# Chapter 14
# Channel Assignment Techniques

There are many methods of allocating a channel upon a new call arrival or handoff attempt. A good channel allocation algorithm is the one that yields high spectral efficiency for a specified grade of service (including link quality, probability of new call blocking, and the probability of forced termination) and given degree of computational complexity. It also keeps the planned cell boundaries intact, allocates a channel to a MS quickly, maintains the best service quality for the MS at any instant, and relieves undesired network congestion. As shown in Fig. 14.1, there are three basic types of channel assignment algorithms, fixed, flexible, and dynamic [317].

Fixed channel assignment (FCA) was used by first generation macrocellular systems where disjoint subsets of the available channels are permanently allocated to the cells in advance according to their *estimated* traffic loads. The cells are arranged in tessellating reuse clusters whose size is determined by the co-channel reuse constraint.

FCA provides adequate capacity performance in macrocellular systems that are characterized by stationary and homogeneous traffic, and a predictable propagation environment. In this case the channel resources can be allocated statically, since the call blocking probabilities can be predicted with reasonable certainty. Under conditions of non-stationary and nonhomogeneous traffic, however, FCA is spectrally inefficient because the channels are literally fixed to the cells. A new call or handoff arrival that finds all channels busy in a cell will be blocked even though there may be several idle channels in the adjacent cells that could service the call. These blocking probabilities can be reduced by using various schemes that borrow channels from neighboring cells. The most basic scheme is simple borrowing, where a MS can be allocated a channel from a neighboring cell, provided that it does not degrade the link quality of other calls by introducing excessive co-channel interference. Once a channel is borrowed, all other cells that are within the co-channel reuse distance are prohibited from using the channel. The efficiency of this borrowing strategy tends to degrade in heavy traffic and the channel utilization is worse than FCA. This problem can be partially solved by using a hybrid channel assignment scheme, where the channels assigned to a cell are divided into two groups: the channels in one group are owned by the cell, while the channels in the other group may be borrowed. There are several variations of this theme. The ratio of the number of owned-to-borrowable channels can be dynamically varied to compensate for traffic changes.

In microcellular systems the propagation environment is highly erratic, and the traffic is characterized by spatial and temporal variations. Furthermore, the decreased cell sizes imply an increase in handoff traffic, since a call may be handed off several times before its natural completion. Because of these properties, the channel assignment problem in microcellular and macrocellular networks is fundamentally different. The uneven nature of the traffic and the larger volume of handoff attempts in microcellular networks demand careful attention. Furthermore, a microcellular channel assignment strategy has to be fast, because the handoffs must be serviced quickly due to the small cell sizes and propagation anomalies such as the street corner effect.

Dynamic channel assignment (DCA) is one well-known solution to the microcellular channel assignment problem, where the dynamic nature of the strategy permits adaptation to spatial and temporal traffic variations while the distribution of control reduces the required computation and communication among base stations (BSs), thereby reducing system latencies. DCA schemes have no exclusive relationship between cells and channels, and in their most general form they allow any cell to use any channel that does not violate the co-channel reuse constraint. DCA schemes are known to outperform FCA under conditions of light non-stationary traffic. However, under conditions of heavy traffic FCA usually provides better performance, because the DCA schemes often yield an inefficient arrangement of channels. Although DCA has clear benefits, the cost can be quite high because it not only requires increased computation and communication among BSs but also an increased number of radio ports at the BSs; in the extreme case each BS must have the ability to use all channels simultaneously.
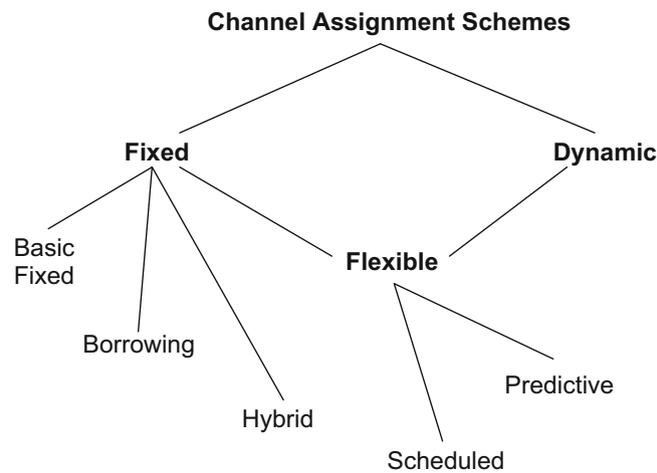
**Channel Assignment Schemes**



**Fig. 14.1** Basic classifications of channel assignment schemes, from [317]

Practical DCA schemes differ in degree of network planning and the required communication among BSs. Centralized DCA schemes require centralized control with system-wide channel information. The extreme example is maximum packing (MP) [117], where a new call or handoff arrival is blocked only if there is no global rearrangement of calls to channels that will accommodate the service need. Unfortunately, the enormous computation and communication among cells render centralized DCA schemes impractical. In fact, the number of channel rearrangements required between two subsequent arrivals in a two-dimensional network with MP can increase without bound with the number of cells in the network [281].

Fully decentralized DCA schemes are the other extreme and require no network planning or communication among BSs [11, 120, 253]. These schemes are ideal for cordless telephone systems that use MCHO, such as DECT. They often rely upon the passive monitoring of idle channels at each BS, allowing the cells to acquire any idle channel that is deemed to provide a sufficient carrier-to-interference ratio (C/I).

Decentralized DCA schemes require limited communication among local clusters of BSs. One DCA scheme is dynamic resource acquisition (DRA) [240]. With DRA, the channel (or carrier) that is acquired due to a new call arrival or handoff is chosen to minimize a cost function, and the channel (or carrier) that is released due a call completion or handoff is chosen to maximize a reward function. The cost and reward functions can be selected to maximize the spectral efficiency of the cellular network for a specified grade of service. The computation of the cost and reward functions for a given cell depends on the usages of the channels (or carriers) in the set of surrounding cells called the DRA neighborhood [240]. Another distributed DCA scheme is simple dynamic channel assignment (SDCA) [349]. SDCA performs slightly worse than DRA, but requires communication among a smaller set of cells called the interference neighborhood [349].

Decentralized and fully decentralized schemes are not without their problems. These include service interruption, deadlock, and instability. A service interruption occurs when a channel allocation causes an existing link to fall below the threshold C/I. The interrupted mobile station (MS) then tries to find an alternate link and if unsuccessful a service termination occurs. This is known as deadlock. A sequence of successive interrupts, or rippling effect, caused by channel allocations is called an instability.

DCA schemes also have the advantage of assigning the same channel to a MS moving from one cell to another provided that the level of co-channel interference is tolerable, while FCA must conduct a handoff with a channel change because the same channel is not available in adjacent cells. Handoffs without channel changes are attractive because they can eliminate the need for channel searching and ultimately relieve the BSs from extra computation. More important, this mechanism is essential for supporting macrodiversity TDMA cellular architectures where the signal from a MS can be simultaneously received by two or more BS yielding a diversity improvement against shadow (and fading) variations. Such architectures provide the same benefit as soft handoff in CDMA systems.

Flexible channel assignment algorithms combine aspects of fixed and dynamic channel assignment schemes. Each cell is assigned a fixed set of channels, but a pool of channels is reserved for flexible assignment. The assignment of flexible channels can be either scheduled or predictive [310]. Scheduled assignment schemes rely on known changes in traffic patterns. The flexible channels are assigned to the cells on a scheduled basis to account for these foreseeable changes in traffic patterns. With predictive assignment, the traffic load is continuously or periodically measured at every BS, and the flexible channels are assigned to the cells according to these measurements.

Forced terminations are generally perceived to severely degrade the quality of service. For this reason, handoff priority schemes are usually employed to allocate channels to handoff requests more readily than to new call arrivals. Handoff priority reduces the probability of forced termination at the expense of a (slight) increase in the probability of new call blocking. Practical cellular systems are designed to have a probability of new call blocking less that 5%, with a probability of forced termination perhaps an order of magnitude smaller.

The use of guard channels is one method of achieving handoff priority, where the channels are divided into two groups: one group is for new calls and handoff requests, and the other group is reserved for handoff requests only [169]. Another method is to queue the handoff requests (but not the new call arrivals) [134, 169]. This method can be combined with guard channels.

This chapter is intended to introduce the various approaches to cellular channel assignment. Unfortunately, most channel assignment schemes are quite detailed and founded largely on ad hoc principles. Furthermore, the channel assignment schemes are almost always evaluated by using detailed simulations with a variety of assumptions concerning the mobile radio environment, e.g., cellular topology and reuse factors, traffic patterns, propagation factors, mobility, etc. The combination of these factors makes a systematic comparison of the various DCA schemes largely infeasible and a true consensus of the best scheme cannot be attained. Therefore, some of the many different DCA schemes will be briefly outlined, followed by a detailed evaluation of a few specific schemes that serve to illustrate the basic concepts.

Throughout the chapter various performance measures will be used to evaluate the channel assignment schemes, including the following:

- Probability of new call blocking, $P_b$, defined as

$$P_b = \frac{\text{number of new calls blocked}}{\text{number of new call arrivals}}.$$

- Probability of forced termination, $P_f$, defined as

$$P_f = \frac{\text{number of handoff calls blocked}}{\text{number of handoff attempts}}.$$

- Grade of service, GOS, defined as

$$\text{GOS} = \frac{P_b R_N}{(R_N + R_H)} + \frac{P_f R_H}{(R_N + R_H)}$$

where $R_N$ and $R_H$ are the new call and handoff arrival rates, respectively.
- Channel changing rate, $R_C$, defined as

$$R_C = \frac{\text{number of channel changes}}{\text{number of handoffs}}.$$

The remainder of this chapter begins with an overview of some important DCA schemes. These include the fully centralized maximum packing (MP) and MAXMIN DCA strategies in Sect. 14.1. Decentralized DCA strategies such as First Available (FA), Nearest Neighbor (NN), and dynamic resource acquisition (DRA) are discussed in Sect. 14.2. Fully decentralized DCA schemes are the topic of Sect. 14.3, including Channel Segregation (CS) and Minimum Interference (MI), along with aggressive and timid strategies. Hybrid FCA/DCA schemes are the subject of Sect. 14.4. The important class of borrowing schemes are the topic of Sect. 14.5, including Borrowing with Channel Ordering (BCO), Borrowing with DireCtional Locking (BDCL), and Compact Pattern based DCA (CPDCA). Finally, our overview of DCA schemes wraps up with a treatment of directed retry (DR) and directed handoff (DH), moving direction (MD) strategies, reduced transceiver coverage and reuse partitioning, and handoff priority schemes in Sects. 14.6, 14.7, 14.8 and 14.9 respectively.

Following our results in [349], Sect. 14.10 provides some detailed and instructive examples of distributed DCA schemes for TDMA microcellular systems. In particular, two DCA strategies are presented that accommodate handoff queueing. An aggressive DCA policy with handoff queueing is also considered where a cell may be forced to terminate calls in progress in order to accommodate handoff requests in neighboring cells. The conditions for forced termination are carefully determined to ensure a performance improvement over a timid policy.

## 14.1   Centralized DCA

Centralized DCA schemes require system-wide information and control for making channel assignments. As expected, centralized DCA schemes can theoretically provide the best performance. However, the enormous amount of computation and communication among BSs leads to excessive system latencies and renders centralized DCA schemes impractical. Nevertheless, centralized DCA schemes often provide a useful benchmark to compare the more practical decentralized DCA schemes.

### 14.1.1   Maximum Packing

The maximum packing (MP) algorithm was originally presented by Everitt and Macfadyen in 1983 [116]. With the MP policy a call is blocked only if there is no global rearrangement of calls to channels that will accommodate the call. Accomplishing this task requires a controller with system-wide information along with the ability to perform call rearrangements. The MP policy has the ability to serve all calls in a network with the minimum number of channels. Equipped with the capability, MP can yield the lowest new call blocking and forced termination probabilities of any DCA scheme under any traffic conditions.

Kelly [178] presented an interesting and enlightening analytical approach to MP DCA, by modeling the MP policy as a circuit-switched network. This allows some very powerful and well-known network analysis tools to be applied to the analysis of MP DCA. The analysis ignores situations where the MS is moving from one cell to another or out of the service area, i.e., the handoff and roaming problem. Upon a call arrival in a particular cell, the MP policy checks to see if all reuse clusters that contain that cell have at least one channel available. If so, then the call can be accommodated through channel rearrangements; otherwise, the call is blocked. For example, consider the simple system consisting of five cells shown in Fig. 14.2. In this example, co-channel cells must be separated by at least two cells so there are three reuse clusters: $CL_1 = (1, 2, 3)$, $CL_2 = (2, 3, 4)$, and $CL_3 = (3, 4, 5)$. When a call arrives in cell 2, it can be accommodated if there is at least one channel available in clusters $CL_1$ and $CL_2$.

The stochastic model for MP uses the following definitions:

$$\mathscr{R} = \text{set of cells in the system.}$$

$$K = |\mathscr{R}| = \text{number of cells in the system.}$$

$$N_T = \text{total number of channels available.}$$

$$n_i = \text{number of calls in progress in cell } i.$$

$$\mathbf{n} = (n_i, i \in \mathscr{R}) = \text{state vector.}$$

$$\mathscr{S} = \text{set of admissible states.}$$

$$\rho_i = \text{traffic load in cell } i.$$

The set of admissible states depends on the particular cell layout. Let $J$ be the number of complete or partial reuse clusters $CL_i, i = 1, \ldots, J$ that can be defined such that (1) each reuse cluster differs by at least one cell, i.e., they are not totally overlapping, and (2) all cells are contained in at least one such cluster. For the example in Fig. 14.2, $J = 3$. Now let $\mathbf{A} = [a_{ij}]_{J \times K}$ be the demand matrix, where $a_{ij} = 1$, if $i = j$ and if cell $j$ is in the same cluster as cell $i$; otherwise, $a_{ij} = 0$. For the example in Fig. 14.2

$$\mathbf{A} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix}. \tag{14.1}$$

**Fig. 14.2**  Five cell deployment with maximum packing (MP)

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|

Matrix **A** tabulates the channel requirements for servicing calls that arrive in each of the cells. For example, a call arrival in cell 2 requires that a channel be available in $CL_1$ and $CL_2$ but not in $CL_3$ and, therefore, $a_{1,2} = a_{2,2} = 1$ and $a_{3,2} = 0$. Finally, let $N_i, i = 1, \ldots, J$ be the number of channels that are available in $CL_i$, $N_i \leq N_T$, and $\mathbf{N} = (N_1, \ldots, N_J)$. Then the set of admissible states is then given by

$$\mathscr{S} = \{\mathbf{n} : \mathbf{A}\mathbf{n}^T \leq \mathbf{N}\}. \tag{14.2}$$

It is well known (e.g., [177]) that **n** has the steady-state distribution

$$\pi(\mathbf{n}) = G(\mathbf{N}) \prod_{i \in \mathscr{R}} \frac{\rho_i^{n_i}}{n_i!}, \quad \mathbf{n} \in \mathscr{S} \tag{14.3}$$

where $G(\mathbf{N})$ is the normalizing constant

$$G(\mathbf{N}) = \left( \sum_{\mathbf{n} \in \mathscr{S}} \prod_{i \in \mathscr{R}} \frac{\rho_i^{n_i}}{n_i!} \right)^{-1}. \tag{14.4}$$

Then the steady-state probability that a call arrival in cell $i$ is blocked is

$$B_i = 1 - \frac{G(\mathbf{N})}{G(\mathbf{N} - \mathbf{A}\mathbf{e}_i^T)} \tag{14.5}$$

where $\mathbf{e}_i$ is a length $K$ vector with a "1" at position $i$ and "0" elsewhere. Even though $B_i$ appears to have a compact closed form expression, the computation of $G(\mathbf{N})$ is prohibitive except for very simple cases. Therefore, approximate methods are usually employed. One approximation assumes that the availability of channels in the clusters $CL_i$ are *independent* events. This independence assumption leads to

$$B_i \approx 1 - \prod_{j \in CL_i} (1 - E_j) \tag{14.6}$$

where the $E_j, j = 1, \ldots, J$ solve the nonlinear equations

$$E_j = E \left( \sum_{r \in \mathscr{R}} a_{jr} \rho_r \prod_{i \in r - \{j\}} (1 - E_i), N_j \right), \quad j = 1, \ldots, J \tag{14.7}$$

with

$$E(\rho, N) = \frac{\rho^N}{N!} \left( \sum_{n=0}^{N} \frac{\rho^n}{n!} \right)^{-1} \tag{14.8}$$

being the Erlang-B formula. Kelly [178] showed that there is an unique solution to the above nonlinear equations. The intuitive notion behind this approximation is that when $a_{jr} = 1$ the call arrivals of rate $\rho_r$ in cell $r$ are thinned by a factor of $1 - E_i$ by each cluster $CL_i, i \in r - \{j\}$ before being offered to $CL_j$.

### 14.1.2 MAXMIN Scheme

The MAXMIN scheme was introduced by Goodman et al. [145]. With the MAXMIN scheme, a MS is assigned a channel that maximizes the minimum C/I that any MS will experience in the system at the time of assignment. Assuming that the link quality depends on the average received C/I, the C/I of $MS_i$ at its serving BS is

$$\Lambda(\mathbf{d})_{(dB)} = \Omega(d_i)_{(dB)} - 10 \log_{10} \sum_{k \in I} 10^{\Omega(d_k)_{(dB)}/10}. \tag{14.9}$$

where the $\Omega(d_j)_{(dB)}$ are independent Gaussian random variables with the density in (1.5) and (1.6), and $d_j$ is the distance between $MS_j$ and the BS for $MS_i$. The set $I$ consists of all MSs other than $MS_i$ that are using the same channel. A MS that requires service is assigned the channel $j$ that gives

$$\max_{j \in C} \min_{i \in S} \{\Lambda_i\} \qquad\qquad (14.10)$$

where $i$ and $j$ index the set of MSs and channels, respectively, $C$ is the set of channels that are available at the BS corresponding to the MS that requires service, $\Lambda_i$ is the C/I of $MS_i$ at its BS, and $S$ is the set of all MS in service including the MS that requires service. Methods for C/I monitoring have been presented in Sect. 13.8.

## 14.2   Decentralized DCA

### 14.2.1   First Available and Nearest Neighbor

In 1972, Cox and Reudnik [85] proposed four basic decentralized DCA algorithms and compared them to FCA for the case of linear highway macrocells: First Available (FA), Nearest Neighbor (NN), Nearest Neighbor+1 (NN+1), and Mean Square (MSQ). All four schemes allow a BS to acquire any idle channel that is not being used in its interference neighborhood, defined as the set of surrounding cells that can interfere with the BS. The schemes differ in the way that the channel selected should more than one channel be available for acquisition. The FA scheme acquires the first available channel found in the search. Assuming that a channel can be reused $D_N$ cells away without causing excessive co-channel interference, the NN policy acquires the channel that is being used by the nearest BS at distance $D_N$ or greater. The NN+1 policy acquires the channel that is in use at the nearest BS at distance $D_N + 1$ or greater with the goal of allowing more MSs to retain the same channel as they cross cell boundaries. The MSQ policy seeks to assign the available channel that minimizes the mean square of the distances among all BSs using the same channel. The DCA schemes were shown to outperform the FCA schemes in terms of probabilities of new call blocking and forced termination, except under conditions of heavy traffic. Of these four DCA schemes, the NN policy performs the best.

### 14.2.2   Dynamic Resource Acquisition

Nanda and Goodman [240] have proposed a distributed DCA strategy called dynamic resource acquisition (DRA). When a channel must be selected for acquisition or release by a BS, DRA calculates a reward/cost function for each channel. The reward associated with a channel release is the number of cells in the interference neighborhood of the BS that could acquire the channel after it is released. When a channel is released, the busy channel giving the largest reward is selected. Channel rearrangements may be required to do this. The cost associated with a channel acquisition is the number of cells in the interference neighborhood of the BS that would be deprived from using the acquired channel. When a channel is acquired, the available channel having the smallest cost is selected. In the event of a tie in the reward/cost function, the released/acquired channel is chosen randomly.

As described in [240], the calculation of the reward/cost function requires channel usage information from all the cells within the DRA neighborhood of a BS. The DRA neighborhood of a BS is the set of cells whose interference neighborhoods overlap with the interference neighborhood of that BS. Any cell outside the DRA neighborhood of a BS will not affect the calculation of the reward/cost function associated with that BS. Figure 14.3 illustrates the reward/cost functions associated with three carriers for a 2-D grid of square cells. The cell under consideration is shaded black. In case of a carrier acquisition, Channel 2 would be selected by the given BS since it has the smallest cost. Channel 3 could not be selected, because it would violate the co-channel reuse constraint. If Channels 1 and 2 are active in the given cell and a carrier is to be released, then Channel 1 would be selected since it gives the largest reward.
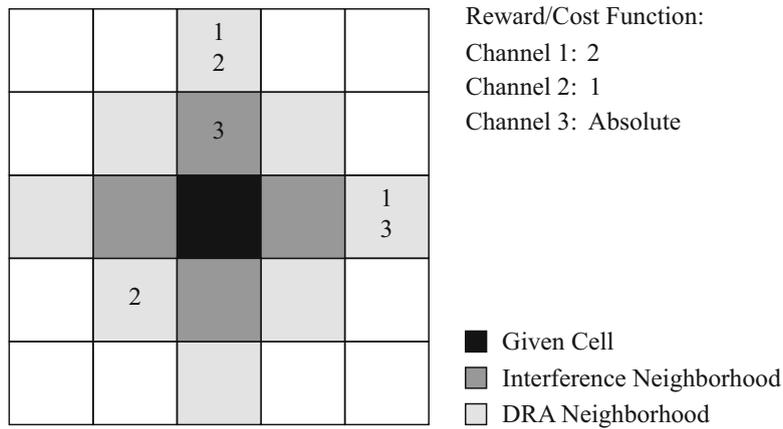
**Fig. 14.3** The DRA (*light shaded*) and interference (*dark shaded*) neighborhoods of a cell under consideration (*shaded black*). The numbers within each cell indicate active channels

## 14.3  Fully Decentralized DCA

### 14.3.1  Channel Segregation

Akaiwa and Andoh [12] proposed a distributed adaptive self-organizing DCA strategy whereby the BSs use Channel Segregation (CS) to develop *favorite* channels through an evolutionary process that is based on the criteria of eliminating unnecessary interference. Their scheme has been developed for TDMA systems with the assumption that each BS can access any channel by tuning a carrier frequency and selecting a time slot. CS also accounts for the effect of unaccessible channels where a call can be blocked in a cell even when there are idle channels because of the restriction placed on the number of different carrier frequencies that may be simultaneously used, i.e., the BS has a finite number of radio ports each of which can be tuned to only one frequency.

A flowchart of the CS algorithm is shown in Fig. 14.4. Each BS ranks the channels according to a priority function $P(i)$, where a large $P(i)$ corresponds to a high priority, e.g., in [12] $P(i) = N_s/N_t$, where $N_s$ is the number of successful uses of the channel plus the number of accesses to the channel when it is idle but unaccessible, and $N_t$ is the total number of trials for the channel. When a call arrives, the BS senses the highest priority channel from the list of channels it is not currently using. If the channel is sensed idle, then the channel is checked for accessibility. If accessible, it is acquired and its priority is increased; otherwise, its priority is increased and the BS recursively senses the next highest priority channel that it is not currently using. If all channels are sensed busy, then the call is blocked. Akaiwa and Andoh [12] demonstrated by simulation that the CS policy outperforms FCA and the FA DCA algorithm.

The steps within the dashed box in Fig. 14.4 are a modification so that the original CS algorithm developed by Akaiwa [11] for FDMA systems can be applied to TDMA systems. Simulation results show that this modification achieves the goal of gathering channels with the highest priorities onto the same carrier frequency, thus reducing the probability of call blocking due to the unavailability of a BS transceiver.

### 14.3.2  Channel Segregation with Variable Threshold

Another Channel Segregation scheme has been proposed by Hanabe et al. [157] that uses prioritized orderings with a variable interference threshold. The channels are ranked from highest to lowest according to their priority values. Each BS measures the interference levels of its currently unused channels. For each channel, the priority value is decreased if the interference level is higher than a predefined threshold and the threshold for that channel is decreased. Likewise, the priority value is increased if the interference level is lower than a predefined threshold and the threshold for that channel is increased. Hanabe et al. do not clearly define their priority function. However, it is likely that the priority function is defined as the ratio of number of times that the interference level of a channel is less than the threshold to the total number of times the channel is sensed. The interference threshold is varied depending on the ranking of the channel in the priority list. For example, the particular threshold that Hanabe et al. proposed is as follows:
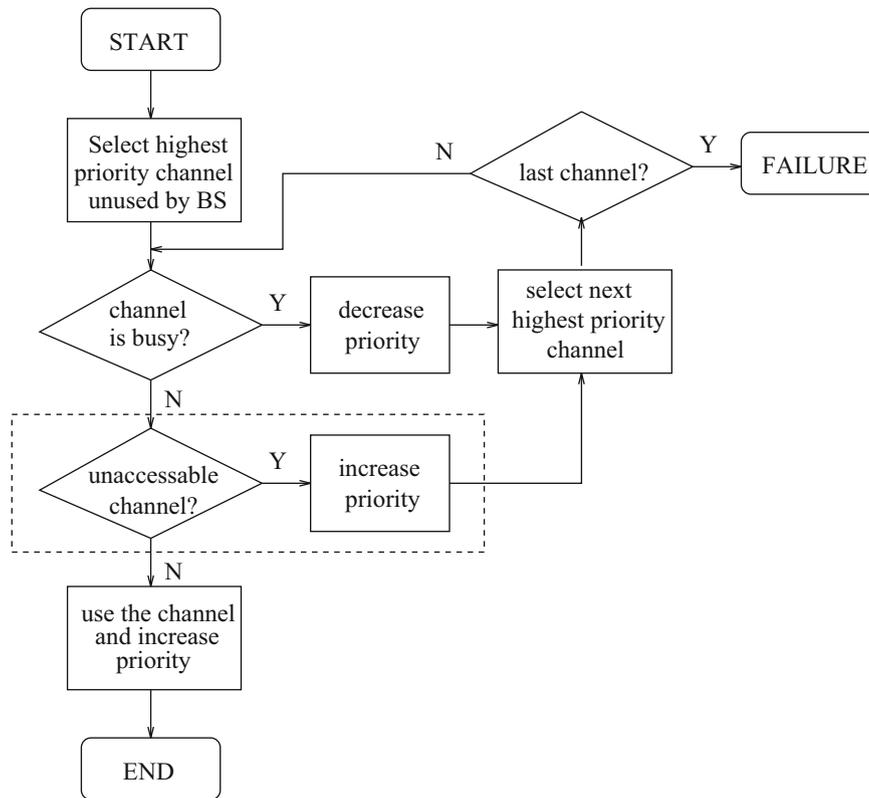
**Fig. 14.4** Channel segregation (CS) algorithm

$$T(k) = \begin{cases} T_o + 15 + S, & k = 1, 2, \ldots N_1 \\ T_o + 10 + S, & k = 9, 10, \ldots N_2 \\ T_o + 5 + S, & k = 17, 18, \ldots N_3 \end{cases} . \tag{14.11}$$

For the example in [157], $N_1 = 8$, $N_2 = 16$, and $N_3 = 72$, where $N_3$ is the total number of channels in the system, $T(k)$ is the threshold, $T_o$ is the minimum required C/I, and $S$ is a constant margin. Upon call arrival, the highest priority idle channel that meets the C/I threshold is chosen. If no suitable channels are available, the call is blocked. If the C/I drops below the required level during a call, a handoff procedure is initiated. In Hanabe et al.'s scheme, handoffs are not prioritized and are treated the same as new call arrivals.

The rationale for using a variable threshold $T(k)$ for each channel in (14.11) can be answered by examining the case where the thresholds are fixed. Allocation of a high priority channel with a fixed threshold is more likely to cause interference since the C/I thresholds for all channels are the same. The reason is that a higher priority channel will be acquired over a lower priority channel if both channels exceed the C/I threshold, regardless of whether or not a lower priority channel would cause less interference to neighboring cells. Thus the allocation of the higher priority channel may cause service interruptions, deadlocks, and instability. For the case of a variable threshold, a higher threshold is assigned to higher priority channels to reduce the probability of co-channel interference, and a lower threshold is assigned to lower priority channels to decrease the probability of blocking.

### 14.3.3 Minimum Interference Schemes

Schemes based on Minimum Interference (MI) have been presented by Goodman et al. [145]. The basic MI scheme has been incorporated into the CT-2 and DECT systems. With these schemes, the MS signals the BS with the strongest paging signal for a channel. The BS measures the interference level on all channels that it is not already using. The MS is then assigned the channel with the Minimum Interference. This policy coupled with mobile controlled handoff (MCHO) guarantees

good performance. Variations of the MI scheme have been proposed that differ in the order in which MSs are assigned channels. These include Random Minimum Interference (RMI), RMI with Reassignment (RMIR), and Sequential Minimum Interference (SMI). The RMI scheme serves calls in the order that they arrive. The RMIR scheme serves the call requests according to the RMI scheme, but afterwards each MS is reassigned according to the MI policy. The order of reassignments is random. Those MSs initially denied service try again to acquire a channel. The procedure is repeated a fixed number of times. The SMI algorithm assigns channels according to the MI scheme but in a sequential order. In [145] linear microcells are considered and the sequence that is followed is to serve a MS only after all MS to its left have had a chance to be served. This, however, requires some co-ordination between BSs and the extension to 2-D schemes is not obvious. Goodman et al. [145] showed that the probability of blocking decreases with FCA, RMI, RMIR, SMI, in that order.

### 14.3.4 Aggressive and Timid DCA Strategies

Distributed self-organizing DCA algorithms that use aggressive and timid strategies were first introduced by Cimini and Foshini [67]. These simple autonomous DCA algorithms can self-organize with little loss in capacity compared to the best globally coordinated channel selection algorithm. In their paper, two classes of algorithms were studied: timid where a MS acquires a channel only if the channel is free of interference, and aggressive where a MS can acquire a channel even if it is not free of interference. The studies in [67] showed that a linear array of cells could self-organize its placement of a single channel to saturate the array from random starting arrangements. An array is saturated when no additional cells can use a channel without violating the co-channel reuse constraint. Channel usage in the array organizes itself according to the DCA policy. The performance of the algorithm is measured in terms of the saturation density, defined as the ratio of the number of cells using a particular channel to the number of cells in the array. Timid algorithms which require no call rearrangements have been shown to have saturation densities that compare favorably with FCA, while the aggressive algorithms have higher saturation densities at the expense of some instability. This is due to a simulated annealing mechanism where an instability perturbs a system so as to escape a local optimum in an attempt to reach the global optimum.

The saturation densities can be derived for the case of linear and hexagonal planar cells with $R$-cell buffering.[1] For linear cells, the maximum and minimum saturation densities are $C_{\max} = 1/(R+1)$ and $C_{\min} = 1/(2R+1)$. The saturation density can also be obtained for the random placement of a channel in a linear array. In this case, cells sequentially acquire the channel; the next cell to acquire the channel is chosen uniformly from those cells not already using the channel that could use the channel without violating the co-channel reuse constraint. The derivation of the saturation density in this case is quite lengthy but leads to the result [69]

$$C_{\text{ran}} = \int_0^1 \exp\left\{2\sum_{i=0}^{R-1} \frac{(v^{i+1}-1)}{i+1}\right\} dv. \tag{14.12}$$

The saturation density can also be obtained as a function of the traffic load $\rho$ as [69]

$$C(\rho)\,(1 - C(\rho)R)^R = \rho\,(1 - (R+1)C(\rho))^{R+1} \tag{14.13}$$

which has a unique solution in the interval $0 < C(\rho) < 1/(R+1)$. For hexagonal planar cells the minimum and maximum saturation densities are

$$C_{\min} = \frac{1}{1 + 3R(R+1)} \tag{14.14}$$

$$C_{\max} = \begin{cases} \frac{4}{3(R+1)^2} & , \quad R \text{ even} \\ \frac{4}{1+3(R+1)^2} & , \quad R \text{ odd} \end{cases}. \tag{14.15}$$

However, expressions for $C_{\text{ran}}$ and $C(\rho)$ for the hexagonal planar array are unknown.

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[1]The reuse factor $N$ is related to the number of buffer rings $R$ as follows. For linear cells $N = R + 1$. For hexagonal planar cells, $N = i^2 + ij + j^2$, where for $R$ odd $i = j = (R+1)/2$, and for $R$ even $i = R/2$ and $j = R/2 + 1$.

**Table 14.1** Normalized channel utilizations $\delta = C_{\mathrm{ran}}/C_{\max}$ for the timid DCA algorithm, from [68]

| $R$ | Linear | Planar hexagonal |
|---|---|---|
| 1 | 0.864 | 0.693 |
| 2 | 0.825 | 0.658 |
| 3 | 0.804 | 0.627 |

For the case of a single channel the blocking probability has the exact form [69]

$$P_b = 1 - C(\rho)/\rho. \tag{14.16}$$

For the case of multiple channels, Cimini et al. have derived a very accurate approximation for the call blocking performance of timid algorithms. They also derived lower bounds on the call blocking performance of aggressive algorithms [68]. If a total of $N_T$ channels are available, the effective number of channels available for use in a reuse cluster of size $N$ is $\delta N$, where $\delta$ is called the normalized channel utilization defined as the saturation density that is achieved with a particular algorithm $C$ to the maximum possible saturation density $C_{\max}$. Values for $\delta$ are tabulated in Table 14.1. For FCA, each cell has $m = N_T/N$ available channels and the blocking probability can be obtained from the Erlang-B formula $P_b = E(\rho, m)$ in (14.8), where $\rho$ is the traffic load per cell. For the case of the timed algorithm a call is blocked if all channels are use in the interference neighborhood. To approximate the blocking probability for the timid algorithm, $\rho$ is replaced by $N\rho$ and $m$ by $\delta N_T$, i.e., $P_b = E(N\rho, \delta N_T)$. To lower bound the blocking probability with an aggressive algorithm, $\rho$ is replaced by $N\rho$ as before, and $m$ by $N_T$ ($\delta = 1$), so that $P_b > E(N\rho, N_T)$. The performance of a practical aggressive algorithm will lie somewhere between the timid algorithm and the aggressive bound. Finally, the blocking probability with an aggressive algorithm includes the calls that are blocked and the calls that are dropped because the aggressive algorithm has taken the channel and another suitable channel cannot be found.

## 14.4 Hybrid FCA/DCA Schemes

DCA schemes perform very well for light non-stationary nonhomogeneous traffic. However, under conditions of uniformly heavy traffic FCA outperforms most of the DCA schemes, except perhaps MP. As a result of this behavior efforts have been directed toward hybrid FCA/DCA schemes that are intended to provide a compromise between FCA and DCA. Cox and Reudink [86] introduced a hybrid scheme, called Dynamic Channel Reassignment (DCR) where each cell is assigned number of fixed channels, while the remaining channels are available for DCA. Fixed channels are used first to accommodate call requests. Calls that cannot be serviced by the fixed channels are offered to the dynamically assigned channels. The dynamic channel that is selected can be obtained by using any of the elementary schemes such as FA, NN, and NN+1. Upon a call completion on a fixed channel, DCR executes a search to determine if a call nominally assigned to a dynamic channel can be reassigned to the newly released fixed channel.

## 14.5 Borrowing Schemes

Engel and Peritsky [109] introduced a FCA scheme with borrowing. The channels that are assigned to each BS are divided into two sets, fixed and borrowable. The fixed channels can only be used by the BS they are assigned to, while the remaining channels can be borrowed by a neighboring BS if necessary. Calls are serviced by using the fixed channels whenever possible. If necessary a channel is borrowed from a neighboring cell to service the call provided that the use of the borrowed channel does not violate the co-channel reuse constraint. The channel is borrowed from the neighboring BS having the largest number of available channels for borrowing. Improvements on this scheme were also proposed by Engel and Peritsky, where a call being serviced by a borrowed channel is transferred to a fixed channel whenever a fixed channel becomes available. The same idea was proposed by Anderson [16]. Scheduled and predictive channel assignment schemes have also been proposed, where the ratio owned to borrowable channels is dynamically varied according to the traffic conditions.
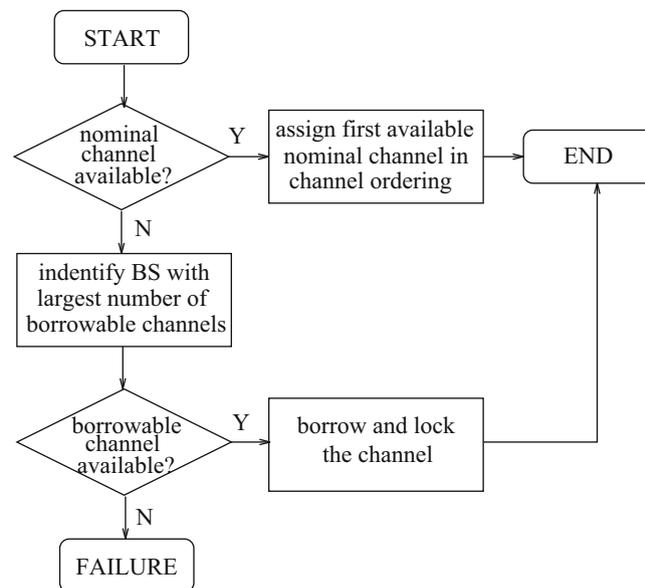
**Fig. 14.5**  Call arrival policy for the BCO algorithm

## 14.5.1  *Borrowing with Channel Ordering*

Elnoubi et al. [108] proposed a channel borrowing strategy that makes use of channel orderings, called Borrowing with Channel Ordering (BCO). A group of channels is initially assigned to each cell according to a fixed channel assignment; these channels are called nominal channels and are arranged in an ordered list. The call arrival policy for BCO is illustrated by the flowchart in Fig. 14.5. Upon a call arrival in a cell, the BS searches for an available nominal channel nearest to the beginning of the channel ordering. If a nominal channel is available it is assigned to the call; otherwise, the BS attempts to borrow a channel from the adjacent cell having the largest number of channels available for borrowing. A channel is available for borrowing if it is unused in the adjacent cell and the other two co-channel cells. To illustrate this point, refer to Fig. 14.7. If cell B1 borrows a channel $c$ from cell $A1$, then cells A1, A2, and A3 are locked from using channel $c$ since their use of channel $c$ will violate the co-channel reuse constraint. Being blocked, channel $c$ can neither be used to service a call in these three cells nor borrowed from these three cells. Finally, when a channel is borrowed from an adjacent cell, the available channel appearing nearest to the end of the channel ordering of the adjacent cell is selected. If no channels are available for borrowing, the call is blocked.

The call departure policy for BCO is illustrated in Fig. 14.6. When a call terminates on a borrowed channel, the borrowed channel is released in the three cells where it is locked. When a call terminates on a nominal channel and there are calls in progress with the same BS on borrowed channels, then the channel that is borrowed from the adjacent cell with the largest number of lent channels is released in the three cells where it is locked and its associated call is reassigned to the newly idle nominal channel. Finally, if a call completes on a nominal channel and there are no calls in progress with the same BS on borrowed channels, the call occupying the nominal channel nearest to the end of the channel ordering is reassigned to the newly idle nominal channel.

Kuek and Wong [187] introduced a DCA scheme called Ordered Dynamic Channel Assignment/Reassignment (ODCAR) that also combines channel ordering with channel rearrangements. The differences between the BCO and ODCAR schemes are very minor and quite subtle. BCO borrows a channel from the adjacent cell having the largest number of available *channels for borrowing*, while ODCAR borrows a channel from the adjacent cell having the largest number of available *nominal channels* that it could use to service its own calls. When a call completes on a nominal channel and there are calls in progress with the same BS on borrowed channels, then BCO releases the channel that is borrowed from the adjacent cell with the *largest number of lent channels* while ODCAR releases the channel that is borrowed from the adjacent cell with the *fewest number of nominal channels*. Finally, when a call completes on a borrowed channel BCO simply releases the channel in the three cells where it is locked, while ODCAR again releases the borrowed channel from the adjacent cell with the fewest number of nominal channels.
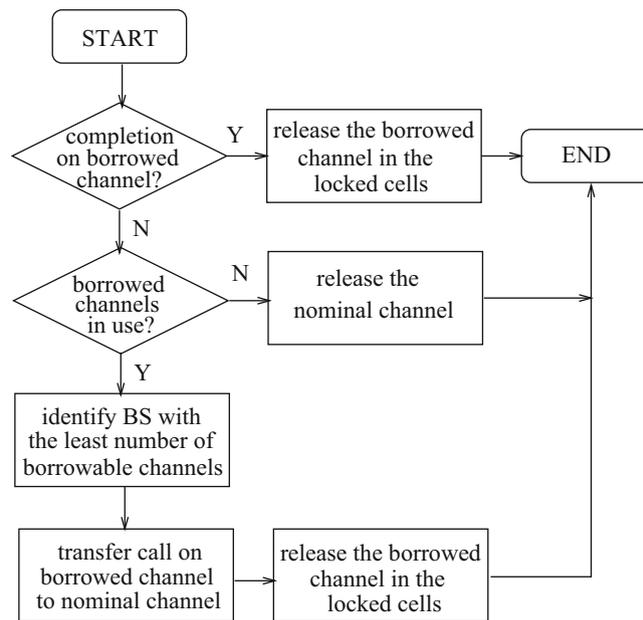
**Fig. 14.6** Call departure policy for the BCO algorithm

## 14.5.2   Borrowing with Directional Locking

Zhang and Yum [375] introduced a new scheme called Borrowing with DireCtional Locking (BDCL) and compared it with Borrowing with Channel Ordering (BCO). Referring to the $N = 7$ cell reuse pattern in Fig. 14.7, the BCO scheme operates as follows. If cell B1 borrows a channel $c$ from cell $A1$, then cells A1, A2, and A3 are locked from using channel $c$ since their use of channel $c$ would violate the co-channel reuse constraint. In the BDCL scheme, instead of locking channel $c$ in cell A3 in all directions, channel $c$ only needs to be locked in directions 1, 2, and 3. Cells that lie in the other three directions from A3, say B2, can freely borrow channel $c$ from cell A3 without violating the co-channel reuse constraint. Whether or not channel $c$ may be borrowed from A3 depends, however, on its locking conditions in A4, A5, and A6. Should the channel happen to be locked in A4, A5, or A6 but the cell locking is beyond B2's interference neighborhood, then B2 could still borrow channel $c$. This scheme increases the number of channels available for borrowing over the straight BCO scheme. Furthermore, the BDCL scheme uses channel rearrangements similar to the channel ordering scheme proposed by Elnoubi et al. [108], except that the directional locking mechanism is accounted for. Zhang and Yum [375] concluded that the BDCL scheme outperforms the BCO and FCA schemes in terms of blocking probabilities when the cells have nonuniform but stationary traffic loads.

## 14.5.3   Borrowing Without Locking

A borrowing scheme, Channel Borrowing Without Locking (CBWL), has been proposed by Jiang and Rappaport [172] that does not require channel locking by using borrowed channels with a reduced power level to limit interference with co-channel cells. This allows the channel to be reused in all cells except the cell from which it has been borrowed. However, it also implies that channels can only be accessed in part of the borrowing cell. To determine if a channel can be borrowed with enough signal strength, the BS broadcast a borrowed channel sensing signal with the same reduced power of a borrowed channel.

The CBWL scheme divides the channels into six groups that can be lent to the neighboring cells, such that channels in the $i$th group can only be lent to the $i$th adjacent cell. This principle of directional lending is illustrated in Fig. 14.8, where channels in the group A1 can be borrowed by MSs in all of the B cells. Because of the reduced power level of borrowed channels, the MSs in the B cells that borrow the group A1 channels will be concentrated along the A-B cell boundaries. The CBWL scheme reduces the BS complexity because each BS does not need to have the capability of transmitting and receiving on all the channels assigned to its neighboring cells, but only a fraction of them in each cell. Furthermore, the division of borrowable channels into six groups limits co-channel interference so that locking is not required.
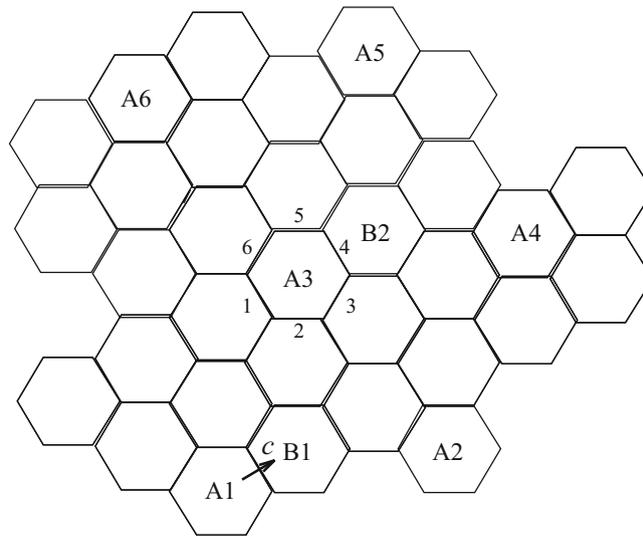
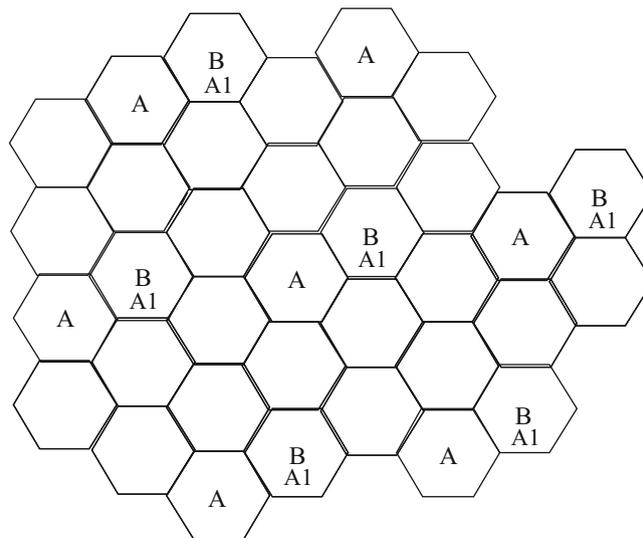**Fig. 14.7**  Principle of Borrowing with DireCtional Channel Locking (BDCL)



**Fig. 14.8**  Principle of Channel Borrowing Without Locking (CBWL)

Various forms of channel rearrangements can be used to enhance the scheme. For example, if cell B wishes to borrow a channel from cell A, the call is blocked if all the channels in group A1 of cell A are busy. However, it may be possible for cell A to transfer one of the calls to another group, say A2, to accommodate the borrow request. If this is not possible, cell A could itself borrow a channel from an adjacent cell to free up a channel to lend to cell B. Many other types of rearrangement policies are also possible.

### 14.5.4   Compact Pattern Based DCA

Yeung and Yum [367] introduced Compact Pattern based DCA (CPDCA), that attempts to dynamically keep the co-channel cells of any channel to a compact pattern, where a compact pattern of a network is the channel allocation pattern with the minimum average distance between co-channel cells. In other words, CPDCA attempts to increase spectral efficiency by keeping all channels at their minimum co-channel reuse distance. CPDCA accomplishes this task in two stages: (1) channel acquisitions where an optimal idle channel is assigned to the MS, and (2) channel packing for the restoration of the compact patterns upon the release of a compact channel. Channel packing is achieved by reassigning at most one call per channel release.

Channels are assigned by using system-wide call arrival rate information to assign a channel that has a compact pattern that will yield the largest reduction in the overall system blocking probability. If a compact pattern is not available, the most optimal noncompact pattern is selected. If a call completes on a compact channel, CPDCA attempts to reassign a call on a noncompact channel to the newly idle compact channel. If no such call exists, CPDCA reassigns a call on the compact pattern that is least utilized to the newly idle channel. The first step minimizes the number of noncompact channels being used, while the second step packs the ongoing calls onto complete compact patterns. Yeung and Yun have shown their CPDCA scheme to outperform BDCL.

## 14.6   Directed Retry and Directed Handoff

Everitt [115] introduced the directed retry (DR) and directed handoff (DH) channel assignment algorithms. If a BS does not have an idle channel available to service a call with the DR policy, the MS tries to acquire an idle channel in any other cell that can provide a satisfactory signal quality. DR exploits the overlapping nature of cells in a practical cellular system, where some percentage of MSs can establish a suitable link with more than one BS. DH also exploits the overlapping nature of cells to direct some of the ongoing calls in a heavily loaded cell to an adjacent cell that is carrying a relatively light load. Both the DR and DH schemes can be used in conjunction with either FCA or DCA, and Everitt concluded that FCA and maximum packing DCA in conjunction with the combination of DR and DH offer about the same performance. Therefore, FCA in conjunction with DR and DH is the preferred scheme, since an improvement over FCA can be gained without the added complexity of DCA.

## 14.7   Moving Direction Strategies

The moving direction (MD) strategy, proposed by Okada and Kubota, exploits information about the MS movement to reduce forced terminations and channel changes [247, 248]. The strategy attempts to assign an available channel from among those channels already assigned to MSs elsewhere in the service area that are moving in the same direction as the MS under consideration. Sets of MSs moving in the same direction are formed. When a MS enters a cell, a MS from the same set is probably leaving a cell. This allows both MSs to retain the same channel, thus reducing both the number of changes and probability of forced termination. This method is particularly useful for highway microcell deployment, where the traffic direction is highly predictable. Okada and Kubota compared the MD strategy with Cox and Reudnick's FA, NN, and NN+1 strategies [248]. The MD strategy was shown to offer the lowest channel changing rate and the lowest probability of forced termination. However, the NN strategy provided a slightly lower probability of new call blocking.

A variation of the MD scheme considers both Speed and Moving Direction (SMD) [246]. MS are divided into two classes: high speed MS (HSMS) who are traveling at 50–60 km/h and low speed MS (LSMS) who are traveling at 0–4 km/h. To reduce the probability of forced termination and channel changing rate, SMD uses the MD policy for its HSMS call requests. For the LSMS, the NN strategy is employed since LSMSs do not experience forced terminations or channel changes as frequently as HSMSs. Again, the SMD scheme was shown to outperform the FA, NN, and NN+1 policies in terms of channel changing rates and the probability of forced termination. Finally, a variety of velocity estimation techniques are available as discussed in Sect. 13.4. Moving direction information can be obtained by using the past signal strength history in LOS environments [26] or the sign of the Doppler.

## 14.8   Reduced Transceiver Coverage

Takeo et al. [311] proposed a scheme where nonuniform traffic is handled by adjusting the BS transmit power level of the control channel according to the traffic variance for every control period. Since the MS uses the control channel to determine which BS to connect to, the effective cell size is dynamically varied. Highly loaded cells decrease the transmit power to shrink the cell sizes, while lightly loaded cells increase the transmit power to enlarge the cell sizes. This scheme may cause some unwanted side effects, for example, handoffs can occur even for stationary MSs. The experimental results in [311] suggest that the call blocking probability increases in proportion to a decrease in the control period and, therefore, frequent

updating of the control channel power should be avoided. Takeo et al. [311] did not address the problem that arises when many adjacent cells are heavily loaded, a potentially deleterious situation since it may result in coverage gaps within a particular reuse cluster.

### 14.8.1   Reuse Partitioning

Reuse partitioning employs a two-level cell plan where clusters of size $M$ are overlaid on clusters of size $N$, $N > M$. Figure 9.20 shows a FCA scheme using reuse partitioning with $M = 3$ and $N = 9$. As discussed in Sect. 9.5.1, reuse partitioning divides the available channels into two sets: one set can be used by the inner cells only, while the other set can be used by both the inner and outer cells. Reuse partitioning uses rearrangements so that whenever possible MSs in the inner cells are assigned channels allocated for use in the inner cells only.

An autonomous reuse partitioning (ARP) scheme has been suggested by Kanai [174]. With this scheme an *identical* ordering of channels is given to all BSs. Upon call arrival, the channels are checked in order and the first one exceeding a C/I threshold for both the forward and reverse links is acquired. If no channels are available the call is blocked. The advantage of using a fixed ordering is that the channels higher in the ordering are used more frequently and, hence, have higher interference levels. This enables each BS to acquire channels with minimum C/I margins without the need for sorting channels according to their interference levels. The algorithm is self-organizing in the sense that channels high in the ordering (with high interference levels) are allocated to MS that are close to a BS (with strong received signal levels). Channels low in the ordering tend to be allocated to MSs that are far from a BS with weak received signal levels.

Another scheme, self-organized reuse partitioning (SORP) has been proposed by Furukawa and Yoshihiko [133]. The BSs allocate channels by measuring the power levels transmitted from the MSs. This method relies upon a table at each BS that contains, for each channel, the average transmit power for MSs using the channel in its cell and all the surrounding cells. The table is updated with each call arrival and the update information is shared among the BSs. When a call arrives, the BS obtains the output power of the calling MS and assigns that channel with the corresponding average transmit power that is closest to that of the calling MS. The channel is acquired if available; otherwise the second closest candidate is examined, and so on. As a result of this procedure in each BS, channels that correspond to the same power are grouped autonomously for self-organizing reuse partitioning. The SORP scheme was shown to offer about the same blocking probability as the ARP scheme, but SORP requires less time to search for a channel and generally provides a higher C/I.

## 14.9   Handoff Priority

Since the forced termination of a call in progress is worse than the blocking of a new call, it is important to consider handoff priority in the design of a channel assignment strategy. This is especially important in microcellular systems with their increased number of handoffs. Two possible methods of achieving handoff priority are to use guard channels where a fraction of the channels are reserved for handoff requests only [169], and handoff queueing where a handoff request from a MS is placed in a queue with the target BS while the MS maintains a radio link with its serving BS [134, 169]. Both methods are known to decrease the probability of dropped calls. However, queueing does this with a smaller increase in the probability of new call blocking.

Handoff queueing exploits the time interval that the MS spends in the handoff region, i.e., between the time when the handoff request is generated and the time when the call will be dropped due to a degradation in link quality. The simplest queueing scheme uses a first in first out (FIFO) policy. More elaborate queueing schemes use measurement based priority, where the queue is ranked according to the measured link quality of the MSs in the queue [317]. MSs with the lowest link quality are placed in the highest priority class, and the handoff queue is sorted continuously according to the priority classes.

## 14.10   Example DCA Schemes for TDMA Systems

A TDMA system is assumed with carrier groupings, where the calls are packed into TDMA carriers such that each cell acquires the minimum number of carriers required to carry the calls. This packing may require channel rearrangements when the channels are released. A benefit of carrier groups is a reduction in the computation required to make decisions
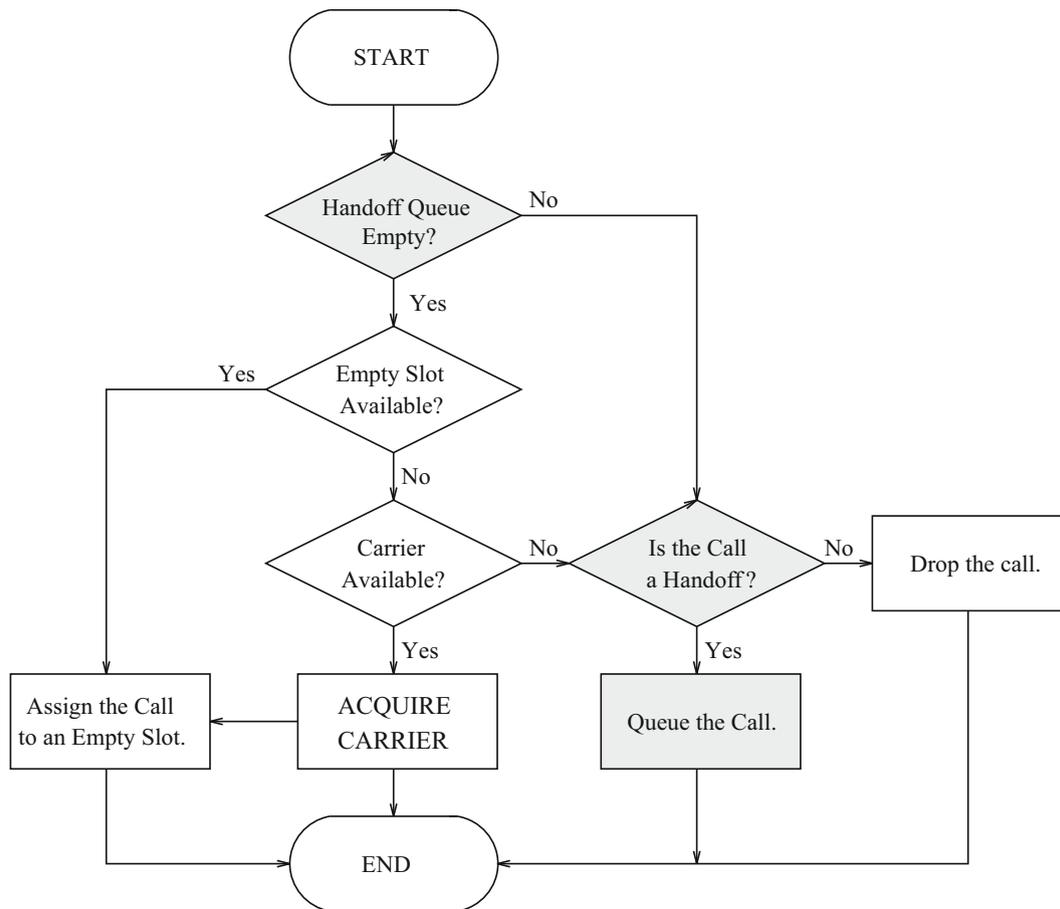
**Fig. 14.9** ACQUIRE CARRIER policy that is executed upon a new call or handoff arrival

regarding acquisitions and releases. This reduction in complexity reduces the time required to select a channel, thus lowering the probability of dropped call.

Whenever a channel is needed a TDMA DCA scheme follows a strategy which, if necessary, selects a carrier for acquisition according to a carrier acquisition criterion. Likewise, when a channel is released another strategy is followed which, if necessary, selects a carrier to be released according to a carrier release criterion. The flowcharts in Figs. 14.9 and 14.10 illustrate the general procedure for acquiring and releasing channels and carriers. The shaded blocks are steps that support handoff queueing and will be discussed later in the chapter.

**ACQUIRE CARRIER Policy (Non-queueing Case)**

As Fig. 14.9 shows, the following policy is executed upon a new call or handoff arrival:

1. If at least one idle channel is available among the already acquired carriers, then assign an idle channel to the call; otherwise attempt to acquire a new carrier according to the carrier acquisition criterion.

   (a) If the carrier acquisition is successful, then assign one channel of the newly acquired carrier to the call; otherwise block the call.

**RELEASE CARRIER Policy (Non-queueing Case)**

As Fig. 14.10 shows, the following policy is executed upon a call completion or a handoff departure:
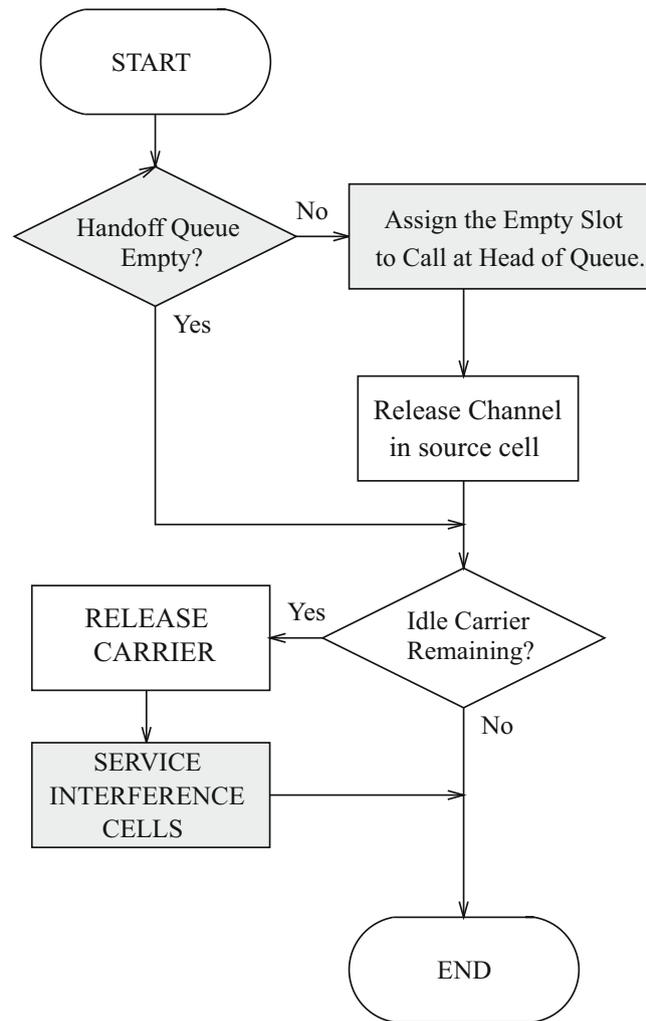
**Fig. 14.10** RELEASE CARRIER policy that is executed upon a call completion or handoff departure

1. If the channel release will not yield an idle carrier, then no carrier is released; otherwise a carrier is selected for release according to the carrier release criterion.

    (a) The call that occupies the carrier selected for release is reassigned to the newly idle channel, and the selected carrier is released.

## 14.10.1  The Simple DCA (SDCA) Strategy

Elnoubi et al. [108] proposed the BCO strategy that makes use of different channel orderings in each cell. Here, a channel assignment strategy is considered that uses carrier orderings rather than channel orderings [349]. However, unlike the BCO strategy, the carriers are not explicitly divided into nominal and borrowed sets with a specified rule for borrowing carriers. In our scheme, each cell has its own carrier ordering, and no two cells separated less than the frequency reuse distance have the same carrier ordering. The orderings are designed so that carriers occurring near the beginning of a cell's carrier ordering occur near the end of the carrier orderings of the cells in its interference neighborhood. For example, suppose there are 9 available carriers with a 3-cell reuse cluster. Three different carrier orderings are necessary to ensure that cells within the frequency reuse distance have distinct carrier orderings. For example, the following carrier orderings will do.

$$A: \quad \{1, 4, 7, 8, 9, 5, 6, 2, 3\}$$
$$B: \quad \{2, 5, 8, 9, 7, 6, 4, 3, 1\} \tag{14.17}$$
$$C: \quad \{3, 6, 9, 7, 8, 4, 5, 1, 2\}$$

These carrier orderings are obtained by first listing the 9 available carriers column-wise until they are all assigned. Then columns 4 and 5 are permutations of the third column, columns 6 and 7 are permutations of the second column, and columns 8 and 9 are permutations of the first column. Notice that Carriers 1, 2, and 3 each appear first in one of the orderings and appear near the end of the other two orderings.

The carrier selection criterion is as follows. When a carrier is needed in a cell, the available carrier occurring nearest to the beginning of the cell's carrier ordering is selected. If there are no available carriers, then the carrier acquisition fails. When a carrier is released in a cell, the busy carrier occurring nearest to the end of the cell's carrier ordering is selected. This may require a rearrangement of calls within a cell to carriers that are closer to the beginning of the cell's carrier ordering. The above strategy is hereafter referred to as the simple dynamic channel assignment (SDCA) strategy, because of the simplicity of the carrier selection criterion.

Note that the SDCA scheme does not need an exchange of information within the interference neighborhoods. The busy/idle status of carriers can be determined by passive non-intrusive monitoring at each BS.

### 14.10.2   A Queueing DCA Strategy

Forced terminations of calls in progress are worse than blocking of new calls. Forced terminations or handoff blocking occurs when an active call crosses a cell boundary, and the target cell cannot accommodate the additional call. As described in [134, 169], one way to establish handoff priority is to queue the handoff attempts. If the target cell is momentarily unable to accommodate the additional call, the MS maintains its link with the source cell and enters a queue in the target cell. A queue failure occurs when either the signal level drops below some threshold before the call can be serviced by the target cell, the time spent in the queue exceeds a time-out interval, or the queue overflows. A queue success occurs when a channel becomes available and the queue is non-empty. The newly available channel is then assigned to the call at the head of the queue, and a channel within the source cell is released. Here handoff queueing is combined with DCA.

In a DCA strategy, there are two ways for a channel to become available in a cell. Either a call terminates (due to a handoff or completion) or a carrier is released somewhere in the interference neighborhood thus allowing the carrier to be acquired by the cell. When a cell releases a carrier, there may be multiple cells in its interference neighborhood that could acquire the released carrier to service their queued calls. However, the frequency reuse constraint will be violated if all these cells acquire the carrier. To determine which cells may acquire the carrier, it may assumed that each cell has a subset of carriers designated as owned carriers. The owned carriers are a subset at the beginning of the carrier orderings. Owned carriers are distributed so that no two cells separated less than the frequency reuse distance share any owned carriers. The remaining carriers are designated as borrowed carriers. Considering the previous example in (14.17) where 9 carriers were distributed among three carrier orderings, the owned and borrowed carrier orderings are

$$
\begin{array}{lll}
 & \underline{\text{Owned}} & \underline{\text{Borrowed}} \\
A: & \{1, 4, 7\} & \{8, 9, 5, 6, 2, 3\} \\
B: & \{2, 5, 8\} & \{9, 7, 6, 4, 3, 1\} \\
C: & \{3, 6, 9\} & \{7, 8, 4, 5, 1, 2\}
\end{array}
\tag{14.18}
$$

Cells tend to use their owned carriers before borrowing carriers from other cells. When a cell releases a borrowed carrier, the cells in the interference neighborhood that own the released carrier are given the first opportunity to service their handoff queues. If any of these cells have queued calls, then they can acquire the carrier without violating the frequency reuse constraint. If none of the owner cells in the interference neighborhood acquire the released carrier, then some of the remaining cells in the interference neighborhood may acquire the carrier to service their handoff queues.

A strategy combines DCA and handoff queueing is described below along with the flowcharts in Figs. 14.9, 14.10, 14.11, and 14.12.
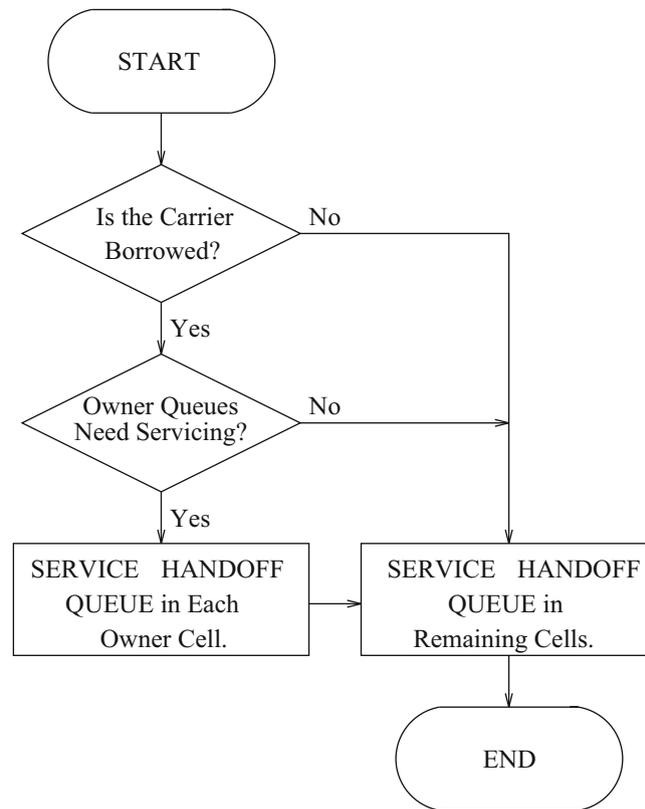
**Fig. 14.11** SERVICE INTERFERENCE CELLS Policy

## ACQUIRE CARRIER Policy (Queueing Case)

Referring to Fig. 14.9, the following policy is executed upon a new call arrival or handoff attempt:

1. If the handoff queue is not empty, then either queue the handoff call or drop the new call; otherwise

    (a) If there is at least one idle channel, then assign an idle channel to the call; otherwise try to acquire according to the carrier acquisition criterion.

        (i) If the carrier acquisition is successful, then assign one channel of the newly acquired carrier to the call; otherwise either queue the handoff call or drop the new call.

## RELEASE CARRIER Policy (Queueing Case)

Referring to Fig. 14.10, the following policy is executed upon a call completion, a handoff, or a failure from the handoff queue of an adjacent cell:

1. If the handoff queue is not empty, then assign the newly available channel to the call at the head of the handoff queue. The channel currently serving the call is released according to the RELEASE CARRIER policy.
2. If the channel release will yield an idle carrier, then a carrier is selected for release according to the carrier release criterion. The call that occupies the carrier selected for release is reassigned to the newly idle channel, the selected carrier is released, and the SERVICE INTERFERENCE CELLS policy is executed.

## SERVICE INTERFERENCE CELLS Policy

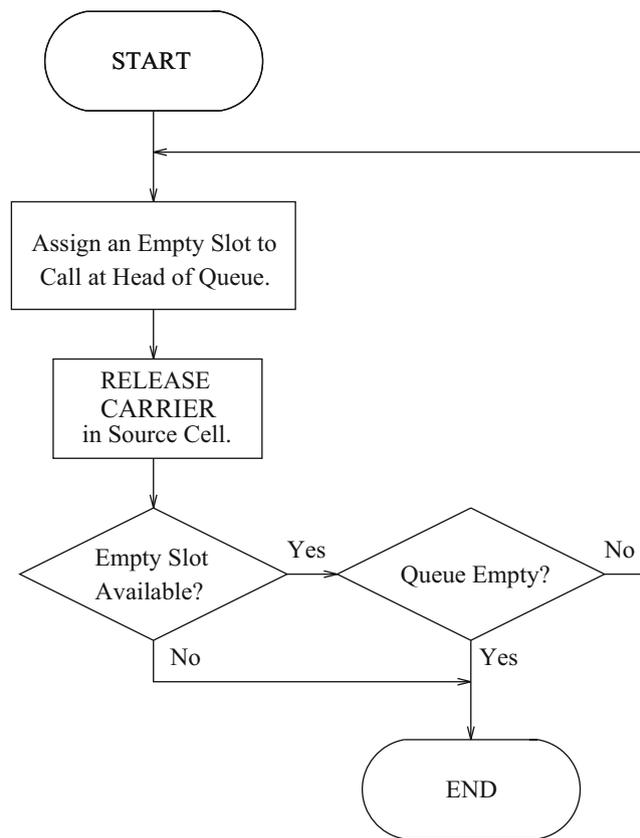Referring to Fig. 14.11, the following policy is executed whenever a carrier is released:

**Fig. 14.12**  SERVICE HANDOFF QUEUE Policy

1. If a borrowed carrier is released, then any owner cell in the interference neighborhood that has a non-empty handoff queue and can acquire the released carrier without violating the reuse constraint will acquire the carrier and service its handoff queue according to the SERVICE HANDOFF QUEUE policy.
2. After the owner cells are given the opportunity to service their queues, the remaining cells in the interference neighborhood are given the opportunity to service their handoff queues by using the SERVICE HANDOFF QUEUE policy.

**SERVICE HANDOFF QUEUE Policy**

Referring to Fig. 14.12, whenever a carrier is acquired in a cell having a non-empty handoff queue, the following policy is executed:

1. An empty slot is assigned to the call at the head of the handoff queue, and the channel currently serving the call is released by using the RELEASE CARRIER policy.

   (a) Step 1. is executed until either all of the available slots are filled or the handoff queue is empty.

## 14.10.3  An Aggressive DCA Strategy

DCA strategies increase trunking efficiency by assigning channels to cells as they are needed. Care must be taken to avoid a poor allocation of channels; otherwise capacity will suffer. With SDCA, the carriers are acquired and released according to a carrier acquisition and release criteria that attempts to maximize capacity by favoring tightly packed arrangements of *co-carrier* cells. This strategy is similar to the 2-D RING strategy in [171] and suffers from the same problem; when a carrier is selected for acquisition, multiple carriers must be available for the carrier acquisition criteria to yield any advantage. The

more carriers available for each selection process the better. At high traffic loads, very few carriers may be available for acquisition. In fact there may be only one or none, in which case there is no choice. Under such conditions, carriers tend to be assigned where they can be assigned, rather than where they should be assigned, and capacity suffers [117]. Under such conditions DCA strategies usually perform *worse* than FCA strategies.

As discussed in Sect. 14.3.4 the performance at high traffic loads can be improved by using an aggressive policy where, under certain conditions, a cell that cannot acquire a carrier may force a surrounding cell to give up a carrier so that it may service one or more calls. Thus, a cell can actually *take* a carrier from its neighbors if none are otherwise available, according to the following TAKE CARRIER policy.

**TAKE CARRIER Policy**

Referring to Fig. 14.13, the following policy is executed when a call is in jeopardy due to a handoff failure (in the no queueing case), a queue failure, or the execution of the TAKE CARRIER policy in another cell:

1. The entire set of carriers is examined. If all carriers are being used, then the TAKE CARRIER policy fails; otherwise, all unused carriers are examined, and the number of calls within the interference neighborhood that will be placed in
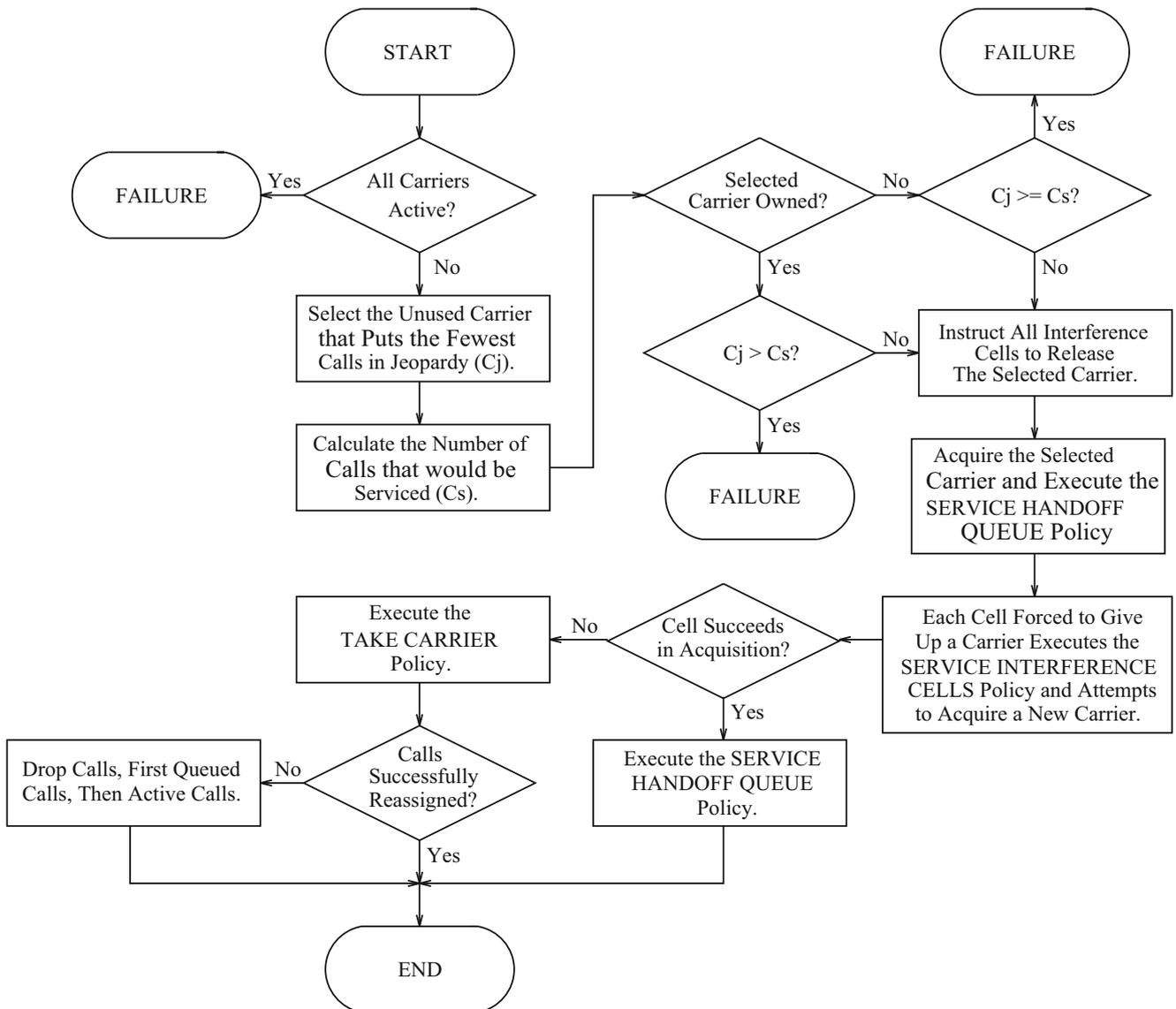


**Fig. 14.13** TAKE CARRIER Policy

jeopardy by taking each carrier is calculated. Note that the number of jeopardized calls must be determined at each cell in the interference neighborhood. The carrier that will place the fewest number of calls in jeopardy is selected. In event of a tie, the carrier appearing earliest in the carrier ordering is selected. Let $C_j$ be the number of calls that will be placed in jeopardy by taking the selected carrier.

2. The number of calls that will be serviced by taking the selected carrier, $C_s$ is calculated. For a handoff attempt and no queueing, $C_s = 1$; for a queue failure, $C_s$ is the minimum of the number of queued calls $C_q$ and the number of slots per carrier $N_s$; for a carrier that is lost to another cell executing the TAKE CARRIER policy, $C_s$ ranges from 1 to $N_s$.

3. If the selected carrier is owned and $C_j > C_s$ or if the selected carrier is not owned and $C_j \geq C_s$, then the TAKE CARRIER policy fails; otherwise all cells in the interference neighborhood that are currently using the selected carrier are told to release it.[2]

4. Each cell in the interference neighborhood releases the selected channel.

5. The selected channel is taken. For a handoff attempt (no queueing), the handoff is completed. For a queue failure, the SERVICE HANDOFF QUEUE policy is executed. For a carrier that is lost to another cell executing the TAKE CARRIER policy, the slots of the taken carrier are assigned to the calls in jeopardy.

6. Each cell that was forced to release the selected carrier executes the SERVICE INTERFERENCE CELLS policy.

7. Each cell that was forced to release the selected channel and still has calls in jeopardy after the cell taking the carrier services its queue executes the ACQUIRE CHANNEL policy.

   (a) If the carrier acquisition is successful, then the cell executes the SERVICE HANDOFF QUEUE policy; otherwise it executes the TAKE CARRIER policy.

   (b) If a cell from which a carrier was taken cannot obtain a new carrier, it must drop some of its calls. Queued calls are dropped first because they are in greater danger of being dropped than active calls. If more calls must be dropped after dropping the queued calls, then active calls are dropped until there are no excess calls.

Note that the TAKE CARRIER policy is only executed if the SCDA carrier acquisition criteria fails to acquire a carrier. Unlike SCDA, the TAKE CARRIER policy acquires carriers that place the fewest number of calls in jeopardy. From a practical standpoint, the aggressive SCDA strategy requires communication among BSs in the interference neighborhood to execute the TAKE CARRIER policy.

### 14.10.4   Simulation Model, Results, and Discussion

Consider a microcellular environment consisting of a rectangular grid of intersecting streets, as shown in Fig. 14.14. It is assumed that MS traffic flowing off an edge of the grid wraps around to the opposite edge. However, the interference neighborhoods of each cell do not wrap around. If two cells are on opposite edges of the grid, such that MSs leaving one cell enter the other, they may simultaneously use the same carrier since they are not spatially adjacent.
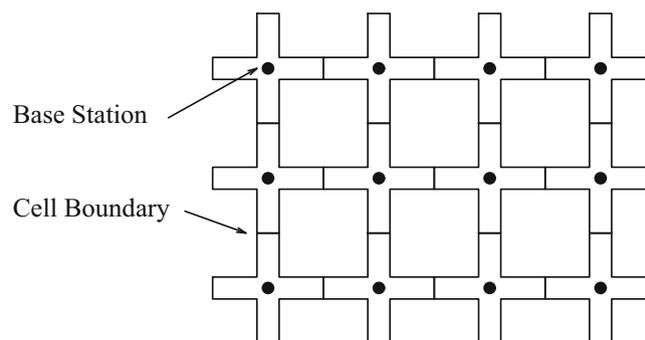


**Fig. 14.14**  Cells and BSs in an urban microcellular environment

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[2]When there is no queueing $C_s = 1$ and, therefore, only an owned carrier can be taken that will not place more than one call in jeopardy.

**Fig. 14.15** Interference neighborhood and cell reuse pattern

| 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 |
|---|---|---|---|---|---|---|---|---|
| 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 |
| 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 |
| 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 |
| 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 |
| 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 |
| 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 |

Line-of-sight co-channel cells must be separated by at least 3 cells. There are no reuse constraints on non-line-of-sight co-channel cells, due to the corner effect. The frequency reuse factor is 4, meaning that the set of carriers must be divided into 4 subsets for FCA, and for SDCA there must be 4 different carrier orderings. The interference neighborhood and cell reuse pattern are shown in Fig. 14.15.

To account for the uneven distribution of teletraffic in the microcellular environment the identical active-dormant Markov model from [240] is used, but modified to account for handoff queueing. The model is Markovian so that all events occur with exponentially distributed interarrival times. However, the parameters of the distributions change with time to reflect the time-varying nature of the model. The state of cell $i$ at any time can be described by the following parameters:

New call arrival rate: $\lambda_i$
Number of active calls: $N_{\text{active},i}$
Number of queued calls: $N_{\text{queued},i}$

**New Call Arrivals**

Call arrivals in cell $i$ are Poisson with rate $\lambda_i$. This parameter is binary valued, where $\lambda \in \{\lambda_{\text{ACT}}, \lambda_{\text{DOR}}\}$. These two new call arrival rates correspond to two different cell modes, active and dormant. The arrivals of new calls in different cells are assumed to be independent, so the global call arrival rate is

$$\Lambda = \sum_i \lambda_i. \tag{14.19}$$

**Call Completions**

The duration of each call is exponentially distributed with mean $\mu$. In cell $i$ there are $N_{\text{active},i}$ active calls and $N_{\text{queued},i}$ queued calls, any of which could be completed at any time. These calls are assumed to be independent, so the call completion rate in cell $i$ is

$$r_{c,i} = \frac{N_{\text{active},i} + N_{\text{queued},i}}{\mu}. \tag{14.20}$$

The completion of calls in different cells are assumed to be independent. Therefore, the global call completion rate is:

$$r_c = \sum_i r_{c,i}. \tag{14.21}$$

**Handoff Attempts**

A handoff is attempted whenever an active call crosses a cell boundary and needs to be serviced by the target cell. To determine the handoff rate, it is assumed that each call is handed off an average of $h$ times over its duration. Since the traffic flows wrap around the grid edges, the handoff calls are uniformly distributed to one of the four neighboring cells. Queued calls can be safely assumed to never cross a cell boundary, because the time required to traverse a cell will be much longer than the maximum time allowed in the handoff queue. Therefore, queued calls do not contribute to the handoff rate. The handoff rate in cell $i$ is

$$r_{h,i} = \frac{h N_{\text{active},i}}{\mu}. \tag{14.22}$$

Call handoffs in different cells are assumed to be independent, so the global handoff attempt rate is

$$r_h = \sum_i r_{h,i}. \tag{14.23}$$

**Mode Transitions**

Each cell remains in its current mode for duration $D$, where $D$ is exponentially distributed with mean $1/\overline{D}$. If the cell is in active mode, then $\overline{D} = \overline{D}_{\text{ACT}}$, and if the cell is in dormant mode, then $\overline{D} = \overline{D}_{\text{DOR}}$. If there are $N_{\text{ACT}}$ active cells and $N_{\text{DOR}}$ dormant cells, then the global active-to-dormant and dormant-to-active transition rates are, respectively,

$$r_{\text{ACT} \to \text{DOR}} = \frac{N_{\text{ACT}}}{\overline{D}_{\text{ACT}}} \tag{14.24}$$

$$r_{\text{DOR} \to \text{ACT}} = \frac{N_{\text{DOR}}}{\overline{D}_{\text{DOR}}} \tag{14.25}$$

The probability of a cell being in the active mode is

$$P_{\text{ACT}} = \frac{\overline{D}_{\text{ACT}}}{\overline{D}_{\text{ACT}} + \overline{D}_{\text{DOR}}}. \tag{14.26}$$

As the simulation progresses, five types of events are generated: new call arrivals, call completions, handoff attempts, active-to-dormant mode transitions, and dormant-to-active mode transitions. All events occur independently. Therefore, five random times are generated and the next event corresponds to the one with the minimum time. Once an event is selected, the event must be randomly assigned to a cell. The probability of cell $i$ being selected for each type of event is

$$\begin{aligned}
&\text{New call arrival:} && \lambda_i/\Lambda \\
&\text{Call completion:} && r_{c,i}/r_c \\
&\text{Handoff Attempt:} && r_{h,i}/r_h \\
&\text{ACT} \to \text{DOR transition:} && \begin{cases} 1/N_{\text{ACT}}, & \text{if cell } i \text{ is active} \\ 0, & \text{if cell } i \text{ is dormant} \end{cases} \\
&\text{DOR} \to \text{ACT transition:} && \begin{cases} 1/N_{\text{DOR}}, & \text{if cell } i \text{ is dormant} \\ 0, & \text{if cell } i \text{ is active} \end{cases}
\end{aligned}$$

The active to dormant traffic ratio $R_{\text{ACT/DOR}} = \lambda_{\text{ACT}}/\lambda_{\text{DOR}}$ specifies the ratio of the new call arrival rates in the active and dormant cells. To complete the model, the offered traffic per cell, $\rho$, is specified. Then the active and dormant call arrival rates are:

$$\lambda_{\text{ACT}} = \frac{\rho R_{\text{ACT/DOR}}}{\mu(1 + P_{\text{ACT}}(R_{\text{ACT/DOR}} - 1))} \tag{14.27}$$

$$\lambda_{\text{DOR}} = \frac{\rho}{\mu(1 + P_{\text{ACT}}(R_{\text{ACT/DOR}} - 1))} \tag{14.28}$$

where $P_{\text{ACT}}$ is as defined in (14.26). The parameters used in the simulations are as follows:

| | |
|---:|:---:|
| Number of cells: | 144 (12 × 12 square) |
| Total number of carriers: | 40 |
| Number of slots per carrier: | 3 |
| Number of channels per cell (FCA): | 30 |
| Number of owned carriers per cell (DCA): | 10 |
| Average call duration: | 120 s |
| Average number of handoffs per call: | 3 |
| Average duration of the ACTIVE mode: | 60 s |
| Average duration of the DORMANT mode: | 600 s |
| ACTIVE to DORMANT traffic ratio: | 5 |
| Offered traffic: | 0–50 Erlangs |
| Queue size: | 10 |

Figures 14.16 through 14.17 compare the probability of new call blocking and the probability of forced termination for the FCA, SDCA, and aggressive SDCA strategies. Results are shown without handoff queueing and with a 5-second handoff queue. Observe from Fig. 14.16 that a substantial reduction in the probability of new call blocking is achieved by using SDCA as compared to FCA. Handoff queueing causes a slight increase in the probability of new call blocking because handoff calls are given priority over new calls when a channel has been released and is available for acquisition. Aggressive SDCA also causes a very slight increase in the probability of new call blocking over non-aggressive SDCA. Figure 14.17 shows that both handoff queueing and SDCA significantly lower the probability of forced termination. Aggressive SDCA tends to be more effective than the non-aggressive SCDA when these schemes are combined with handoff queueing.
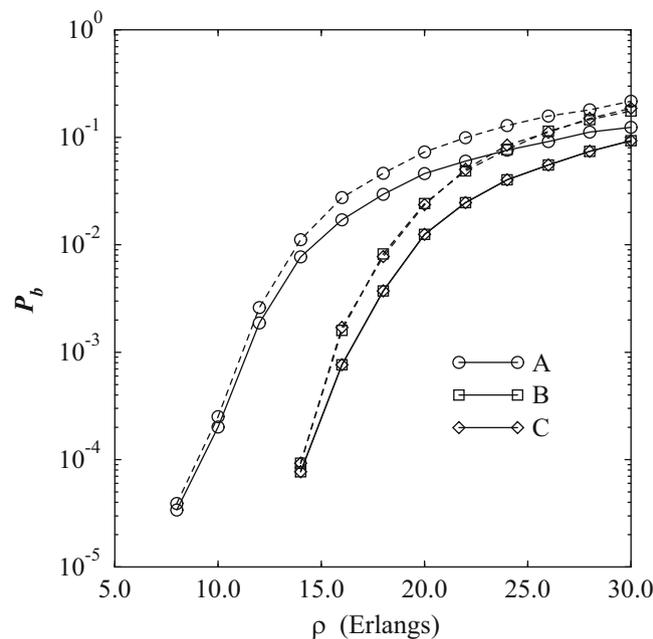


**Fig. 14.16** Probability of new call blocking versus offered traffic without queueing (*solid*) and 5-second handoff queue (*dashed*). Legend: A = FCA, B = SDCA, C = Aggressive SDCA, from [349]
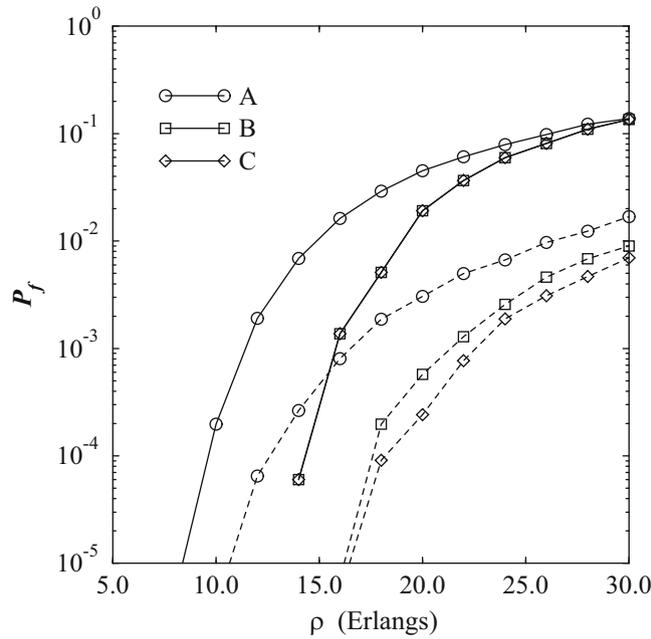
**Fig. 14.17** Probability of forced termination versus offered traffic without queueing (*solid*) and a 5-second handoff queue (*dashed*). Legend: A = FCA, B = SDCA, C = Aggressive SDCA, from [349]
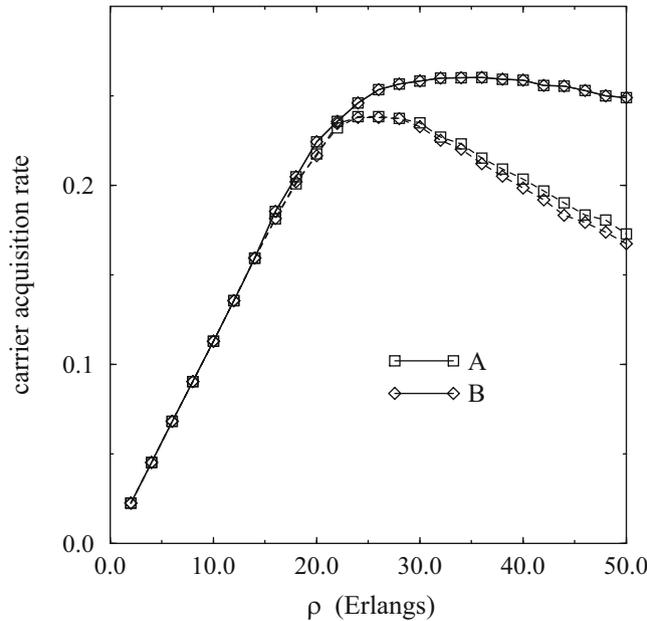


**Fig. 14.18** Carrier acquisitions per second (per cell) versus offered traffic without queueing (*solid*) and a 5-second handoff queue (*dashed*). Legend: A = SDCA, B = Aggressive SDCA, from [349]

## Carrier Acquisitions

It is useful to determine the increase in the rate of carrier acquisitions that results from using aggressive SDCA. Figure 14.18 plots the cell carrier acquisition rate for aggressive and non-aggressive SDCA. Notice that the carrier acquisition rates at lower traffic loadings are almost the same. At higher traffic loadings handoff queueing has the largest effect on the carrier acquisition rate. However, aggressive SDCA causes only a very slight increase in the carrier acquisition rate over non-aggressive SDCA.

   The results presented here have been obtained under the assumption that the interference (and DRA) neighborhoods are symmetrical (cell A interferes biconditionally with cell B) and the average traffic loading is identical for all cells. This is not true of a practical system and, therefore, preassigned carrier orderings should not be used. In an actual microcellular system an adaptive, self-organizing algorithm for ordering of carriers and the selection of owned carriers is preferable. Also, an adaptive aggressive strategy may be employed that uses current performance (e.g., the current new call blocking and forced termination probabilities) and perhaps forward-looking strategies [117] to make a more informed decision when to *take* a carrier. It is expected that some performance deterioration will result over the ideal symmetrized case presented here, because of the aforementioned network asymmetries and the finite convergence rate of the adaptive algorithms.

   Finally, the channel assignment strategies as described do not take into consideration the arrangement of calls on the carriers. In reality, the C/I is not the same for each channel. A more effective strategy also arranges the calls in order to combat the unpredictable signal and interference variations present in microcells. Finally, the use of handoff queueing will exaggerate the cell boundaries thereby causing increased co-channel interference. Unlike the purely statistical model that is used here, the study of these issues will require explicit models for the mobility of MSs and the radio propagation environment.

## 14.11   Concluding Remarks

Although it is very difficult to arrive at a consensus as to what the best channel assignment algorithm is, an effective DCA algorithm should possess distributed control mechanisms, handoff prioritization, high channel utilization, and stability. Unfortunately, there is no single DCA algorithm that combines all these features and the *best* solution is sure to depend on the service area characteristics. For example, cordless phones require a fully decentralized algorithm while urban microcells should allow some limited communication among BSs. Although some very interesting DCA schemes have been proposed in the literature, not all the issues have been sufficiently addressed to make them practical. Many of the current systems either require too much computation and communication among BSs yield low channel utilization, or exhibit instability. As a result, DCA will be an active area of research for some time.

   In general, the analytical treatment of DCA algorithms is quite difficult and few results have appeared in the literature. Most of DCA algorithms are derived on an ad hoc basis and evaluated by computer simulation. The development of new analytical tools is important for systematic development and will yield valuable insight into the performance of new DCA algorithms.

   Much of the existing literature has separated the handoff problem from the channel assignment problem. However, these two problems linked and it is desirable that they receive unified treatment. For example, one performance measure for a handoff algorithm is the mean number of handoffs against the handoff delay. However, such an analysis usually proceeds under the assumption that a channel will always be available for a handoff. Clearly, this is not the case in practice. Moreover, channel assignment schemes have to support a variety of multimedia applications that have different quality of service requirements and require different types and amounts of network resources including channel resources, delay, etc.

## Problems

**14.1.** Suppose that the maximum packing (MP) policy is used with the system shown in Fig. 14.2. Suppose that ten channels are available for use within each of the three reuse clusters $CL_i, i = 1, 2, 3$.

**a)** Compute the number of admissible states $|\mathscr{S}|$.
**b)** By using the approximation in (14.6) compute the approximate blocking probabilities for each cell assuming a traffic load of $\rho = 2$ Erlangs in each cell.
**c)** Compare the blocking probabilities in part (b) with FCA for the same traffic load.

**14.2.** Show that the maximum and minimum saturation densities for a linear array of cells are $C_{\max} = (R + 1)^{-1}$ and $C_{\min} = (2R + 1)^{-1}$.

**14.3.** Show that the maximum and minimum saturation densities for a planar array of cells are

$$C_{\min} = \frac{1}{1 + 3R(R + 1)}$$

$$C_{\max} = \begin{cases} \frac{4}{3(R+1)^2} & , \quad R \text{ even} \\ \frac{4}{1+3(R+1)^2} & , \quad R \text{ odd} \end{cases} .$$

**14.4.** Consider a linear array of cells with $R = 1$ and a total of $N_T = 24$ channels. Plot the blocking probability, $P_b$, against the offered traffic per cell, $\rho$, with FCA, timid DCA, and aggressive DCA. What conclusions can you make?

**14.5.** Derive Eq. (14.12).