efficiency of our handoff scheme compared to the conventional reservation scheme, as will be demonstrated in section 5.2.

4.2.2. K_2 *threshold*

If the new call is not blocked by the first part of the threshold scheme, it is accepted if there are idle channels in the cell. Otherwise, if there are no idle channels (from which we infer that the number of enabled channels is less than or equal to K_1), we then attempt to obtain an accessible channel from sharing cells, as described in section 3.1. The second part of the threshold scheme is now applied to limit the sharing accessibility associated with individual sharing cells. Specifically, we first set the value of a second threshold K_2, where $K_2 \leqslant N_2/r'$ in the linear case, or $K_2 \leqslant N_2/R'$ in the 2-D case. Then, in the protocol described in section 3.1.1, we send out sharing requests only to the adjacent cells that have fewer than K_2 sharable channels currently being used in the local cell. In this way we prevent new calls from excessively using up sharable chan-

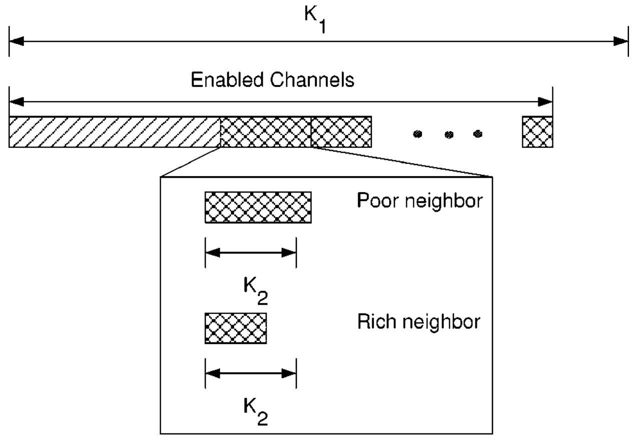

Figure 11. K_2 threshold scheme.

nels associated with any particular sharing cell, and thus prioritize potential handoffs from that sharing cell.

Figure 11 illustrates the K_2 threshold scheme. Note that the number of enabled channels here is not more than K_1 (for otherwise the K_2 threshold does not take effect). In the figure, we use the term *rich neighbor* to denote a neighboring cell that has fewer than K_2 sharable channels *in the local cell*. If the neighboring cell has more than or equal to K_2 channels *in the local cell*, we use the term *poor neighbor*. In other words, we send out sharing requests for new calls only to rich neighbors.

5. Simulation results

In this section, we provide simulation results to compare the performance of our LCS scheme with the tightest fixed channel assignment scheme. We consider the following two scenarios. In the first scenario, we do not distinguish new calls from handoff calls in the channel assignment. In this case, the quality of service (QoS) measure that we are interested in is P_{b}, the blocking probability of a call arrival into a cell. In the second scenario, we investigate the performance of our LCS scheme with handoff prioritization, as well as the channel reservation scheme based on the tightest fixed channel assignment. Here, we distinguish between the blocking of new and handoff calls. The QoS measures we are interested in this case are: P_{bN}, the blocking probability of new calls, and P_{bH}, the blocking probability of handoff calls. We conclude the section by showing an example of further improvements that may be obtained if sharing requests are allowed to propagate across more than one cell.

We investigate both the linear and 2-D hexagonal cases by simulation. Our simulation model for the linear cellular system consists of 30 cells, where each cell has two adjacent cells. The boundary cells on the two sides are then connected to each other to avoid the "edge" effect at the boundaries. To model the 2-D cellular system, we use a 36-cell configuration, with each cell having six adjacent cells. Again, the cells on the boundary of one side of the configuration are connected to the cells on the boundary of the other side. For both the linear and 2-D cases, the call traffic is assumed to be symmetrically distributed over all the cells. The simulation is discrete-event driven. There are three types of events: new call request arrival, handoff request arrival, and call termination. New calls are assumed to arrive at each cell according to a Poisson process with rate λ_{n}. The time until a call terminates is assumed to be exponentially distributed with mean $1/\mu$. The time a user spends in a cell before making a handoff request to go to another cell is assumed to be exponentially distributed with mean $1/\lambda_{\mathrm{H}}$. In our simulation model, users in a cell may direct a handoff request to each of the adjacent cells with equal probability. The blocking probabilities P_{bN} and P_{bH} are estimated as follows:

$$P_{\mathrm{bN}} \approx \frac{\text{number of new call requests rejected}}{\text{number of new call requests generated}}, \tag{5.1}$$

$$P_{\mathrm{bH}} \approx \frac{\text{number of unsuccessful handoffs}}{\text{number of handoff requests generated}}. \tag{5.2}$$

To estimate P_{bN} and P_{bH}, we count the events of new call request generations, handoff request generations, new call requests rejected, and handoff requests rejected. Since we are interested in the performance of a typical cell, the statistics obtained are averaged over all cells.

5.1. Channel allocation without handoff

In this study, we do not consider handoffs. Further, in our simulation, users that arrive in each cell do not migrate to other cells. This is typical of assumptions made in the literature (e.g., in [10]).

Maximum call arrival rate

We compare the maximum call arrival rate λ_{n} that can be admitted by our LCS scheme and the tightest fixed channel assignment scheme, respectively, for various blocking probabilities P_{b}. More precisely, we define the following optimization problem for the LCS scheme:

$$\begin{aligned} &\underset{\lambda_{\mathrm{n}}, N_2}{\text{maximize}}\ \lambda_{\mathrm{n}} \\ &\text{subject to } P_{\mathrm{b}} \leqslant B_{\max}. \end{aligned} \tag{5.3}$$

The constraint $B_{\max}$ used in our simulation varies between 3×10^{-3} and 5×10^{-2} and the corresponding maximum value of λ_{n} is obtained by tuning the parameters N_2 and λ_{n}. We define a similar optimization problem for the tightest fixed channel allocation scheme: $\text{maximize}_{\lambda_{\mathrm{n}}} \lambda_{\mathrm{n}}$, subject to $P_{\mathrm{b}} \leqslant B_{\max}$. In figure 12, we plot the optimal values of λ_{n} versus $B_{\max}$ for both schemes for the linear case with $r = 2$ and $r = 4$. In figure 13, we plot the optimal values of λ_{n} versus $B_{\max}$ for both schemes for the 2-D case with $R = 3$, 7, 12, and 19. For both figures, we use $\mu = 1$. To make our results comparable for different minimum reuse factors, we keep $N/r = 15$ for all the curves in figure 12. Thus, $N = 30$ when $r = 2$, and $N = 60$ when $r = 4$. Similarly in figure 13, we set $N/R = 15$ for all R.

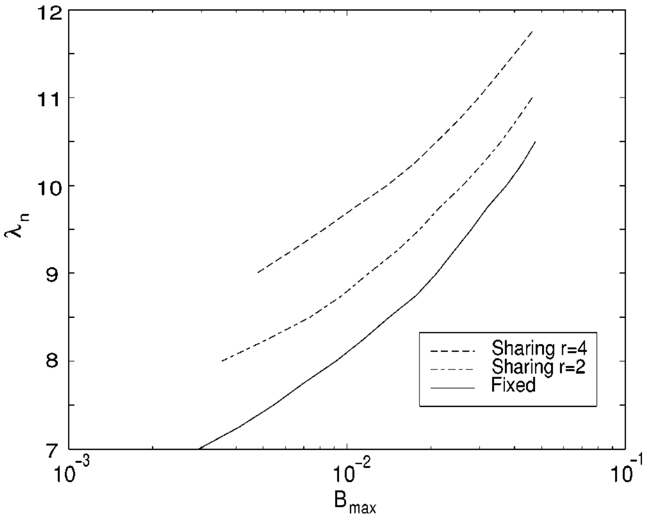

Figure 12. Plot of optimal λ_n versus B_{max} in the linear case, for the problem defined in equation (5.3). The parameters used in this plot are: $N/r = 15$, $\mu = 1$.

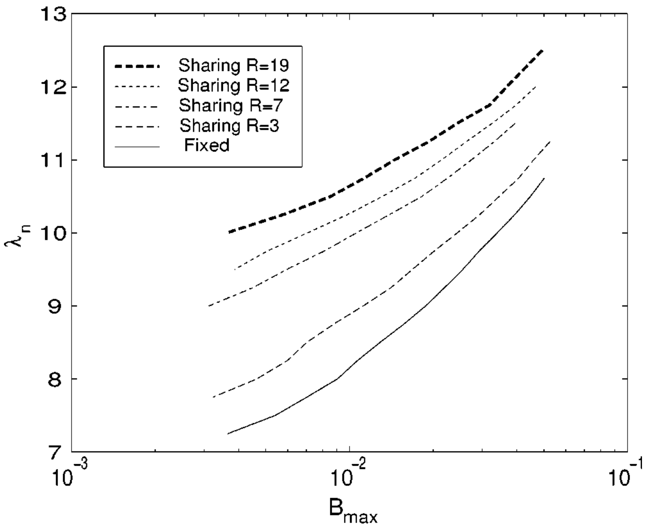

Figure 13. Plot of optimal λ_n versus B_{max} in the 2-D case, for the problem defined in equation (5.3). The parameters used in this plot are: $N/R = 15$, $\mu = 1$.

From figures 12 and 13, we observe that for any P_b constraint, the LCS scheme allows a higher call rate than the tightest fixed scheme. For a typical constraint of $P_b \leqslant 10^{-2}$, our scheme can admit approximately 20% more calls into the network than the fixed scheme with $r = 4$ in the linear case or with $R = 7$ in the 2-D case. Note that in the 2-D case, even when the minimum possible reuse factor $R = 3$, our scheme outperforms the fixed scheme more than 10%. Of course, when the reuse factor becomes larger, for example for $R = 19$, the improvement is about 30%. Also, as shown in the figures, for lower blocking probability constraints, the improvement is even greater.

An observation from figures 12 and 13 is that the improvement of the LCS scheme becomes more significant as the value of reuse factor increases. This can be explained as follows. First note that in figures 12 and 13, we keep N/r and N/R fixed, respectively. In the tightest fixed channel allocation scheme, as long as we keep N/r or N/R (the number of channels allocated per cell) fixed, the performance metrics remain unchanged. This is why in each figure, for the tightest fixed allocation scheme, we only have one curve for different values of r (or R), since N/r (or N/R) is kept constant. However, when we increase r (and correspondingly increase N), in the case of the sharing scheme (for the linear case), the price we need to pay for channel mobility $N/r - N/(r+1) = 1/(r(r+1))$ decreases. Hence, the improvement of our sharing scheme over the FCA scheme is also higher.

Another interesting observation in our simulation is that for any given value of R, the optimal tuning parameter N_2 takes on only a few values. For example, in figure 13, $N_2 = 15, 50, 96$ ($N_2/R' = 3, 5, 6$), for the curves of $R = 3, 7, 12$, respectively. That is, the optimal N_2 actually remains constant for each of the corresponding curves. When $R = 19$, $N_2 = 192$ ($N_2/R' = 8$) for B_{max} less than 2.44×10^{-2}, and $N_2 = 96$ ($N_2/R' = 4$) for the remaining portion of the curve. Moreover, if we use $N_2 = 192$ for the entire curve, the performance degradation, in terms of λ_n for a given B_{max}, is less than 2%. In fact, we have observed that the performance metric is insensitive to moderate variations in N_2 around the optimal value. For simplicity, we will use a fixed value of N_2 for each individual curve in the next section.

We next investigate the protocol complexity for those optimum combined LCS schemes obtained for figures 12 and 13. We first estimate the expected number of inter-cell communications used to serve a call arrival, by dividing the total number of sharing requests that have been submitted in simulation to the total number of call arrivals. Here we count all sharing request signals, including those that are not granted. We find that the expected number of sharing requests per call arrival does not exceed 0.2 in all the cases shown in figure 12, or 0.6 for those in figure 13. There is a difference between the linear and 2-D cases because, in the latter, each cell has more adjacent cells, and thus more sharing requests have to be sent. Note that the expected number of sharing requests per call arrival depends on both the traffic load and the combined LCS scheme (N_1, N_2). For a given N_1, N_2 setting, it increases with the traffic load.

We next estimate the expected number of intra-cell channel swappings needed to serve a call arrival, by dividing the total number of channel swappings observed in simulation to the total number of call arrivals. We find that the maximum number of channel swappings per call arrival needed is less than 0.04 for the combined LCS schemes in figure 12, or less than 0.25 for those in figure 13. These results suggest that the computational overhead to implement our protocol is not significant.

5.2. Channel allocation with handoff

In this study, we evaluate the performance of our LCS scheme for the handoff problem by taking into account handoffs in the simulation traffic model. To systematically compare our handoff scheme with the channel reservation scheme, we investigate three design problems. Note that in reality the parameters N_2, K_1, and K_2 in the LCS scheme can only be optimized according to one design criterion, and that generally the optimal parameters for one problem may not be optimal for another. The reason that we provide comparisons for three optimization problems is to evaluate our scheme under a variety of design criteria. In the interest of saving space, we provide only simulation results for the 2-D case.

Minimum blocking probability of new calls

Here we provide plots of P_{bN} under varying load conditions for the LCS and reservation schemes. The performance measures depend on the parameters N_2, K_1, and K_2 in the LCS scheme, and the parameter K in the reservation scheme. To meaningfully compare our combined scheme with the reservation scheme, we determine the optimal values of P_{bN} for the two schemes, given a constraint on P_{bH}. Here, for simplicity, we use a fixed value of N_2 in the LCS scheme for a given reuse factor. Therefore, in the LCS scheme, to appropriately choose K_1 and K_2, we consider the following optimization problem:

$$\begin{aligned} &\underset{K_1,K_2}{\text{minimize}}\ \ P_{\mathrm{bN}} \\ &\text{subject to } P_{\mathrm{bH}} \leqslant H_{\max}, \end{aligned} \tag{5.4}$$

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 variables are now replaced with the threshold parameter K. For a fair comparison of the LCS scheme with the reservation scheme, we calculate the optimal values of P_{bN} for the two schemes, given the same $H_{\max}$.

Figure 14 shows plots of the optimal values of P_{bN} for the reservation and LCS schemes under varying λ_{n}. For this figure we use the following parameters: $\lambda_{\mathrm{H}} = 5$, $\mu = 1$, $N/R = 15$, (for example $N = 45$ when $R = 3$), and $N_2 = 30, 90, 144, 264$, for $R = 3, 7, 12, 19$, respectively. The call handoff blocking probability P_{bH} is constrained by $H_{\max} = 10^{-4}$, a typical value. The new arrival rate λ_{n} ranges from 6 to 11. From the figure, we can see that these traffic loads are, in fact, quite heavy for the channel reservation scheme, because in order to meet the QoS constraint of P_{bH}, the threshold K must be set sufficiently low, thus resulting in fairly high new call blocking probability ($P_{\mathrm{bN}} > 10^{-1}$ for the whole range of λ_{n} in the figure). Figure 14 shows that the combined LCS scheme achieves uniformly lower values of P_{bN} than the reservation scheme. We also notice that at low traffic load, there is virtually no new call blocking for the LCS scheme. To provide some insight into the optimization, in table 1 we list the set of K_1 and K_2 data that were used to generate the curve for $R = 7$ in figure 14.

Table 1
Optimal K_1, K_2 used for the curve of $R = 7$ in figure 14.

λ_{n}	6	7	7.5	8	9	10	11
K_1	24	24	24	24	10	9	8
K_2	3	3	2	2	2	2	2

Note that in figure 14, some of the curves for the LCS scheme do not start from $\lambda_{\mathrm{n}} = 6$. The reason is that when λ_{n} is low, P_{bN} is too small to be estimated accurately in our simulation. The same applies to figure 15.

Maximum call arrival rate

In this experiment, we compare the maximum new call arrival rate λ_{n} that can be admitted by the LCS and the reservation schemes for various handoff blocking probabilities P_{bH}. More precisely, we define the following opti-

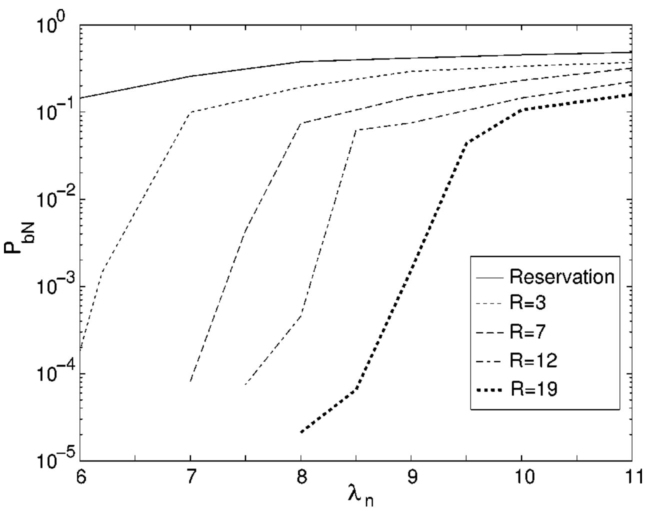

Figure 14. Plot of optimal P_{bN} versus λ_{n} for the problem defined in equation (5.4). The parameters used in this plot are: $N/R = 15$, $\lambda_{\mathrm{H}} = 5$, $\mu = 1$, $H_{\max} = 10^{-4}$.

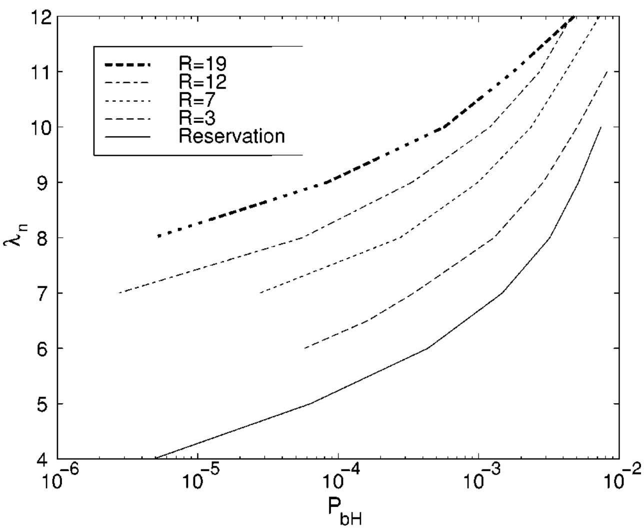

Figure 15. Plot of optimal λ_{n} versus P_{bH} for the problem defined in equation (5.5). The parameters in this figure are: $N/R = 15$, $\lambda_{\mathrm{H}} = 5$, $\mu = 1$, $N_{\max} = 10^{-2}$.

mization problem for the LCS scheme:

$$\begin{aligned} &\underset{K_1,K_2,\lambda_n}{\text{maximize}}\ \lambda_n \\ &\text{subject to } P_{bN} \leqslant N_{max},\ P_{bH} = H. \end{aligned} \tag{5.5}$$

Here, the constraint H for P_{bH} is varied between 10^{-6} and 10^{-2} and the corresponding maximum value of λ_n is obtained. Again, a similar optimization problem is defined for the reservation scheme by replacing K_1, and K_2 by K. In figure 15, we plot the optimal values of λ_n versus P_{bH} for the LCS scheme and the reservation scheme scheme with $R = 3$, 7, 12, and 19. For this figure we use the following parameters: $\lambda_H = 5$, $\mu = 1$, $N/R = 15$, $N_{max} = 10^{-2}$, and $N_2 = 30, 70, 144, 264$, for $R = 3, 7, 12, 19$, respectively. We observe that the LCS scheme allows a higher new call rate than the reservation scheme over all values of P_{bH}. For a typical value of $P_{bH} = 10^{-4}$, the LCS scheme with $R = 19$ can admit approximately 64% more calls into the network than the reservation scheme. For the same P_{bH} constraint, the performance improvement for the LCS scheme is about 50% when $R = 7$, a typical reuse factor value, and is 20% when $R = 3$, the minimum possible value. As is also shown in the figure, for lower handoff probability constraints, this difference is even larger. Improving the admissible arrival rate results in increased revenue for the network provider.

Maximum utilization

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

$$\gamma = \frac{\text{average number of users in one cell}}{\text{total number of available channels in one cell}}, \tag{5.6}$$

where the total number of available channels in one cell is N/R. The parameter γ is directly related to the revenue of a cellular network because it incorporates both new and handoff calls.

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

$$\begin{aligned} &\underset{K_1,K_2}{\text{maximize}}\ \gamma \\ &\text{subject to } P_{bH} \leqslant H_{max}. \end{aligned} \tag{5.7}$$

Once again, we define a similar optimization problem for the reservation scheme by replacing the decisions variables by K.

In figure 16, we plot values of γ under varying λ_n. The parameters used for this figure are: $\lambda_H = 5$, $\mu = 1$, $N/R = 15$, $H_{max} = 10^{-4}$, and $N_2 = 30, 90, 144, 264$, for $R = 3, 7, 12, 19$, respectively. The LCS scheme achieves uniformly higher values of γ under various loads. The difference between the combined 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 γ. On the other hand, due to channel sharing,

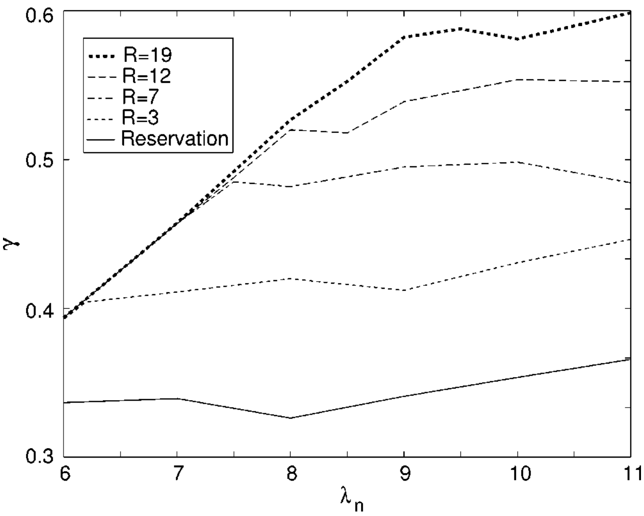

Figure 16. Plot of optimal γ versus λ_n for the problem defined in equation (5.7). The parameters used in this figure are: $N/R = 15$, $\lambda_H = 5$, $\mu = 1$, $H_{max} = 10^{-4}$.

the threshold to maintain the QoS constraint on P_{bH} is not as low. When $R = 19$, the channel utilization for the LCS scheme at high loads is over 64% more than the reservation scheme. The performance improvement for the LCS scheme is about 33% for $R = 7$, a typical reuse factor value, and is 22% for $R = 3$, the minimum possible value.

5.3. Sharing requests across more than one cell

So far, in all of the simulation results shown (sections 5.1 and 5.2), when a sharing request is received from an adjacent cell, if the request cannot be granted, it is simply rejected. In other words the sharing request is allowed to *propagate only one step*. However, as we have discussed earlier in sections 2.1 and 3.1.2, to further exploit the advantage of channel sharing, we could allow sharing requests to propagate across more than one cell. Clearly, increasing the number of propagation steps will improve performance at the cost of increased complexity (due to more sharing requests that need to be processed, etc.).

We next quantitatively investigate the performance improvement as more propagation steps are allowed for sharing. For simplicity, we consider the case without handoffs, as in section 5.1. We define the following optimization problem for the LCS scheme, similarly to that in section 5.1 (equation (5.3)):

$$\begin{aligned} &\underset{\lambda_n,N_2}{\text{maximize}}\ \lambda_n \\ &\text{subject to } P_b \leqslant B_{max}, \\ &\qquad \text{number of propagation steps} \leqslant S_{max}. \end{aligned} \tag{5.8}$$

For illustration, we show the results for the linear case with $r = 4$ in figure 17. For this figure, we use the following parameters: $B_{max} = 10^{-2}$, $\mu = 1$, $N/r = 15$. The constraint S_{max} is allowed to vary from 0 to 12 in our simulation, where $S_{max} = 0$ represents the case when

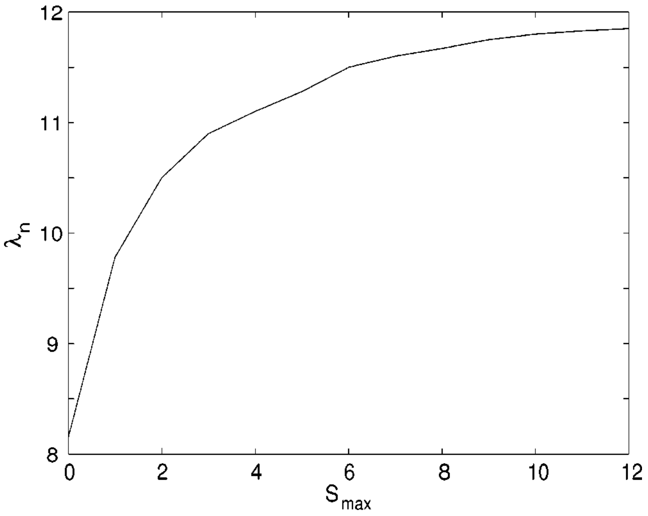

Figure 17. Plot of optimal λ_n versus $S_{\max}$ in the linear case, for the problem defined in equation (5.8). The parameters used in this plot are: $N/r = 15,\ B_{\max} = 10^{-2},\ \mu = 1$.

no sharing is allowed, i.e., the fixed channel assignment scheme. In figure 17, we plot the optimal values of λ_n versus $S_{\max}$. As expected, for a given constraint of blocking probability, the maximum admissible arrival rate increases as more propagation steps are allowed. The improvement is most significant when the value of $S_{\max}$ is small, but it reaches a point of diminishing returns around $S_{\max} = 6$. Hence, depending on the allowable implementation complexity and latency, one could conceive of improving the performance by increasing the maximum allowable propagation steps, although only a small increase would be justified.

6. Conclusion

We have presented a novel LCS scheme to improve system capacity and QoS in wireless cellular systems. Our basic idea is to allow channels to be shared between adjacent cells without co-channel coordination with other cells. For this purpose, we introduce the concept of meta-cells to facilitate localized channel management. Further, to maximize channel reuse efficiency, we develop a channel assignment method based on the distance measure between meta-cells. We then illustrate our channel assignment for both the linear and 2-D hexagonal cellular models. In general, the LCS scheme leads to channel access in a statistical multiplexed fashion, but at the expense of some nominal capacity. An attractive feature of the LCS scheme is that it does not require complex power control techniques, global channel coordination, or on-line optimization, which simplifies its implementation.

To make the LCS scheme practically useful, we then propose two important refinements, which provide useful design parameters to maximize system performance under various QoS constraints. Via simulation, we compare the LCS scheme with the fixed channel assignment scheme (for channel assignment considerations) and the channel reservation scheme (for handoff considerations). Simulation results show that our scheme significantly improves system capacity over a large range of traffic conditions and a variety of QoS requirements, in some cases resulting in over 60% better network utilization than the channel reservation scheme (in the 2-D hexagonal case).

References

[1] Y. Akaiwa and H. Andoh, Channel segregation – a self organized dynamic allocation method: application to TDMA/FDMA microcellular system, IEEE Journal on Selected Areas in Communications 11 (1993) 949–954.

[2] M.-L. Cheng and J.-I. Chuang, Performance evaluation of distributed measurement-based dynamic channel assignment in local wireless communications, IEEE Journal on Selected Areas in Communications 14 (May 1996) 698–710.

[3] T.-P. Chu and S. Rappaport, Generalized fixed channel assignment in microcellular communication system, IEEE Transactions on Vehicle Technology 43 (August 1994) 713–721.

[4] D. Cox and D. Reudink, Dynamic channel assignment in high-capacity mobile communication systems, Bell System Technical Journal 50 (1971) 1833–1857.

[5] D. Cox and D. Reudink, Dynamic channel assignment in two dimension large-scale mobile radio systems, Bell System Technical Journal 51 (1972) 1611–1628.

[6] D. Goodman, J. Grandhi and A. Sudheer, Distributed channel assignment schemes, in: *Proc. IEEE Vehicle Technology Conference* (1993) pp. 532–535.

[7] D. Hong and S. Rappaport, Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and non-prioritized handoff procedures, IEEE Transactions on Vehicle Technology 35 (1986) 77–92.

[8] C.-L. I and P.-H. Chao, Local packing – distributed dynamic channel allocation at cellular base station, in: *Proc. IEEE GLOBECOM* (1993).

[9] J.W.C. Jakes, *Microwave Mobile Communications* (Wiley, New York, 1974).

[10] H. Jiang and S. Rappaport, CBWL: A new channel assignment and sharing method for cellular communication systems, IEEE Transactions on Vehicle Technology 43 (May 1994) 313–322.

[11] H. Jiang and S. Rappaport, Handoff analysis for CBWL schemes in cellular communications, in: *Proc. IEEE International Conference on Universal Personal Communications, ICUPC'94* (1994) pp. 496–500.

[12] H. Jiang and S. Rappaport, Hybrid CBWL and directed retry in cellular communications, in: *Proc. IEEE Vehicle Technology Conference* (1996) pp. 716–720.

[13] I. Katzela and M. Naghshineh, Channel assignment schemes for cellular mobile telecommunication systems: a comprehensive survey, IEEE Personal Communications Magazine (June 1996) 10–31.

[14] S. Kuek and W. Wong, Ordered dynamic channel assignment scheme with reassignment in highway microcells, IEEE Transactions on Vehicle Technology 41(3) (1992) 271–276.

[15] W. Lee, *Mobile Cellular Communication Systems* (Wiley, New York, 1989).

[16] J. Li, N. Shroff and E. Chong, Channel carrying: a novel handoff scheme for mobile cellular networks, in: *Proc. IEEE INFOCOM* (1997) pp. 909–917.

[17] J. Li, N.B. Shroff and E.K.P. Chong, A new localized channel sharing scheme for cellular networks, Technical report, Purdue University, West Lafayette, IN (June 1998).

[18] S. Oh and D. Tcha, Prioritized channel assignment in a cellular radio networks, IEEE Transactions on Communications 40 (1992) 1259–1269.

[19] K. Okada and F. Kubota, A proposal of a dynamic channel assignment strategy with information of moving directions, IEICE Transactions on Fundamentals 75-a (1992) 1667–1673.

[20] R. Ramjee, R. Nagarajan and D. Towsley, On optimal call admission control in cellular networks, in: *Proc. IEEE INFOCOM* (1996) pp. 43–50.

[21] G. Senarath and D. Everitt, Performance of handover priority and queueing systems under different handoff request strategies for microcellular mobile communication systems, in: *Proc. IEEE Vehicle Technology Conference* (1995) pp. 897–901.

[22] S. Tekinay and B. Jabbari, Handover and channel assignment in mobile cellular networks, IEEE Communications Magazine (November 1991) 42–46.

[23] C. Yoon and C. Un, Performance of personal portable radio telephone systems with and without guard channels, IEEE Journal on Selected Areas in Communications 11 (1993) 911–917.

[24] M. Zhang and T.-S. Yum, Comparisons of channel-assignment strategies in cellular mobile telephone systems, IEEE Transactions on Vehicle Technology 38 (1989) 211–215.

[25] M. Zhang and T.-S. Yum, The non-unifrom compact pattern allocation algorithm for cellular mobile systems, IEEE Transactions on Vehicle Technology 40 (1991) 387–391.

Junyi Li received the B.S. degree and M.S.E.E. degrees from Shanghai Jiao Tong University, China. His M.S. thesis “Intelligent Predictive Control” was awarded the 1991 Best Science and Technology Papers of Shanghai Young Scholars Under the Age of 35 Prize. From 1991 to 1994, he was an Assistant Professor in the Department of Automatic Control at Shanghai Jiao Tong University. In 1998, he received a Ph.D. degree in electrical and computer engineering from Purdue University, and has been working in Digital Communications Research at Bell Labs, Lucent Technologies, Holmdel, NJ, since February 1998.
E-mail: junyi@dnrc.bell-labs.com

Ness B. Shroff received the B.S. degree from the University of Southern California, the M.S.E. degree from the University of Pennsylvania, and the M.Phil and Ph.D. degrees from Columbia University. He is currently an Assistant Professor in the School of Electrical and Computer Engineering at Purdue University. During his doctoral study Dr. Shroff worked at AT&T Bell Labs (1991) and Bell Communications Research (1992), on problems involving fault management in telephone networks. His current research interests are in high speed broadband and wireless communication networks. He is especially interested in studying issues related to performance modeling and analysis, routing, network management, scheduling, and control in such networks. Dr. Shroff has received research and equipment grants to conduct fundamental work in broadband and wireless networks, and source coding from the National Science Foundation, AT&T, Hewlett Packard, Intel, LG Electronics, and the Purdue Research Foundation. He received the NSF CAREER Award from the National Science Foundation in 1996. Dr. Shroff has served on the technical program committees of various conferences and on NSF review panels. He is the Program Chair for the 14th Annual IEEE Computer Communications Workshop (CCW) to be held in October 1999.
E-mail: shroff@ecn.purdue.edu

Edwin K.P. Chong joined the School of Electrical and Computer Engineering at Purdue University in 1991, where he is currently an Associate Professor. He received the B.E. (Hons.) degree with First Class Honors from the University of Adelaide, South Australia, in 1987; and the M.A. and Ph.D. degrees in 1989 and 1991, respectively, both from Princeton University, where he held an IBM Fellowship. He received the NSF CAREER Award in 1995 and the ASEE Frederick Emmons Terman Award in 1998. He is a Senior Member of IEEE, and is chairman of the IEEE Control Systems Society Technical Committee on Control Theory and the Working Group on Discrete Event Systems. He has served on the editorial board of the IEEE Transactions on Automatic Control, and on various conference committees. His current interests are in communication networks and optimization methods. He spent a sabbatical at Bell Laboratories, Holmdel, in the fall of 1998. He co-authored a recent book entitled An Introduction to Optimization (Wiley-Interscience, 1996).
E-mail: echong@ecn.purdue.edu