Abstract

This article provides a detailed discussion of wireless resource and channel allocation schemes. The authors provide a survey of a large number of published papers in the area of fixed, dynamic, and hybrid allocation schemes and compare their trade-offs in terms of complexity and performance. We also investigate these channel allocation schemes based on other factors such as distributed/centralized control and adaptability to traffic conditions. Moreover, we provide a detailed discussion on reuse partitioning schemes, the effect of handoffs, and prioritization schemes. Finally, we discuss other important issues in resource allocation such as overlay cells, frequency planning, and power control.

Channel Assignment Schemes for Cellular Mobile Telecommunication Systems: A Comprehensive Survey

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Technological advances and rapid development of handheld wireless terminals have facilitated the rapid growth of wireless communications and mobile computing. Taking ergonomic and economic factors into account, and considering the new trend in the telecommunications industry to provide ubiquitous information access, the population of mobile users will continue to grow at a tremendous rate. Another important developing phenomenon is the shift of many applications to multimedia platforms in order to present information more effectively.

The tremendous growth of the wireless/mobile user population, coupled with the bandwidth requirements of multimedia applications, requires efficient reuse of the scarce radio spectrum allocated to wireless/mobile communications. Efficient use of radio spectrum is also important from a cost-of-service point of view, where the number of base stations required to service a given geographical area is an important factor. A reduction in the number of base stations, and hence in the cost of service, can be achieved by more efficient reuse of the radio spectrum. The basic prohibiting factor in radio spectrum reuse is interference caused by the environment or other mobiles. Interference can be reduced by deploying efficient radio subsystems and by making use of channel assignment techniques.

In the radio and transmission subsystems, techniques such as deployment of time and space diversity systems, use of low-noise filters and efficient equalizers, and deployment of efficient modulation schemes can be used to suppress interference and to extract the desired signal. However, co-channel interference caused by frequency reuse is the most restraining factor on the overall system capacity in the wireless networks, and the main idea behind channel assignment algorithms is to make use of radio propagation path loss [1, 2] characteristics in order to minimize the carrier-to-interference ratio (CIR) and hence increase the radio spectrum reuse efficiency.

The focus of this article is to provide an overview of different channel assignment algorithms and compare them in terms of performance, flexibility, and complexity. We first start by giving an overview of the channel assignment problem in a cellular environment and discuss the general idea behind major channel allocation schemes. Then we proceed to discuss different channel allocation schemes within each category.

Channel Allocation Schemes

What Is Channel Allocation?

A given radio spectrum (or bandwidth) can be divided into a set of disjoint or noninterfering radio channels. All such channels can be used simultaneously while maintaining an acceptable received radio signal.[1] In order to divide a given radio spectrum into such channels many techniques such as frequency division (FD), time division (TD), or code division (CD) can be used. In FD, the spectrum is divided into disjoint frequency bands, whereas in TD the channel separation is achieved by dividing the usage of the channel into disjoint time periods called time slots. In CD, the channel separation is achieved by using different modulation codes. Furthermore, more elaborate techniques can be designed to divide a radio spectrum into a set of disjoint channels based on combining the above techniques. For example, a combination of TD and FD can be used by dividing each frequency band of an FD scheme into time slots. The major driving factor in determining the number of channels with certain quality that can be used for a given wireless spectrum is the level of received signal quality that can be achieved in each channel.

Let $S_i(k)$ be denoted as the set (i) of wireless terminals that communicate with each other using the same channel k. By taking advantage of physical characteristics of the radio environment, the same channel k can be reused simultaneously by another set j if the members of sets i and j are spaced sufficiently apart. All such sets which use the same channel are referred to as *co-channel sets* or simply *co-channels*. The minimum distance at which co-channels can be reused with

[1] *In practice, each channel can generate some interference in the adjacent channels. However, the effect of such interference can be reduced by adequate adjacent channel separation.*

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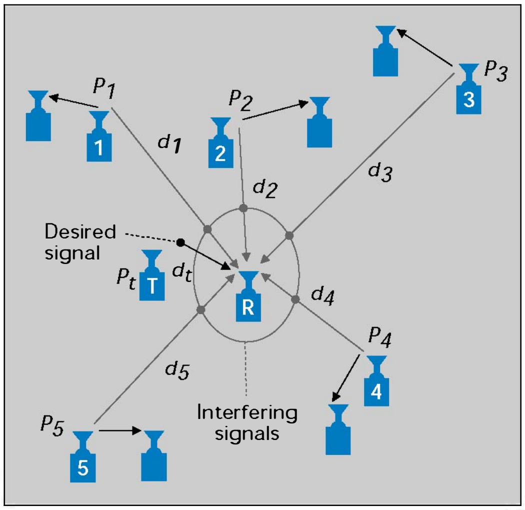
acceptable interference is called the "*co-channel reuse distance*," σ.

This is possible because due to propagation path loss in the radio environment, the average power received from a transmitter at distance d is proportional to $P_T d^{-\alpha}$ where α is a number in the range of 3–5 depending on the physical environment, and P_T is the average transmitter power. For example, for an indoor environment with α = 3.5, the average power at a distance $2d$ is about 9 percent of the average power received at distance d. Thus, by adjusting the transmitter power level and/or the distance between co-channels, a channel can be reused by a number of co-channels if the CIR in each co-channel is above the required value CIR_{min}. Here the carrier (C) represents the received signal power in a channel, and the interference (I) represents the sum of received signal powers of all co-channels.



■ **Figure 1.** *Interference.*

As an example, consider Fig. 1 where a wireless station labeled R is at distance d_t from a transmitter station labeled T using a narrowband radio channel. We refer to the radio channel used by T to communicate to R as the reference channel. In this figure, we have also shown five other stations labeled 1, 2, …, 5, which use the same channel as the reference channel to communicate with some other stations. Denoting the transmitted power of station i by P_i and the distance of station i from R by d_i, the average CIR at the reference station R is given by:

$$\mathrm{CIR} = \frac{P_t d_t^{-\alpha}}{\sum^{5} P_i d_i^{-\alpha} + N_0} \qquad (1)$$

where N_0 represents the environmental noise. To achieve a certain level of CIR at the reference station R, different methods can be used. For example, the distance between stations 1, 2, …, 5 using the co-channel and the reference station R can be increased to reduce the co-channel interference level. Many channel allocation schemes are based on this idea of physical separation. Another solution to reduce the CIR at R is to reduce the interfering powers transmitted from five interfering stations and/or to increase the desired signal's power level P_t. This is the idea behind power control schemes. These two methods present the underlying concept for channel assignment algorithms in cellular systems. Each of these algorithms uses a different method to achieve a CIR_{min} at each mobile terminal by separating co-channels and/or by adjusting the transmitter power.

Different Channel Allocation Schemes

Channel allocation schemes can be divided into a number of different categories depending on the comparison basis. For example, when channel assignment algorithms are compared based on the manner in which co-channels are separated, they can be divided into fixed channel allocation (FCA), dynamic channel allocation (DCA), and hybrid channel allocation (HCA).

In FCA schemes, the area is partitioned into a number of cells, and a number of channels are assigned to each cell according to some reuse pattern, depending on the desired signal quality. FCA schemes are very simple, however, they do not adapt to changing traffic conditions and user distribution. In order to overcome these deficiencies of FCA schemes, DCA strategies have been introduced.

In DCA, all channels are placed in a pool and are assigned to new calls as needed such that the CIR_{min} criterion is satisfied. At the cost of higher complexity, DCA schemes provide flexibility and traffic adaptability. However, DCA strategies are less efficient than FCA under high load conditions. To overcome this drawback, HCA techniques were designed by combining FCA and DCA schemes.

Channel assignment schemes can be implemented in many different ways. For example, a channel can be assigned to a radio cell based on the coverage area of the radio cell and its adjacent cells such that the CIR_{min} is maintained with high probability in all radio cells. Channels could be also assigned by taking the local CIR measurements of the mobile's and base station's receiver into account. That is, instead of allocating a channel blindly to a cell based on worst-case conditions (such as letting co-channels be located at the closest boundary), a channel can be allocated to a mobile based on its local CIR measurements [3, 4].

Channel assignment schemes can be implemented in centralized or distributed fashion. In the centralized schemes the channel is assigned by a central controller, whereas in distributed schemes a channel is selected either by the local base station of the cell from which the call is initiated or selected autonomously by the mobile. In a system with cell-based control, each base station keeps information about the current available channels in its vicinity. Here the channel availability information is updated by exchange of status information between base stations. Finally, in autonomously organized distributed schemes, the mobile chooses a channel based on its local CIR measurements without the involvement of a central call assignment entity. Obviously, this scheme has a much lower complexity at the cost of lower efficiency. It is important to note that channel assignment based on local assignment can be done for both FCA and DCA schemes.

Fixed Channel Allocation

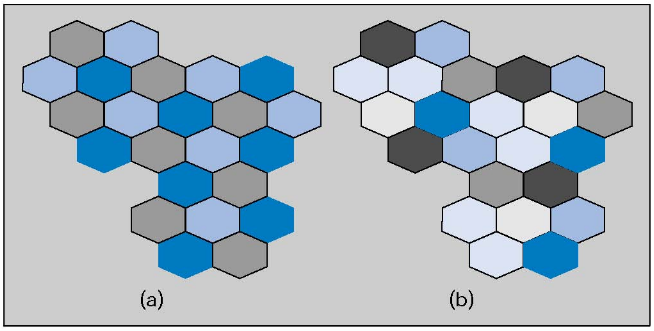
In the FCA strategy a set of nominal channels is permanently allocated to each cell for its exclusive use. Here a definite relationship is assumed between each channel and each cell, in accordance to *co-channel reuse constraints* [5–12].

The total number of available channels in the system C is divided into sets, and the minimum number of channel sets N required to serve the entire coverage area is related to the reuse distance s as follows [6, 12]:

$$N = (1/3)\sigma^2, \text{ for hexagonal cells} \qquad (2)$$

Here σ is defined as D/R_a, where R_a is the radius of the cell and D is the physical distance between the two cell centers [5]. N can assume only the integer values 3, 4, 7, 9, … as generally presented by the series, $(i + j)2 - ij$, with i and j being integers [5, 7]. Figures 2a and 2b give the allocation of channel sets to cells for $N = 3$ (σ = 3) and $N = 7$ (σ = 4.45), respectively.

In the simple FCA strategy, the same number of nominal channels is allocated to each cell. This uniform channel distribution is efficient if the traffic distribution of the system is also uniform. In that case, the overall average blocking proba-



■ **Figure 2.** *a) N = 3; b) N = 7.*

bility of the mobile system is the same as the call blocking probability in a cell. Because traffic in cellular systems can be nonuniform with temporal and spatial fluctuations, a uniform allocation of channels to cells may result in high blocking in some cells, while others might have a sizeable number of spare channels. This could result in poor channel utilization. It is therefore appropriate to tailor the number of channels in a cell to match the load in it by *nonuniform channel allocation* [13, 14] or *static borrowing* [15, 16].

In nonuniform channel allocation the number of nominal channels allocated to each cell depends on the expected traffic profile in that cell. Thus, heavily loaded cells are assigned more channels than lightly loaded ones. In [13] an algorithm, namely *nonuniform compact pattern allocation*, is proposed for allocating channels to cells according to the traffic distribution in each of them. The proposed technique attempts to allocate channels to cells in such a way that the average blocking probability in the entire system is minimized. Let there be N cells and M channels in the system. The allocation of a channel to the set of co-channel cells forms a pattern which is referred to as the *allocation pattern* [13]. In addition, the *compact allocation pattern* of a channel is defined as the pattern with minimum average distance between cells. Given the traffic loads in each of the N cells and the possible compact pattern allocations for the M channels, the *nonuniform compact pattern allocation* algorithm attempts to find the compatible compact patterns that minimize the average blocking probability in the entire system as nominal channels are assigned one at a time. A similar technique for nonuniform channel allocation is also employed in the algorithms proposed in [14].

Simulation results in [13] show that the blocking probability using nonuniform compact pattern allocation is always lower than the blocking probability of uniform channel allocation. It is interesting to note that the reduction of blocking probability is almost uniformly 4 percent for the range of traffic shown in [13].[2] Also for the same blocking probability, the system can carry, on the average, 10 percent (maximum 22 percent) more traffic with the use of the nonuniform pattern allocation [13].

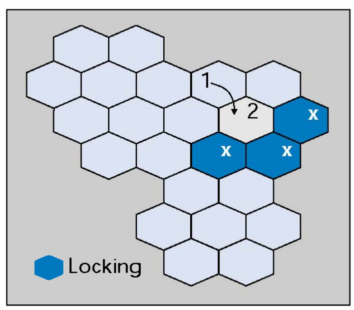
In the static borrowing schemes proposed in [15, 16], unused channels from lightly loaded cells are reassigned to heavily loaded ones at distances ≥ the minimum reuse distance σ. Although in static borrowing schemes channels are permanently assigned to cells, the number of nominal channels assigned in each cell may be reassigned periodically according to spatial inequities in the load. This can be done in a *scheduled* or *predictive* manner, with changes in traffic known in advance or based on measurements, respectively.

Channel Borrowing Schemes

In a channel borrowing scheme, an acceptor cell that has used all its nominal channels can borrow free channels from its neighboring cells (donors) to accommodate new calls. A channel can be borrowed by a cell if the borrowed channel does not interfere with existing calls. When a channel is borrowed, several other cells are prohibited from using it. This is called *channel locking*. The number of such cells depends on the cell layout and the type of initial allocation of channels to cells. For example, for a hexagonal planar layout with reuse distance of one cell ($\sigma = 3$), a borrowed channel is locked in three additional neighboring cells, as is shown in Fig. 3, while for a one-dimensional layout or a hexagonal planar grid layout with two-cell reuse distance, it is locked in two additional neighboring cells.

In contrast to static borrowing, channel borrowing strategies deal with short-term allocation of borrowed channels to cells; once a call is completed, the borrowed channel is returned to its nominal cell. The proposed channel borrowing schemes differ in the way a free channel is selected from a donor cell to be borrowed by an acceptor cell.

The channel borrowing schemes can be divided into *simple* and *hybrid*. In simple channel borrowing schemes, any nominal channel in a cell can be borrowed by a neighboring cell for temporary use. In hybrid channel borrowing strategies, the set of channels assigned to each cell is divided into two subsets, A (standard or local channels) and B (nonstandard or borrowable channels). Subset A is for use only in the nominally assigned cell, while subset B is allowed to be lent to neighboring cells. Table 1 summarizes the channel borrowing schemes proposed in the literature. In the next two subsections we discuss the simple and hybrid borrowing schemes in detail.



■ **Figure 3.** *Channel locking.*

Simple Channel Borrowing Schemes — In the simple borrowing (SB) strategy [15–20], a nominal channel set is assigned to a cell, as in the FCA case. After all nominal channels are used, an available channel from a neighboring cell is borrowed. To be available for borrowing, the channel must not interfere with existing calls. Although channel borrowing can reduce call blocking, it can cause interference in the donor cells from which the channel is borrowed and prevent future calls in these cells from being completed [21].

As shown in [20], the SB strategy gives lower blocking probability than static FCA under light and moderate traffic, but static FCA performs better in heavy traffic conditions. This is due to the fact that in light and moderate traffic conditions, borrowing of channels provides a means to serve the fluctuations of offered traffic, and as long as the traffic intensity is low the number of donor cells is small. In heavy traffic, the channel borrowing may proliferate to such an extent, due to channel locking, that the channel usage efficiency drops drastically, causing an increase in blocking probability and a decrease in channel utilization [22].

Because the set of borrowable channels in a cell may contain more than one candidate channel, the way a channel is selected from the set plays an important role in the performance of a channel borrowing scheme. The objective of all the schemes is to reduce the number of locked channels

[2] *Call arrival rates of 20–200 calls/s for each cell.*

Category	Scheme
Simple channel borrowing	Simple borrowing (SB) Borrow from the richest (SBR) Basic algorithm (BA) Basic algorithm with reassignment (BAR) Borrow first available (BFA)
Hybrid channel borrowing	Simple hybrid borrowing scheme (SHCB) Borrowing with channel ordering (BCO) Borrowing with directional channel locking (BDCL) Sharing with bias (SHB) Channel assignment with borrowing and reassignment (CABR) Ordered dynamic channel assignment with rearrangement (ODCA)

Table 1. *Channel borrowing schemes.*

caused by channel borrowing. The difference between them is the specific algorithm used for selecting one of the candidate channels for borrowing. Along these lines, several variations of the SB strategy have been proposed where channels are borrowed from nonadjacent cells [13, 15, 16, 17, 19, 20]. In the following, we discuss briefly each of the proposed schemes.

Borrow from the Richest (SBR) — In this scheme, channels that are candidates for borrowing are available channels nominally assigned to one of the adjacent cells of the acceptor cell [15]. If more than one adjacent cell has channels available for borrowing, a channel is borrowed from the cell with the greatest number of channels available for borrowing. As discussed earlier, channel borrowing can cause channel locking. The SBR scheme does not take channel locking into account when choosing a candidate channel for borrowing.

Basic Algorithm (BA) — This is an improved version of the SBR strategy which takes channel locking into account when selecting a candidate channel for borrowing [15, 16]. This scheme tries to minimize the future call blocking probability in the cell that is most affected by the channel borrowing. As in the SBR case, channels that are candidates for borrowing are available channels nominally assigned to one of the adjacent cells of the acceptor cell. The algorithm chooses the candidate channel that maximizes the number of available nominal channels in the worst-case nominal cell[3] in distance σ to the acceptor cell.

Basic Algorithm with Reassignment (BAR) — This scheme provides for the transfer of a call from a borrowed channel to a nominal channel whenever a nominal channel becomes available. The choice of the particular borrowed channel to be freed is again made in a manner that minimizes the maximum probability of future call blocking in the cell most affected by the borrowing, as in the BA scheme [16].

Borrow First Available (BFA) — Instead of trying to optimize when borrowing, this algorithm selects the first candidate channel it finds [15]. Here, the philosophy of the nominal channel assignment is also different. Instead of assigning channels directly to cells, the channels are divided into sets, and then each set is assigned to cells at reuse distance σ. These sets are numbered in sequence. When setting up a call, channel sets are searched in a prescribed sequence to find a candidate channel.

***Performance Comparison* —** A general conclusion reached by most studies on the performance comparison of the previous schemes is that adopting a simple test for borrowing (e.g., borrowing the first available channel that satisfies the σ constraint) yields performance results quite comparable to systems which perform an exhaustive and complex search method to find a candidate channel [13, 15–17]. SBR, BA, and BFA were evaluated by simulation in [15] using a two-dimensional hexagonal cell layout with 360 service channels. The offered load was adjusted for an average blocking of 0.02. The results show that all three schemes exhibit nearly the same average blocking probability versus load with about 25 percent increase in offered load to achieve an average blocking of 0.02. The BFA has an advantage over the other two in that its computing effort and complexity are significantly less. Here the complexity of each algorithm is determined based on the average number of channel tests per call while searching for a candidate channel to borrow. In [15], simulation results showed a large variation in the complexity of these algorithms depending on network load. For example, for a 20 percent increase in the traffic, SBR requires 50 percent, and the BA 100 percent, more channel tests compared to BFA. A summary of the comparison results between the BFA, SBR, BA, and BAR schemes is given in Table 2.

Scheme	Complexity	Flexibility	Performance # of tests to locate borrowable channel
Borrow from the richest (SBR)	Moderate	Moderate	Few
Basic algorithm (BA)	High	Moderate	A lot
Basic algorithm with reassignment (BAR)	High	Moderate	A lot
Borrow first available (BFA)	Low	Low	Very few

Table 2. *Comparison between BFA, SBR, BA, and BAR.*

***Hybrid Channel Borrowing Schemes* —** In the following we will describe different hybrid channel borrowing schemes.

Simple Hybrid Channel Borrowing Strategy (SHCB) — In the SHCB strategy [5, 13, 17] the set of channels assigned to each cell is divided into two subsets, A (standard) and B (borrowable) channels. Subset A is nominally assigned in each cell, while subset B is allowed to be lent to neighboring cells. The ratio $|A|:|B|$ is determined a priori, depending on an estimation of the traffic conditions, and can be adapted dynamically in a scheduled or predictive manner [17].

Borrowing with Channel Ordering (BCO) — The BCO, introduced in [20] and analyzed in [13, 17], outperforms SHCB by dynamically varying the local to borrowable channel ratio according to changing traffic conditions [17, 20]. In the BCO strategy, all nominal channels are ordered such that the first channel has the highest priority for being assigned to the next local call, and the last channel is given the highest priority for being borrowed by the neighboring cells. A variation of the BCO strategy, called *BCO with reassignment*, allows intercel-

3 Those cells to which a given channel is nominally assigned are its nominal cells.

lular handoff, that is, immediate reallocation of a released high-rank channel to a call existing in a lower-rank channel in order to minimize the channel locking effect.

Borrowing with Directional Channel Locking (BDCL) — In the BCO strategy, a channel is suitable for borrowing only if it is simultaneously free in three nearby co-channel cells. This requirement is too stringent and decreases the number of channels available for borrowing. In the BDCL strategy, the channel locking in the co-channel cells is restricted to those directions affected by the borrowing. Thus, the number of channels available for borrowing is greater than that in the BCO strategy. To determine in which case a "locked" channel can be borrowed, "lock directions" are specified for each locked channel. The scheme also incorporates reallocation of calls from borrowed to nominal channels and between borrowed channels in order to minimize the channel borrowing of future calls, especially the multiple-channel borrowing observed during heavy traffic.

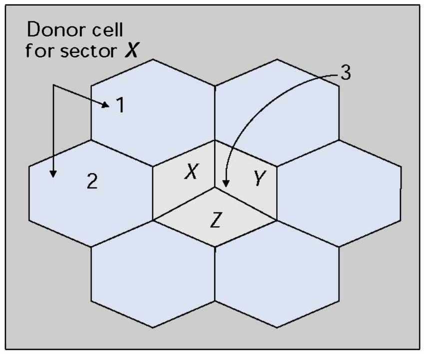


Figure 4. *Sharing with bias.*

***Performance Comparison* —** As shown by simulation in [13],[4] BDCL gives the lowest blocking probability, followed by BCO and FCA, for both uniform and nonuniform traffic. The reduction of the blocking probability for BDCL and BCO over FCA for the system in [13] is almost uniformly 0.04 and 0.03, respectively, for the range of traffic load tested.

Note that the nonuniform pattern allocation FCA scheme, discussed in the previous section, can be also applied in the case of the hybrid channel borrowing strategies. With the use of nonuniform pattern allocation the relative performance of the BDCL, BCO, and uniform FCA schemes remain the same as before, but the traffic-carrying capacity of a system can be increased by about 10 percent. This advantage is in addition to those gained from the channel borrowing strategies [13]. A summary of the comparison results between the BCO, BDCL, and FCA schemes is given in Table 3.

Sharing with Bias (SHB) — In [23] SHB was proposed: a scheme of channel borrowing with coordinated sectoring. The SHB strategy is similar to the join biased queue rule [24], which is a simple but effective way to balance the load of servers in the presence of unbalanced traffic. Each cell in the system is divided in three sectors, X, Y, Z, as shown in Fig. 4. Only calls initiated in one of these sectors can borrow channels from the two adjacent cells neighboring it (donor cells). In addition, the nominal channels in donor cells are divided in two subsets, A and B, as in the SHCB case. Channels from set A can only be used inside the donor cell, while channels in set B can be loaned to an acceptor cell.

[4] *The system in [13] consists of 49 hexagonal cells, where each cell is allocated 10 channels, and traffic load varying from 20–200 calls/h.*

An example is shown in Fig. 4. A call initiated in sector X of cell number 3 can only borrow a channel from set A of the cells numbered 1 and 2.

Channel Assignment with Borrowing and Reassignment (CARB) — The CARB scheme proposed in [16] is statistically optimum in a certain min-max sense. Here channels are borrowed on the basis of causing the least harm to neighboring cells in terms of future call blocking probability. Likewise, reassignment of borrowed channels is done in a way to cause maximum relief to neighboring cells.

Ordered Channel Assignment Scheme with Rearrangement (ODCA) — The ODCA scheme, proposed in [25], combines the merits of CARB and BCO with improvements to yield higher performance. In ODCA, when a call requests service, the base station of the cell checks to see if there are any nominal channels available. If there are channels available, the user will be assigned one on an ordered basis, as in BCO. Here all channels are numbered in predetermined order according to the same criterion as in the CARB scheme, and the lowest-numbered available idle channel is always selected. If all nominal channels are busy, the cell may borrow a *nonstandard* channel from a neighboring cell. Once a nonstandard channel is assigned, the availability lists of all affected cells where the assigned channel can cause interference are updated. Whenever a channel is no longer required, the availability lists of the affected cells are updated accordingly. Whenever a standard channel is available, the channel reassignment procedure is initiated to ensure efficient utilization. If there is a nonstandard channel in use in the cell, the call served by that channel is switched to the newly freed standard channel; the necessary availability lists are also updated. If no nonstandard channels are used in the cell, a call served by a standard channel with lower priority than the newly freed one is switched to the newly freed channel [25].

***Performance Comparison* —** The performance of ODCA was studied in [25] for a highway microcellular environment with nonuniform tele-traffic load. Performance comparison with the FCA and CARB shows significant improvement. The ODCA scheme exhibits better channel utilization compared to the CARB and FCA; the ODCA scheme also performs better than CARB and FCA at blocking probabilities below 0.1. For example, at a blocking probability of 0.05 ODCA is capable of supporting 4 percent more traffic than CARB and 35 percent more traffic than FCA [25]. However, the ODCA scheme incurs a higher computational overhead in assigning and reassigning channels, and more frequent switching of channels due to the reassignment propagation effect. The performance comparison results between ODCA, CARB, and FCA schemes are summarized in Table 4. Finally, a summary of the comparison between FCA schemes is given in Table 5.

Category	Results
Traffic carried capacity	FCA, BCO, BDCL →
Blocking probability	BCDL, BCO, FCA →

Table 3. *Comparison betwen BCO, BDCL and FCA.*

Category	Results
Channel utilization	FCA, CARB, ODCA →
Computational complexity	ODCA, CARB, FCA →
Traffic carried capacity	FCA, CARB, ODCA →

Table 4. *Comparison between FCA, CARB, and ODCA.*

Scheme	Complexity	Flexibility	Performance
Simple FCA	Low	Low	Better than dynamic and hybrid borrowing in heavy traffic
Static borrowing	Low-moderate	Moderate	Better than FCA
Simple channel borrowing	Moderate-high	High	Better than FCA and static borrowing in light and moderate traffic
Hybrid channel borrowing	Moderate	Moderate	Better than FCA in light and moderate traffic Better than simple channel borrowing in heavy loads

■ **Table 5.** *Comparison between fixed channel allocationschemes.*

Dynamic Channel Allocation

Due to short-term temporal and spatial variations of traffic in cellular systems, FCA schemes are not able to attain high channel efficiency. To overcome this, DCA schemes have been studied during the past 20 years. In contrast to FCA, there is no fixed relationship between channels and cells in DCA. All channels are kept in a central pool and are assigned dynamically to radio cells as new calls arrive in the system [18, 26]. After a call is completed, its channel is returned to the central pool.

In DCA, a channel is eligible for use in any cell provided that signal interference constraints are satisfied. Because, in general, more than one channel might be available in the central pool to be assigned to a cell that requires a channel, some strategy must be applied to select the assigned channel [10]. The main idea of all DCA schemes is to evaluate the cost of using each candidate channel, and select the one with the minimum cost provided that certain interference constraints are satisfied. The selection of the cost function is what differentiates DCA schemes [10].

The selected cost function might depend on the future blocking probability in the vicinity of the cell, the usage frequency of the candidate channel, the reuse distance, channel occupancy distribution under current traffic conditions, radio channel measurements of individual mobile users, or the average blocking probability of the system [22].

Although many claims have been made about the relative performance of each DCA scheme to one or more alternative schemes, the trade-off and the range of achievable capacity gains are still unclear, and questions remain unanswered: How does each dynamic scheme produce its gain? What are the basic trade-offs? Why do some schemes work only under certain traffic patterns? Can different schemes be combined? What is the value of additional status information of the nearby cells? What is the best possible use of the bandwidth [18]?

Based on information used for channel assignment, DCA strategies could be classified either as call-by-call DCA or adaptive DCA schemes [27]. In the call-by-call DCA, the channel assignment is based only on current channel usage conditions in the service area, while in adaptive DCA the channel assignment is adaptively carried out using information on the previous as well as present channel usage conditions [27, 28]. Finally, DCA schemes can be also divided into centralized and distributed schemes with respect to the type of control they employ. Table 6 gives a list of the proposed DCA schemes.

Centralized DCA Schemes

In centralized DCA schemes, a channel from the central pool is assigned to a call for temporary use by a centralized controller. The difference between these schemes is the specific cost function used for selecting one of the candidate channels for assignment.

First Available (FA) — The simplest of the DCA schemes is the FA strategy. In FA the first available channel within the reuse distance encountered during a channel search is assigned to the call. The FA strategy minimizes the system computational time; and, as shown by simulation in [10] for a linear cellular mobile system, it provides an increase of 20 percent in the total handled traffic compared to FCA for low and moderate traffic loads.

Category Scheme	
Centralized DCA	First available (FA) Locally optimized dynamic assignment (LODA) Selection with maximum usage on the reuse ring (RING) Mean square (MSQ) Nearest neighbor (NN) Nearest neighbor + 1 (NN + 1) 1 - clique
Distributed DCA	Locally packing distributed DCA (LP-DDCA) LP-DDCA with ACI constraint Moving direction (MD)
CIR measurement DCA schemes	Sequential channel search (SCS) MSIR Dynamic channel selection (DCS) Channel segregation
One Dimension Systems	MINMAX Minimum interference (MI) Random minimum interference (RMI) Random minimum interference with reassignment (RMIR) Sequential minimum interference SMI

■ **Table 6.** *Dynamic channel allocation schemes.*

Locally Optimized Dynamic Assignment (LODA) — In the LODA strategy [13, 17] the selected cost function is based on the future blocking probability in the vicinity of the cell in which a call is initiated.

Channel Reuse Optimization Schemes — The objective of any mobile system is to maximize the efficiency of the system. Maximum efficiency is equivalent to maximum utilization of every channel in the system. It is obvious that the shorter the channel reuse distance, the greater the channel reuse over the whole service area. The cost functions selected in the following schemes attempt to maximize the efficiency of the system by optimizing the reuse of a channel in the system area.

Selection with Maximum Usage on the Reuse Ring (RING) — In the

RING strategy [10], a candidate channel is selected which is in use in the most cells in the co-channel set. If more than one channel has this maximum usage, an arbitrary selection among such channels is made to serve the call. If none is available, the selection is made based on the FA scheme.

Mean Square (MSQ), Nearest Neighbor NN) Nearest Neighbor plus One (NN + 1) — The MSQ scheme selects the available channel that minimizes the mean square of the distance among the cells using the same channel. The NN strategy selects the available channel occupied in the nearest cell in distance ≥ σ, while the NN + 1 scheme selects an eligible channel occupied in the nearest cell within distance ≥ σ + 1 or distance σ if an available channel is not found in distance σ + 1 [10].

Category	Results
Blocking probability	NN, MSQ, FA, NN+1 →
Forced termination rate	NN + 1, NN, MSQ, FA →
Channel changing	NN + 1, NN, MSQ, FA →
Carried traffic	NN, NN + 1, RING, MSQ, FA →

Table 7. *Channel reuse optimization schemes.*

***Performance Comparison* —** Computer simulations of FCA, MSQ, NN, and NN + 1 strategies show that under light traffic conditions, NN exhibits the lowest blocking rate, followed by MSQ, FA, and NN + 1 [27]. Also, the NN + 1 strategy, when applied to a microcellular system, leads to lower forced call termination and channel changing because the mobile unit is more likely to keep the same channel when it moves to an adjacent cell [29].

In addition, simulation results of FA, RING, and NN [10, 30] show that for both one- and two-dimensional mobile systems, all of the above schemes operate at very low blocking rates until the offered traffic reaches some critical value. A small increase in the offered traffic above this value produces a considerable increase in the blocking probability of new calls and results in very little increase in the traffic carried by the system; the load at which blocking begins to occur in one-dimensional systems [30] is somewhat greater than that in two-dimensional systems [10]. Finally, the simulation results in [30] show that strategies like RING and NN, which use a channel reuse optimization approach, are able to carry 5 percent more traffic at a given blocking rate of 3 percent compared to a channel assignment strategy like FA, which does not employ any channel reuse optimization. A summary of the performance comparison of the channel reuse optimization schemes is given in Table 7.

1-Clique — All four previous schemes employ local channel reuse optimization schemes. A global channel reuse optimization approach is used in the 1-clique strategy. The 1-clique scheme uses a set of graphs, one for each channel, expressing the non-co-channel interference structure over the whole service area for that channel. In each graph a vertex represents a cell, and cells without co-channel interference are connected with edges. Thus, each graph reflects the results of a possible channel assignment. A channel is assigned from the several possibilities such that as many vertices as possible still remain available after the assignment. This scheme shows a low probability of blocking, but when there are a lot of cells the required computational time makes quick channel selection difficult [26].

Schemes with Channel Rearrangement — Compared to FCA schemes, DCA schemes do not carry as much traffic at high blocking rates because they are not able to maximize channel reuse as they serve the randomly offered call attempts. In order to improve the performance of DCA schemes in large traffic conditions, channel reassignment techniques have been suggested [8, 10, 31]. The basic goal of channel reassignment is to switch calls already in process, whenever possible, from the channels these calls are using to other channels, with the objective of keeping the distance between cells using the same channel simultaneously to a minimum. Thus, channel reuse is more concentrated, and more traffic can be carried per channel at a given blocking rate.

Distributed DCA Schemes

Microcellular systems have shown great potential for capacity improvement in high-density personal communication networks [2, 32, 33, 34]. However, propagation characteristics will be less predictable and network control requirements more intense than in the present systems. Several simulation and analysis results have shown that centralized DCA schemes can produce near-optimum channel allocation, but at the expense of a high centralization overhead [28, 35–38]. Distributed schemes are therefore more attractive for implementation in microcellular systems, due to the simplicity of the assignment algorithm in each base station.

The proposed distributed DCA schemes use either local information about the current available channels in the cell's vicinity (*cell-based*) [39–42] or signal strength measurements [43–45].

In cell-based schemes a channel is allocated to a call by the base station at which the call is initiated. The difference with the centralized approach is that each base station keeps information about the current available channels in its vicinity. The channel pattern information is updated by exchanging status information between base stations. The cell-based scheme provides near-optimum channel allocation at the expense of excessive exchange of status information between base stations, especially under heavy traffic loads.

Particularly appealing are the DCA interference adaptation schemes that rely on signal strength measurements [43]. In these schemes a base station uses only local information, without the need to communicate with any other base station in the network. Thus, the system is self-organizing, and channels can be placed or added everywhere, as needed, to increase capacity or to improve radio coverage in a distributed fashion. These schemes allow fast real-time processing and maximal channel packing[5] at the expense of increased co-channel interference probability with respect to ongoing calls in adjacent cells, which may lead to undesirable effects such as interruption, deadlock, and instability.

Cell-Based Distributed DCA Schemes

Local Packing Dynamic Distributed Channel Assignment (LP-DDCA) — In the LP-DDCA scheme proposed in [39], each base station assigns channels to calls using the augmented channel occupancy (ACO) matrix, which contains necessary and sufficient local information for the base station to make a channel assignment decision. Let M be the total number of available channels in the system and k_i the number of neighboring cells to cell i within the co-channel interference distance. The ACO matrix, as shown in Table 8, has M + 1

[5] *Channel packing refers to the area where a channel cannot be reused and how closely these areas are packed.*

columns and $k_i + 1$ rows. The first M columns correspond to the M channels. The first row indicates the channel occupancy in cell i and the remaining k_i rows indicate the channel occupancy pattern in the neighborhood of i, as obtained from neighboring base stations. The last column of the matrix corresponds to the number of current available channels for each of the $k_i + 1$ co-channel cells. Thus, an empty column indicates an idle channel which can be assigned to cell i. When a call requests service from cell i, its base station uses the ACO matrix and assigns the first channel with an empty column. The content of the ACO table is updated by collecting channel occupancy information from interfering cells. Whenever a change of channel occupancy happens in one cell, the base station of the cell informs the base stations of all the interfering cells regarding the change in order to update the information in the local ACO matrices.

Base station number	Channel number								Number of assignable channels
	1	2	3	4	5	6	..	M	
i		x					..		0
i_1	x			x			..		0
i_2		x					..		2
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
i_{k_i}			x		x				4

Table 8. *ACO matrix at base station i.*

Adjacent Channel Interference Constraint — In addition to constraining co-channel interference, the design of a wireless cellular system must also include measures to limit adjacent channel interference (ACI). Channel impairments such as crosstalk, premature handoffs, and dropped calls may result from ACI, leading to degradation of quality of service. Although channel filters in both the base station and the mobile unit receivers significantly attenuate signal from adjacent channels, severe interference may occur in circumstances where the received signal level of an adjacent channel greatly exceeds that of the desired channel. This situation arises often in mobile cellular environments due to the distance differences between the mobile units and the base stations. To reduce ACI, typical cellular systems employing FCA avoid the use of adjacent channels in the same base station.

All the DCA schemes discussed so far assign channels to calls based on the constraint imposed only by co-channel interference, overlooking ACI. Any of the previous described DCA schemes could be modified so that they assign channels to calls respecting both the minimum co-channel interference and ACI constraints at the expense of a reduction in the total carried traffic.

LP-DDCA with ACI Constraint — In [10], a modified version of the LP-DDCA scheme was proposed that incorporates the ACI constraint.

The variation of LP-DDCA imposes additional conditions on the channel selection from the ACO matrix [40]. If the required channel separation between channels to avoid ACI interference is N_{adj}, the $N_{adj} - 1$ columns to the left and right of that channel should have empty entries in the first row of the ACO matrix. When a call requests service from cell i, its base station searches in the first row of the ACO matrix for a group of $2N_{adj} - 1$ consecutive empty entries where the center column of the group is empty. If successful, it assigns the channel; otherwise, the base station searches for $2N_{adj} - 1$ consecutive empty entries in the first row, where the center columns has only one mark. If a channel is found, it checks to see whether the cell that uses the channel has additional channels available. In that case, it sends a message to the corresponding cell, and the base station of that cell switches the call using the channel in relation to a new one. Thus, the base station of cell i can use the channel. Otherwise the call is blocked.

The simulation results of modified LP-DDCA [40] show that when the co-cell channel separation is less than four, which is the case in most real systems, the impact of the additional constraint on the complexity of the channel selection procedure is insignificant. Also, the fact that modified LP-DDCA is robust to ACI interference is primarily due to its ability to provide flexible reuse packing of channels by allowing up to one local reassignment to accommodate a new call.

Moving Direction (MD) — The MD strategy was proposed in [41, 42] for one-dimensional microcellular systems. In these systems, forced call termination and channel changing occur frequently because of their small cell size [42]. The MD strategy uses information on moving directions of the mobile units to decrease both the forced call termination blocking probability and the channel changing. An available channel is selected among those assigned to mobile units that are elsewhere in the service area and moving in the same direction as the mobile in question. The search for such a channel starts from the nearest noninterfering cell to the one where the new call was initiated, and stops at the cell that is α reuse distances away, where α is a parameter.

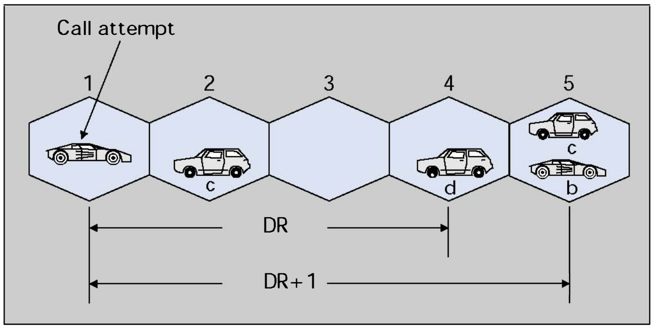
A channel assignment example is given in Fig. 5 where b, c, d, and e are the available channels, and DR is the minimum reuse distance. For this example the parameter α is set to one. The new call attempt is assigned channel b because the mobile requesting the channel is moving in the same direction as the mobile in cell number 5.

The sets of mobiles moving in the same direction and assigned the same channel are thus formed. Thus, when a mobile of a set crosses a cell boundary, it is likely that a same-set of mobiles has already crossed out of its cell to the next cell. In this manner, a mobile can use the same channel after handoff with higher probability. This lowers the probability of both changing channels and forced call termination. The strategy is efficient in systems where mobiles move at nearly the same speed through the cells laid along a road or a highway and for one-dimensional microcellular systems.

The simulation results in [42] for a one-dimensional system show that the MD strategy provides lower probability of forced call termination compared to the NN, NN + 1, and FCA strategies. Although the MD scheme has attractive features, it is not obvious how it could be expanded to a two-dimensional system. A summary of the comparison results is given in Table 9.

Signal Strength Measurement-Based Distributed DCA Schemes — A large body of research has been published on the performance analysis of channel allocation schemes, both FCA and DCA [3, 5, 12, 46, 47], in which knowledge of the mobiles' locations is not taken into account. In all of these schemes, channels are allocated to cells based on the assumption that the mobile may be located anywhere within the boundary of the cell. Thus, the packing of channels is not maximal. These schemes suffer from the fact that the selected fixed reusability distance might be too pessimistic.

In the interference adaptation schemes, mobiles measure the amount of co-channel interference to determine the reusability of the channel. If a mechanism is assumed to exist by which mobiles and base stations can measure the amount of interference, as was done in [48], then maximal channel



■ **Figure 5.** *Moving direction strategy illustration.*

packing could be achieved. An example of a system based on this principle is the Digital European Cordless Telecommunications (DECT) standard [49].

However, local decisions can lead to suboptimal allocation. In interference adaptation DCA schemes, mobiles and base stations estimate CIR and allocate a channel to a call when predicted CIRs are above a threshold. It is possible that this allocation will cause the CIR of established calls to deteriorate, in which case a *service interrupt* occurs. If the interrupted call cannot find an acceptable new channel immediately, the result is a premature service termination, referred to as *deadlock*. Even if the interrupted call finds an acceptable channel, setting up a link using the new channel can cause interruption of another established link. These successive interruptions are referred as *instability*. If no channel is available for the initial call request, the call is blocked [43, 50]

Sequential Channel Search (SCS) — The simplest scheme among the interference adaptation DCA schemes is the SCS strategy [43], where all mobile/base station pairs examine channels in the same order and choose the first available with acceptable CIR. It is expected that SCS will support a volume of traffic by suboptimal channel packing at the expense of causing many interruptions.

Minimum Signal-to-Noise Interference Ratio (MSIR) — In MSIR [43], a base station searches for the channel with the minimum interference ratio in the uplink direction. Because it first assigns unused or lightly loaded channels to new calls, MSIR has a relatively lower interruption probability than SCS; on the other hand, it is more vulnerable to blocking than SCS. It is generally observed by the simulation results that there is a trade-off between the goals of avoiding call blocking and avoiding interruptions [43].

Dynamic Channel Selection (DCS) — DCS, as presented in [51], is a fully distributed algorithm for flexible mobile cellular radio resource sharing based on the assumption that mobiles are able to measure the amount of interference they experience in each channel. In DCS, each mobile station estimates the interference probability and selects the base station which minimizes its value. The interference probability is a function of a number of parameters, such as the received signal power from base stations, the availability of channels, and co-channel interference. In order to evaluate the interference probability, specific models for each of the above parameters should be developed. In [70], models are developed to calculate probabilities of channel availability, desired carrier power, and the CIR for constant traffic load.

Channel Segregation — The channel segregation strategy was proposed in [44, 45] as a self-organized dynamic channel assignment scheme. By scanning all channels, each cell selects a vacant channel with an acceptable co-channel interference level. The scanning order is formed independently for each cell in accordance with the probability of channel selectability, $P(i)$, which is renewed by learning [44]. For every channel i in the system, each cell keeps the current value of $P(i)$. When a call request arrives at the base station, the base station channel with the highest value of $P(i)$ under observation is selected. Subsequently, the received power level of the selected channel is measured in order to determine whether the channel is used or not. If the measured power level is below (or above) a threshold value, the channel is determined to be idle (or busy). If the channel is idle, the base station starts communication using the channel, and its priority is increased. If the channel is busy, the priority of the channel is decreased and the next-highest-priority channel tried. If all channels are busy, the call is blocked [44, 45]. The value of $P(i)$ and the update mechanism determine the performance of the algorithm. In [44], $P(i)$ is updated to show the successful transmission probability on channel i as follows:

$$\begin{aligned} &P(i) = [P(i)N(i) + 1]/[N(i) + 1] \text{ and} \\ &N(i) = N(i) + 1 \text{ if the channel is idle} \\ &P(i) = [P(i)N(i)]/[N(i)+1] \text{ and} \\ &N(i) = N(i) + 1 \text{ if the channel is busy} \end{aligned} \tag{3}$$

Here $N(i)$ is the number of times channel i is accessed. In [45] the update mechanism for $P(i)$ is defined as $P(i) = N_s(i)/N(i)$, where $N_s(i)$ is the number of successful uses of channel i.

Because no channel is fixed to any specific cell, channel segregation is a dynamic channel assignment method. It is also autonomous, for no channel reuse planning is required and it is adaptive to changes in the mobile environment [45]. The simulation results in [44] show that the channel segregation scheme uses channels efficiently and decreases the number of intracell handoffs, that is, the reassignment of channels to avoid interference. It also decreases the load of the switching system as well as quality degradation during a handoff period [44]. Simulation results show that interference due to carrier sense error is reduced by 1/10–1/100 with channel segregation [44]. Also, the blocking probability is greatly reduced compared to FCA and DCA schemes. Speed of convergence to the optimum global channel allocation is an important issue in implementing channel segregation. Based on the analysis in [44], channel segregation quickly reaches some suboptimal allocation, but convergence to the optimum global allocation takes a prohibitively large amount of time because there are many local optimum allocations.

The discussion in [45] shows that channel segregation can be successfully applied to a TD multiple access/FD multiple access (TDMA/FDMA) or multicarrier TDMA system. As discussed in [45], the difference in the performance of the FDMA and TDMA/ FDMA systems using channel segregation is small, and one-carrier TDMA and FDMA have, in principle, similar performance. The advantages of *channel segregation* are summarized in Table 10.

One-Dimensional Cellular Systems

All the DDCA schemes described in this section are applicable for one-dimensional cellular mobile systems. One-dimensional structures can be identified in cases such as streets with tall buildings shielding interference on either side [50].

Minimum Interference (MI) — The MI scheme is well known and among the simplest for one-dimensional cellular systems. It is incorporated in the Enhanced Cordless Telephone (CT-2) and DECT systems [50]. We present here the MI and its modifications.

In an MI scheme, a mobile signals its need for a channel to

Category	Results
Blocking probability	NN, MD, NN + 1, FCA
Forced call termination	MD, NN + 1, NN, FCA
Channel changing	MD, NN + 1, FCA, NN
Carried traffic	FCA, NN + 1, NN, MD

Table 9. *Comparison between MD, NN, NN + 1, and FCA.*

Fully distributed
Autonomous
Adaptive to traffic changes
Decrease the number of intracell handoffs
Decrease load to switching system
Reduce interference due to carrier sense error
Reduce blocking probability
Quickly reaches a sub-optimal allocation

Table 10. *Advantages of channel segregation.*

its nearest base station. The base station then measures the interfering signal power on all channels not already assigned to other mobiles. The mobile is assigned the channel with the minimum interference. The order in which mobiles are assigned channels affects the efficiency of channel reuse. Taking into consideration the order of service we discuss three variations of the MI scheme:

- *Random minimum interference (RMI)*: In this scheme, the mobiles are served according to the MI scheme in a random order or, equivalently, in the order in which calls arrive in the system.
- *Random minimum interference with teassignment (RMIR)*: In RMIR, mobiles are first served according to the RMI scheme. Each mobile is then reassigned a channel by its base station according to the MI scheme. Those mobiles denied service by the initial RMI scheme also try to obtain a channel again. The order in which mobiles are reassigned is random. The number of times this procedure is carried out is the number of reassignments, R [50].
- *Sequential minimum interference (SMI)*: In the SMI scheme, mobiles are assigned channels according to the MI scheme in a sequential order. The sequence followed is such that any mobile is served only after all the mobiles that are ahead of it have had a chance to be served. This procedure would require some coordination between base stations because of the sequential order of service.

***MINMAX* —** Another scheme applicable for one-dimensional cellular systems is the MINMAX strategy. In this scheme a mobile is assigned a channel that maximizes the minimum of the CIRs of all mobiles being served by the system at that time. A mobile is served only after all mobiles to the left of it have had a chance to be served. This sequential (left to right) order of service is chosen because it appears to be the best way for reusing the channel [50]. The mobile immediately to the right of a given set of mobiles with channels assigned is the one that will cause the most interference at the base station servicing the given set of mobiles, and is also the one which has the most interference from that set of mobiles.

***Performance Comparison* —** In [50], RMI, RMIR, and SMI are compared for a one-dimensional microcellular system. Also, their performance was compared to the MINMAX scheme, which gives an upper bound on the performance of distributed channel assignment schemes for one-dimensional systems. The system performance is defined as the probability of call blocking as a function of load. The simulation results in [50] show that the call blocking probability decreases for FCA, RMI, RMIR, SMI, and MINMAX schemes in that order. RMI exhibits approximately 30 percent improvement in the blocking probability compared to FCA. RMIR gives an additional 8 percent improvement over RMI, and SMI gives an additional 2 percent over RMIR.

One would expect that the relative behavior of RMI, RMIR, SMI and MINMAX schemes would not change very much in a two-dimensional system; however, it is not obvious how one could implement these schemes in a two-dimensional system because an order of service is difficult to recognize in a two-dimensional system. A summary of the performance comparison between the *centralized*, *cell-based*, and *measurement-based* distributed DCA schemes is given in Table 11.

Comparison Between FCA and DCA

In general, there is a trade-off between quality of service, the implementation complexity of the channel allocation algorithms, and spectrum utilization efficiency.

Simulation [5, 9,10] and analysis [18] results show that under low traffic intensity, DCA strategies performs better. However, FCA schemes become superior at high offered traffic, especially in the case of uniform traffic. In the case of nonuniform traffic and light to moderate loads, it is believed that the DCA scheme will perform better due to the fact that under low traffic intensity, DCA uses channels more efficiently than FCA. In the FCA case channels are preassigned to cells, so there are occasions when, due to fluctuation in traffic, calls are blocked, even though there are channels available in adjacent cells. In addition, a basic fact of telephone traffic engineering is that a server with capacity C is more efficient than a number of small ones with the same total aggregate capacity. That is, for the same average blocking probability a system with high capacity has higher utilization [52]. FCA schemes behave like a number of small groups of servers, while DCA provides a way of making these small groups of servers behave like a larger server.

The initiation of requests for service from cell to cell is a random process; therefore, when dynamic assignment is used, different channels are assigned to serve calls at random too. Because of this randomness, it is found that cells which have borrowed the same channel for use are, on average, spaced a greater distance apart than the minimum reuse distance. Consequently, dynamic assignment schemes are not always successful in reusing the channels the maximum possible number of times. On the other hand, in FCA a specific channel can be assigned to cells that are the minimum distance apart such that no interference occurs. The assignment is done in such a way that the maximum reusability of channels is always achieved. That is why the FCA exhibits superior performance compared to DCA under heavy load conditions.

Simulation results [9, 15, 53] agree with the above and show that in the case of DCA schemes, the system is not overly sensitive to time and spatial changes in offered traffic, giving rise to almost stable performance in each cell. In addition, in the DCA the grade of service within an interference group of cells depends on the average loading within that group, not on its spatial distribution [9, 15, 53]. On the other hand, in the case of FCA the *service deviation*, a measure of the grade-of-service fluctuations from one cell to another, is very much worsened by time and spatial traffic changes.

In general, for the same blocking rate DCA has a lower forced call termination rate than FCA. In FCA a call must be handed off into another channel at every handoff because the same channel is not available in adjacent cells. In DCA the

	Centralized DCA	Cell-based Control distributed DCA	Measurement-based distributed DCA
Advantages	Near optimum channel allocation	Near optimum channel allocation	Sub-optimum channel allocation Simple assignment algorithm Use of local information Minimum communication with other base stations Self organized Increases system capacity, efficiency, radio coverage Fast real time processing Adaptive to traffic changes
Disadvantages	High centralized overhead	Extensive communication with other stations	Increased co-channel interference Increased interruption, deadlock probability and instability

■ **Table 11.** *Comparison between DCA schemes.*

same channel can be assigned in the new cell if co-channel interference does not occur. In microcellular systems, mobiles cross cell boundaries frequently and the traffic of each cell varies drastically. Thus, a large amount of channel assignment control is required, which results in frequent invocation of network control functions. Application of DCA schemes in these systems will be advantageous in solving the above problems due to flexibility in channel assignment. As shown by simulation in [54], the traffic performance of FCA deteriorates when cells are small, while DCA provides much steadier performance. If we also add the geographical load variations, the gain of DCA over FCA will be drastically increased.

System Complexity Comparison — In FCA, the assignment control is made independently in each cell by selecting a vacant channel among those allocated to that cell in advance. In DCA, the knowledge of occupied channels in other cells as well as in the cell in question is necessary. The amount of control is different in each DCA strategy. If the DCA requires a lot of processing and complete knowledge of the state of the entire system, the call setup delay would be significantly long without high-speed computing and signaling. As discussed in [55], the implementation complexity of the DCA is higher than FCA. The physical implementation of DCA requires a great deal of processing power to determine optimal allocations, and a heavy signaling load. On the other hand, FCA requires a complex and labor-intensive frequency planning effort to set up a system, which is not the case for the DCA schemes [40].

Regarding type of control, FCA is suitable for a centralized control system, while DCA is applicable to a decentralized control system. A centralized control scheme creates a huge control volume in a microcellular system, which can lead to bottleneck. One solution is to divide the control area into several subareas of suitable size. To capture all of the above trade-offs, a summary of the performance comparison of FCA and DCA schemes is given in Table 12.

Comparison Models — Due to the complexity of the problem, most of the performance comparison studies between FCA and DCA strategies are based on simulation models [18]. A principal problem with simulation comparison is the lack of common context and scenarios within each strategy. Thus, more unified realistic quantitative studies are necessary. Simulations to compare the performance must be done under common conditions such as cell structure, number of channels, and traffic intensity in each cell. In addition, simulation with time-varying traffic is necessary for more realistic scenarios.

The problem of performance analysis of cellular mobile systems using dynamic channel allocation has been discussed in several papers [3, 56, 57]. In [58] an improved simulation model suitable for future mobile systems was proposed which can be used for the teletraffic calculations and dimensioning of the system, and to describe the radio coverage of the system with an appropriate level of detail. The main difference between that model and ones used in other papers is that it allows overlapping cell areas.

If some practical aspects, such as fading handoffs and adjacent channel interference, are ignored, the channel assignment problem is essentially a queuing optimization problem [21]. Along these lines, Kelly [59, 60] studied analytically the benefits of *maximum packing* over FCA, providing a capacity upper bound for some dynamic schemes. The analysis in [61] finds a bound of the blocking probabilities for a similar system. In [62], a "Shannon type bound" for a single service class was derived. However, all of these studies ignore handoffs entirely. In [63], dynamic and fixed allocation using the notion of stochastic dominance, which incorporates handoffs, was studied. Furthermore, the conditions in which dynamic schemes, for the case of uniform traffic and well defined cells, perform better were derived [18].

In [18], a comparison is made between the maximum packing allocation,[6] fixed allocation, and optimal control policies.[7] Here the system model is a specific example of a multiple-server, multiple-resource system similar to that described in [64]. The cellular system is modeled as a multidimensional time-reversible Markov chain in which states are the number of calls in progress in each cell. The strength of the model is that both basic frequency reuse constraints and any additional DCA constraints can be incorporated in the same model; therefore, competing strategies can be compared equally and the differences between them easily understood. The principal weakness of the model is that it ignores handoffs, which is necessary to achieve a tractable form for the stationary distribution and optimal control. In addition, computational considerations limit the size of the state space for which the optimal policies under specific traffic loads can be calculated [18].

The analysis in [18] showed that for a symmetric cellular system (same size of cells, uniformly distributed traffic load), the total system throughput for the FCA, maximum packing, and optimal policies are increasing and concave with the increase in system capacity; the same behavior is observed in the case of an increase in cell load. At low loads, the total throughput under maximum packing is higher than under fixed allocation, while at high loads the total throughput under maximum packing is lower than under fixed allocation. Therefore, there exists a unique crossover point of the two throughputs versus load curves.

However, at low loads both policies achieve throughput close to the offered load, but maximum packing obtains a lower probability of blocking. At high loads both strategies

[6] *This provides an upper bound on the performance for every DCA policy.*

[7] *This provides an exact upper bound on the maximum achievable throughput of the system and gives insight on how increased performance is gained.*

FCA	DCA
Performs better under heavy traffic	Performs better under light/moderate traffic
Low flexibility in channel assignment	Flexible allocation of channels
Maximum channel reusability	Not always maximum channel reusability
Sensitive to time and spatial changes	Insensitive to time and time spatial changes
Not stable grade of service per cell in an interference cell group	Stable grade of service per cell in in an interference cell group
High forced call termination probability	Low to moderate forced call termination probability
Suitable for large cell environment	Suitable in micro-cellular environment
Low flexibility	High flexibility
Radio equipment covers all channels assigned to the cell	Radio equipment covers the temporary channels assigned to the cell
Independent channel - control fully centralized to fully distributed	Control dependent on the scheme
Low computational effort	High computational effort
Low call set up delay	Moderate to high call set up delay
Low implementation complexity	Moderate to high implementation complexity
Complex, labor intensive frequency planning	No frequency planning
Low signaling load	Moderate to high signaling load
Centralized control	Centralized, decentralized, distributed control depending on the scheme

Table 12. *Comparison between FCA and DCA.*

achieve a throughput close to the capacity of the cellular system, but FA obtains lower probability of blocking because it more often avoids states in which the instantaneous throughput is suboptimal.

At a moderate load it is natural to ask whether it might be valuable to combine these two strategies by reserving some of the channels for each cell and sharing the remainder among the cells. Indeed, as will be discussed in the next section, a lot of policies have been proposed along these lines. In [18] a policy was considered that at low loads resembles maximum packing, at high loads FCA.

Hybrid Channel Allocation

Hybrid channel assignment schemes are a mixture of the FCA and DCA techniques. In HCA, the total number of channels available for service is divided into *fixed* and *dynamic* sets. The fixed set contains a number of nominal channels that are assigned to cells as in the FCA schemes and, in all cases, are to be preferred for use in their respective cells. The second set of channels is shared by all users in the system to increase flexibility. When a call requires service from a cell and all of its nominal channels are busy, a channel from the dynamic set is assigned to the call. The channel assignment procedure from the dynamic set follows any of the DCA strategies described in the previous section. For example, in the studies presented in [5, 65], the FA and RING strategies are used, respectively, for DCA. Variations of the main HCA schemes include HCA with channel reordering [65] and HCA schemes where calls that cannot find an available channel are queued instead of blocked [6]. The call blocking probability for an HCA scheme is defined as the probability that a call arriving to a cell finds both the fixed and dynamic channels busy.[8]

Performance evaluation results of different HCA schemes have been presented in [5, 6, 8, 66]. In [5], a study is done for an HCA scheme with Erlang-b service discipline for uniform size and shape cells where traffic is uniformly distributed over the whole system. The measure of interest is the probability of blocking as the load increases for different ratios of fixed to dynamic cells. As shown in [5], for a system with fixed to dynamic channel ratio 3:1, the HCA gives a better grade of service than FCA for load increases up to 50 percent. Beyond this load HCA has been found to perform better in all cases studied in [5]. A similar pattern of behavior is obtained from the analysis in [6] where the HCA scheme employed uses the FA DCA scheme and Erlang-c service discipline (calls that cannot find an available channel are queued instead of blocked). In addition, the HCA scheme with Erlang-c service discipline [6] has lower probability of blocking than the HCA scheme with Erlang-b service discipline [5]. This phenomenon is expected because in the former case calls are allowed to be queued until they can be served.

The ratio of fixed to dynamic channels is a significant parameter which defines the performance of the system. It would be interesting to find the optimum ratio in order to achieve better system performance. In general, the ratio of fixed to dynamic channels is a function of the traffic load and would vary over time according to offered load distribution estimations.

Simulation results in [5, 6] showed that systems with the most dynamic channels give the lowest probability of queuing for load increase up to 15 percent over the basic load. For load increase of 15–32 percent, systems with the medium dynamic channels give the best performance. From load of 32–40 percent, systems with low dynamic channels give the best performance. Finally, for loads of over 40 percent systems with no dynamic channels give the best performance. The general nature of the results presented in [5, 6] is very reasonable. As discussed earlier, DCA performs best at low load offerings. When the load is increased substantially, the fixed allocation performs best because of its optimal reuse of the channel. HCA at load offerings close to the base load behaves as if the load offered to the dynamic channels is low. This is because the traffic offered is shared, though not equally, between the fixed and dynamic channels; therefore, there is not much blocking at low-percentage load increases. However, as the load increases more than a certain percentage above the base load, schemes with a lot of dynamic channels begin to block calls with substantial probability. This phenomenon is again a characteristic of the DCA scheme. In the case of nonuniform traffic distribution, a similar performance trend is expected when HCA is used. It is believed that the HCA scheme would show its superior performance with nonuniform traffic because it includes dynamic channels which could move around to serve the random fluctuation in the offered traffic [5, 6].

Studies in [5, 6, 8] have provided some simulation results for HCA schemes. Because simulation to study the behavior of a large system is time-consuming and costly, an analytical method would be appealing. Unfortunately, an exact analytical solution for the blocking probability in the HCA system is not feasible, and one must use approximations. In [66], two different approximating models were presented. In the first model the traffic offered in the dynamic channels is modeled as an interrupted poison process, while the second modeled

[8] *This is a simplified assumption; there is a possibility that some dynamic channels are free, but the call cannot use them because the interference constrains are violated.*

the system is modeled as a GI/M/m(m) queuing model. The blocking probability versus the arrival rate for both models present the same pattern of behavior as the simulation results of [5, 6].

Finally, HCA schemes have variants which add channel reordering, that is, switching channels assigned to some of the calls in progress to maintain a nearly optimum separation between coverage areas by simultaneously using the same channel in order to reduce inefficiency at high load. As in the hybrid borrowing strategy, channel reordering is done when nominal (fixed) channels become vacant. Namely, a nominal channel is assigned instead of the dynamic channel, which requires channel handoffs between occupied channels to realize an optimal allocation. This improves performance greatly by producing a significant increase in channel occupancy, but a huge amount of computing is required for channel rearrangement in a large system. For example, in the system analyzed in [65], which has a uniform distribution of fixed channels and was operated with a uniform spatial distribution of offered traffic, the channel occupancy was increased by two-thirds over a pure FCA system at the blocking rate of one percent. This corresponds to a channel savings of 40 percent for the same carried traffic at one percent blocking by the hybrid systems that were studied.

Hand-off prioritizing schemes provide improved performance at the expense of a reduction in the total admitted traffic and an increase in the blocking probability of new calls.

Flexible Channel Allocation

In the flexible channel allocation (FlCA) schemes, the set of available channels is divided into *fixed* and *flexible* sets. Each cell is assigned a set of fixed channels that typically suffices under a light traffic load. The flexible channels are assigned to those cells whose channels have become inadequate under increasing traffic loads. The assignment of these emergency channels among the cells is done in either a scheduled or predictive manner [67]. In the literature proposed FlCA techniques differ according to the time at which and the basis on which additional channels are assigned.

In the predictive strategy, the traffic intensity or, equivalently, the blocking probability is constantly measured at every cell site so that the reallocation of the flexible channels can be carried at any point in time [22]. Fixed and flexible channels are determined and assigned (or released) to (or from) each cell according to the change in traffic intensity or blocking probability measured in each cell. The number of dynamic channels required in a cell is determined according to the increase in measured traffic intensity. The acquired flexible channels can be used in a manner identical to the fixed channels in a cell as long as the cell possesses the channels. As long as a cell has several free fixed channels, no flexible channels are assigned to it if the traffic intensity is below a certain threshold [67.

If the flexible channels are assigned on a scheduled basis, it is assumed that the variation of traffic, such as the movement of traffic peaks in time and space, are estimated a priori. The change in assignment of flexible channels is then made at the predetermined peaks of traffic change [22].

Flexible assignment strategies use centralized control and require the central controller to have up-to-date information about the traffic pattern in its area in order to manage the assignment of the flexible channels [22]. In addition, the scheduled flexible assignment is not adaptive to unexpected changes of traffic. However, as presented in [67], the flexible allocation schemes sufficiently reduce the processing load of the system controller as compared to the DCA scheme.

Fixed and Dynamic Channel Allocation

Fixed and dynamic channel assignment is a combination of FCA and DCA which tries to realize the lower of each technique's blocking rate depending on traffic intensity. In low traffic intensity the DCA scheme is used; in heavy traffic situations the FCA strategy is used. The transition from one strategy to the other should be done gradually because a sudden transition will cause a lot of blocking. In [42], the authors developed an optimization model involving a single channel, a donor group, and an acceptor group of cells. An explicit formula is derived for the value of the load below dynamic assignment of the channel from the donor group to the acceptor group to minimized the overall blocking probability. This study analytically validates the belief that a strategy for DCA should be sensitive to the load of the system, and yields an important insight in that DCA should be disallowed in certain situations even if channels are free. The fixed and dynamic strategies allow assignment of channels in a dynamic fashion only if a minimum number of channels are free. This number depends on the value of the measured load. As the load increases, the minimum number of channels decreases; and eventually, under heavy loads, the scheme starts to resemble the fixed allocation scheme [42].

Handling Handoffs

All the allocation schemes presented in the previous sections did not take into account the effect of handoffs in the performance of the system. "Handoff" is defined as the change of radio channel used by a wireless terminal. The new radio channel can be with the same base station (intracell handoff) or with a new base station (intercell handoff).

In general, the handoff event is caused by the radio link degradation or initiated by the system that rearranges radio channels in order to avoid congestion. Our focus in this section is on the first kind of handoff, where the cause of handoff is poor radio quality due to a change in the environment or the movement of the wireless terminal. For example, the mobile subscriber might cross cell boundaries and move to an adjacent cell while the call is in process. In this case, the call must be handed off to the neighboring cell in order to provide uninterrupted service to the mobile subscriber. If adjacent cells do not have enough channels to support the handoff, the call is forced to be blocked. In systems where the cell size is relatively small (so-called microcellular systems), the handoff procedure has an important effect on the performance of the system. Here, an important issue is to limit the probability of forced call termination, because from the point of view of a mobile user forced termination of an ongoing call is less desirable than blocking a new call. Therefore, the system must reduce the chances of unsuccessful handoffs by reserving some channels explicitly for handoff calls. For example, handoff prioritizing schemes are channel assignment strategies that allocate channels to handoff requests more readily than new calls.

The queuing of hand-off requests, with or without the employment of guard channels, is another prioritizing scheme which reduces the probability of forced termination of hand-off calls at the expense of an increased call blocking probability and a decrease in the ratio of carried to admitted traffic.

Handoff prioritizing schemes provide improved performance at the expense of a reduction in the total admitted traffic and an increase in the blocking probability of new calls. Recently, a number of wireless call admission control schemes have been proposed and studied which can be used to limit the handoff blocking probability to a predefined level [68, 69]. Moreover, in [14, 29, 70–73] different prioritizing schemes were presented.

The simplest way of giving priority to handoff calls is to reserve some channels for handoff calls explicitly in each cell. In the literature, this scheme is referred to as the *cutoff priority scheme* (*CPS*) [14, 70, 71] or the *guard channel scheme* [72, 73]. Other prioritizing schemes allow either the handoff to be queued [71, 72] or new calls to be queued [73] until new channels are obtained in the cell. Several variations of the basic cutoff priority scheme, with queuing of handoff requests or of new call requests, have also been discussed in the literature [71–73].

The guard channel concept can be used in FCA or DCA schemes. Here guard channels are not assigned to cells permanently; instead, the system can keep a collection of channels to be used only for handoff requests, or have a number of flexible channels with associated probabilities of being allocated for handoff requests.

Guard Channels Schemes

The guard channel concept was introduced in the mid-'80s for mobile systems [70, 72, 74, 75]; however, policies based on guard channels, have long been used in telecommunication systems [76, 77].[9] The guard channel approach offers a generic means of improving the probability of successful handoffs by simply reserving a number of channels exclusively for handoffs in each cell. The remaining channels can be shared equally between handoffs and new calls. The penalty is a reduction in the total carried traffic due to the fact that fewer channels are granted to new calls. This disadvantage may be bypassed by allowing the queuing of new calls. Intuitively, we can say that the latter method is feasible because new calls are less sensitive to delay than handoff calls [22]. Another shortcoming of the employment of guard channels, especially with FCA schemes, is the risk of insufficient spectrum utilization. Careful estimation of channel occupancy time distributions and knowledge of the traffic pattern are essential in order to minimize this risk by determining the optimum number of guard channels [22].

Handoff Queuing Schemes

The queuing of handoff requests, with or without employing guard channels, is another prioritizing scheme which reduces the probability of forced termination of handoff calls at the expense of increased call blocking probability and a decrease in the ratio of carried to admitted traffic [71, 72]. The reason is that in this scheme no new call is granted a channel before the handoff requests in the queue are served. The scheme is briefly described as follows. When the power level received by the base station in the current cell reaches a certain threshold, namely the *handoff threshold*,[10] the call is queued for service from a neighboring cell. The call remains queued until either an available channel in the new cell is found or the power by the base station in the current cell drops below a second threshold, called the *receiver threshold*.[11] If the call reaches the receiver threshold and a new channel has not been found, then the call is terminated. Queuing handoff requests is made possible by the existence of the time interval that the mobile station (MS) spends between these two thresholds. This interval defines the maximum allowable waiting time in the queue [14, 22]. Based on the traffic pattern and the expected number of handoff requests, the maximum size of the handoff queue could be determined.

In the handoff queuing scheme, the probability of forced termination is decreased. However, a handoff call may still be dropped because the handoff requests can only wait until the receiver threshold is reached; in the case of high demand for handoffs, handoff calls will be denied queuing due to the limited size of the handoff queue. The basic queuing discipline in queuing handoff requests is first-in first-out (FIFO) [22, 70]. One of the goals of current research is to improve the performance of the handoff queuing scheme by modifying the queuing discipline . In [71], a nonpreemptive priority queuing discipline based on a mobile's subscriber measurement was used for queuing handoffs. A handoff request is ranked according to how close the mobile stands to, and possibly how fast it is approaching, the receiver level. Because the radio measurements are already made, there is no additional complexity in the employment of this scheme. The simulation and analysis results in [71] clearly indicate that the proposed scheme offers a better performance in terms of quality of service and spectrum efficiency.

New Call Queuing Schemes

The delay insensitivity of new calls makes it more feasible to queue new call attempts instead of handoff attempts. In [31], a method was proposed involving the introduction of guard channels and the queuing of new calls. The performance analysis in [73] showed that the blocking of handoff calls decreases much faster than the queuing probability of new calls increases; the result agrees with the analysis in [72]. In addition, the analysis in [31] shows that the method not only minimizes blocking of handoff calls, but also increases total carried traffic. This is due to the fact that the decrease in the blocking probability of handoff calls results in an increase of total carried traffic; and because the new calls are allowed to be queued, they will ultimately receive service. Thus, the total traffic carried by the system is increased. The gain in total carried traffic between a system with guard channels and queuing of new calls and one without queuing is substantial: about 2.4 Erlangs for a system with 44 channels and 38 Erlangs of offered traffic [73].

System Dimensioning Procedures for Prioritized Channel Assignment

In systems with prioritized channel assignment, one important issue is to decide the minimum number of guard channels required in each cell so that a desired level of quality of service (in terms of a limit on forced termination probability) for

9 *Referred as "trunk reservation schemes."*

10 *The handoff threshold is set at the point where the power received by the base station in a neighboring cell has started to exceed the power received by the current base station.*

11 *The receiver threshold is the point at which the received power from the current base station is at the minimum acceptable level [22].*

handoff calls is met. Traffic models and performance measures of typical handoff priority schemes are discussed in [14, 70, 72, 73]. FCA with priority is simulated, and a method for selecting the number of reserved channels suggested, in [75]. However, this scheme fails to guarantee a prescribed level of quality of service (in terms of call acceptance probability) for new call attempts. Here, the overall blocking probability is used as the performance measure, and due to the computational intensity of simulation and its long runtime, it may not be used adaptively to deal with changes in traffic parameters such as arrival rates and/or holding times of calls.

In [14], dimensioning procedures for prioritized channel assignment were considered. Moreover, under the cutoff priority discipline, the prioritized channel assignment procedure for single- and multicell systems were formulated as nonlinear discrete capacity allocation problems. Exact incremental algorithms which efficiently solve the proposed problems are derived based on the properties of the blocking probabilities of new and handoff calls. As shown from analysis in [71], for any ratio of guard to regular channels in a cell, the probability of blocking handoff calls is less than the probability of blocking new calls. Also, the probability of blocking handoff calls decreases whenever an additional channel is assigned to the cell. Finally, the probability of blocking new cell attempts is decreased if one or more channels are assigned as ordinary channel(s) to the cell and increases if one or more channels are assigned as guard channel(s) in the cell.

In the remainder of this section we briefly describe three different dimensioning procedures (algorithms SP1, SP2, and MP) proposed in [14]. Given the number of available channels together with the arrival rates and the required blocking probabilities for both new and handoff calls in each cell, SP1 generates an optimal channel assignment which ensures priority of handoff calls. Given the arrival rates of he required blocking probabilities for new and handoff calls, SP2 finds the minimum number of regular and guard channels required in each cell. Finally, algorithm MP extents algorithm SP1 to a multicell system and provides the prioritized channel assignment for all cells in the system.

Algorithm SP1 — Given the number of available channels in a cell, the arrival rate of new calls, and handoff calls, and a limit for blocking probability of new calls, algorithm SP1 generates an optimal channel assignment between regular and guard channels which ensures priority of handoff calls and guarantees the desired blocking probability of the new calls [14]. The algorithm is simple. First, the number of guard channels is set to zero, and the smallest number of ordinary channels (using the Erlang B formula) that guarantee the blocking probability for the new calls is found. Then the number of guard channels is incremented one at a time as far as the blocking probability for new calls is not violated, and the total number of ordinary and guard channels is less than the total number of channels allowed to the cell.

Algorithm SP2 — In cells with few call handoff attempts, only a small number of guard channels would sufficiently reduce the chances of unsuccessful handoffs. In order to avoid giving excessive priority to handoffs in these cells, a desired blocking probability of handoff calls can be prescribed in addition to the blocking probability of new calls. Given the arrival rates of both types of traffic and the distinct blocking probabilities of new and handoff calls, algorithm SP2 finds the minimum number of channels required in each cell in order to limit both probabilities of blocking to a guaranteed level. The procedure of SP2 is as follows. First, the number of ordinary channels is found so that the blocking probability of the new calls are met. Then, guard channels are added one at a time as long as the blocking probability of new calls is not violated and the total number of channels is less than the maximum available number of channels in the cell. If there are still channels available and the blocking probability of new calls is violated, the number of ordinary channels is increased by one and the procedure of adding new guard channels is repeated.

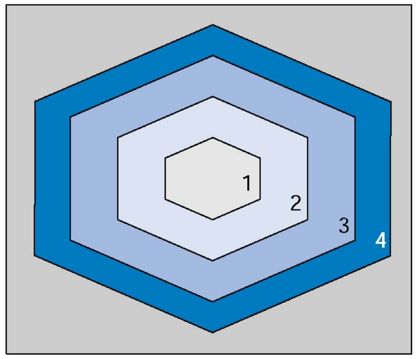


Figure 6. *Concentric sub-cells.*

Algorithm MP — The previous two algorithms are applicable in a single cell system. Algorithm MP extents algorithm SP1 in a multicell system and provides the prioritized channel assignment for all cells in the system. The model could be extended in a multicell environment where the weighted average of the blocking probability of handoff calls is used as the performance measure for the entire system. In FCA, the total number of available channels in the system is divided into disjoint sets. Each channel set is then assigned to cells in the noninterfering cell cluster, and clusters are deployed in a regular pattern to provide continuous service across the service region. By applying the MP algorithm to each cluster in the system, the procedure can be implemented adaptively so that the total number of channels in the cluster is allocated to cells according to the traffic fluctuation. Given the arrival rates of handoff and new calls in each cell of the cluster and the desired probabilities of blocking of new calls in each cell in the cluster, algorithm MP finds the best allocation of regular and guard channels in each cell of the cluster so that a weighted average of the blocking probabilities of handoff calls is minimized; details of the procedure are given in [14].

Algorithm SP1 could be incorporated into a fixed allocation procedure very well. Given the set of nominal channels allocated to each cell by an FCA scheme, it determines the number of guard channels in each cell. The algorithm can be executed in each cell site separately.

Algorithm SP2 can be applied to various assignment schemes. For example, it can be incorporated in the FCA scheme described in [67] in both the scheduled and predictive cases. If algorithm SP2 is applied to this scheme, not only the total number of channels but also the ratio between the ordinary and guard channels in each cell can be determined. The third scheme could be applied to both the fixed and flexible assignment schemes. Given the number of available channels in the cluster, it determines the number of ordinary and guard channels for each cell in the cluster. The third algorithm for the cluster may, because of interference issues, force a nonoptimal assignment in other clusters, but this problem is common anyway to systems that employ the fixed allocation scheme.

All three algorithms can solve problems of practical size efficiently; therefore, they can be incorporated into an adaptive assignment scheme where new assignment of channels must be provided immediately whenever arrival rates of calls of both types of traffic vary with time.

Reuse Partitioning

What Is Reuse Partitioning?

Reuse partitioning (RUP) is an effective concept to get high spectrum efficiency in cellular systems. In RUP, as shown in

Category	Scheme
Fixed reuse partitioning	Simple reuse partitioning Simple sorting channel assignment algorithm
Adaptive reuse partitioning	Autonomous reuse partitioning ARP Flexible reuse FRU DDCA All channel con-centric allocation ACCA Self organized reuse partitioning SORP

Table 13. *Reuse partitioning.*

Fig. 6, each cell in the system is divided into two or more cocentric subcells (zones). Because the inner zones are closer to the base station located at the center of the cell, the power level required to achieve a desired CIR in the inner zones can be much lower compared to the outer zones. Thus, the channel reuse distance (i.e., the distance between cells using the same channel) can be smaller for the inner zones than for the outer ones, resulting in higher spectrum efficiency. Reuse partitioning schemes could be divided into fixed [37, 57, 78, 79] and adaptive [41, 80–85], and are summarized in Table 13. We discuss these schemes in the following subsections.

Fixed Reuse Partitioning

Simple Reuse Partitioning — Simple RUP was introduced in [78]. In this scheme, available channels are split among several overlaid cell plans with different reuse distances. The underlying principle behind RUP [78, 79] is to reduce signal-to-interference ratio (SIR) for those units that already have more than adequate transmission quality while offering greater protection to those units that require it. The goal is to produce an overall SIR distribution that satisfies system quality objectives while bringing about a general increase in system capacity. For the same SIR objective, reuse partitioning has the potential to obtain a significant increase in system capacity when compared to a system that uses only a single reuse factor [78].

Simple RUP can be implemented by dividing the spectrum allocation into two [37, 78, 79] or more [57] groups of mutually exclusive channels. Channel assignment within the *i*th group is then determined by the reuse factor N_i for that group. Mobile units with the best received signal quality will be assigned to the group of channels with the smallest reuse value factor value, while those with the poorest received signal quality will be assigned to the group of channels with the largest reuse factor value. As the received signal quality for a mobile unit changes, it can be handed off to a channel that belongs to a different reuse group on the same zone at the same cell, to a channel that belongs to the same or to a different group on another zone at the same cell, or to a channel belonging to the same or a different group at another cell. Typically, the mobile units closer to a cell site will be served by channels from a group having a small value of N_i [78].

There are two main design issues related to the simple RUP concept. The first issue is the capacity allocation problem, which is to decide how many channels should be assigned to each zone. The second issue is the actual assignment of channels to calls. In [57] the performance limits of the RUP concept were explored, and methods for allocating capacity to the different cell zones as well as optimum real-time channel assignment schemes have been presented [57, 86].

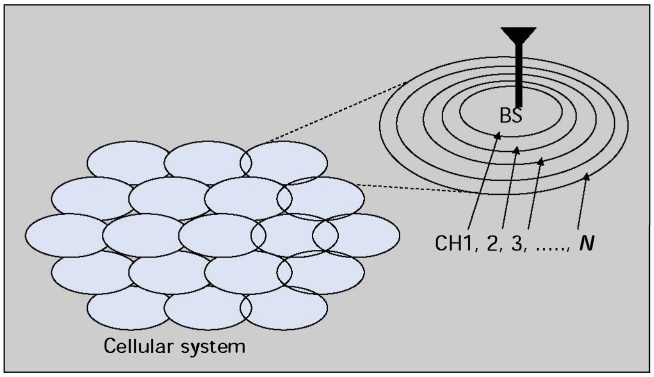
Simple Sorting Channel Assignment Algorithm — In [57, 86], a generalized RUP method called the "simple sorting channel assignment algorithm" is presented. Here, each cell is divided into a number of cocentric zones and assigned a number of channels, as in simple RUP. For each mobile in the cell, the base station measures the level of SIR and places the measurements in a descending order. Then it assigns channels to the set of at most M mobiles with the largest values of SIR, where M is the number of available channels in the entire cell. The mobile in the set with the smallest value of SIR is assigned a channel from the outer cell zone. The assignment of mobile channels according to ascending values of SIR continues until all channels from the outer zone are used. The base station continues to assign channels in the next zone, and so on, until all mobiles in the set have been assigned channels [86].

As shown in [86], the simple sorting channel algorithm achieves almost optimum performance. It also allows 1.4–3 times more traffic than the FCA scheme [86]. An important remaining issue is that the sorting scheme only determines which cell plan each mobile should use; it does not assign actual channels, which must be done with some care. In addition, if all cells using a certain channel group started the channel assignment by using the first channel in the group, we would get an exceptionally high interference level on that particular channel. A random selection procedure would be one way to solve this problem [86].

Performance Comparison — The simple RUP schemes proposed in [57, 78, 79, 86] are improved versions of the FCA scheme. Therefore, they suffer from the drawbacks of the FCA schemes, such as the difficulty in handling time-variant traffic [12]. In addition, the employment of microcells in a system results in increasing complexity of propagation patterns and further complicates the reuse pattern design process. When the RUP concept is applied to a microcellular system, the planning or channel assignment becomes difficult because the distribution of channels among zones should be frequently changed to match the changes in traffic. In addition, the capacity allocated to different cell zones is based on an estimation of co-channel interference, which is harder task in a microcell environment due to complicated deformed cell shapes. Therefore, an autonomous or self-organized method for channel assignment is desired [44].

Adaptive Channel Allocation Reuse Partitioning Schemes

Several researchers have investigated adaptive channel allocation (ACA) RUP schemes in an attempt to avoid the drawbacks of the fixed RUP schemes [80–85]. With ACA RUP, any channel in the system can be used by any base station, as long as the required CIR is maintained. It should be noted that reducing the CIR margin in each channel leads to an improvement in the traffic handling capacity. Based on this fact, a number of approaches such as flexible reuse schemes [81] and self-organizing schemes [38, 80, 82, 84, 85, 87, 88] have been proposed. In [80], autonomous RUP (ARP) was proposed, which assigns to a call the first channel found to exceed a CIR threshold in an ordered sequential channel search for each cell. The ARP technique was further improved in another scheme called *flexible reuse*, in which the channel with the minimum CIR margin is assigned [81]. Another scheme based on the ARP concept, called the distributed control channel allocation (DCCA) scheme, was proposed in [87–89]. In [84] all-channel concentric allocation (ACCA), which is an improved distributed version of the RUP scheme, was proposed. Another scheme, self-organized RUP (SORP), which is based on signal power measurements at each station, was proposed in [85]. In [38, 82] the channel assignment



■ **Figure 7.** *Principle of the all-channel concentric allocation.*

under the RUP concept was formulated as an optimization problem that maximizes the number of served calls. In the following, we provide a detailed description and discussion of the above-mentioned RUP schemes.

Autonomous Reuse Partitioning — The first ACA RUP scheme — ARP — was discussed in [80]. It is based on the RUP concept and real-time CIR measurements. In this technique, all the channels are viewed in the same order by all base stations, and the first channel which satisfies the threshold condition is allocated to the mobile attempting the call. Thus, each channel is reused at a minimum distance with respect to the strength of the received desired signal. ARP easily achieves "reuse partitioning" in which channels higher in the order are used at shorter distance by mobile stations from which stronger signal levels are received at the base station. The resulting pattern is similar to that of the simple RUP [78]. In ARP base stations conduct their allocations independent of one another, and no cooperative control is necessary.

Performance of the ARP scheme has been evaluated in [80] by means of simulations. As compared to simple FCA, ARP doubles the traffic-handling capacity of the system and decreases the co-channel interference by 1/4. ARP improves the traffic handling at the cost of the SIR margin in each channel. This creates problems to fast-moving mobile stations such as car-mounted units, which suffer from rapid fluctuations in signal level. If power control is employed, an additional 9 percent improvement in the capacity is observed.

Flexible Reuse — The ARP was further improved in another ACA RUP scheme, flexible reuse (FRU) [81]. In the FRU scheme, whenever a call requests service, the channel with the smallest CIR margin among those available is selected. If there is no available channel, the call is blocked. Simulations in [81] showed that FRU can effectively improve system capacity, especially for users with portable units. More specifically, a capacity gain of 2.3–2.7 of FRU over FCA was observed. However, the FRU strategy requires a large number of CIR measurements, which makes it virtually impractical for high-density microcellular systems.

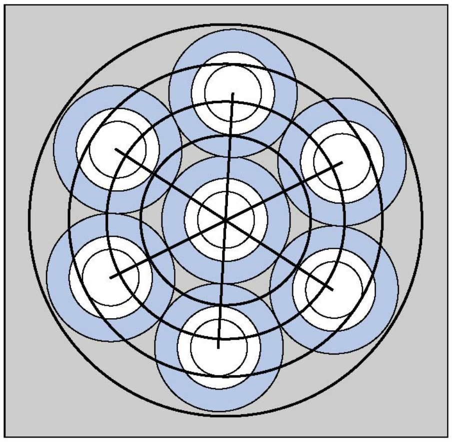
Self-Organized Reuse Partitioning Scheme — In [85] another SORP scheme was proposed. In this method, each base station has a table in which average power measurements for each channel in its cell and the surrounding cells are stored. When a call arrives, the base station measures the received power of the calling mobile station (in order to define at which subcell the mobile station is located) and selects a channel, which shows the average power closest to the measured power. The channel is used if available; otherwise, the second closest candidate is tried. The content of the table for the chosen channel is updated with the average value of the measured power and the power of the mobile stations using the same channel. The power level of the other mobile stations is broadcast by their base station. As a consequence of this procedure, in each base station channels that correspond to the same power are grouped autonomously for self-organized partitioning.

In [85], a performance comparison is made between SORP, conventional ARP, and random DCA schemes. The simulation analysis showed that SORP and ARP show almost the same performance, which is far superior to random DCA. Moreover, SORP can reduce the occurrence of intracell handoff and can reach a desired channel quickly, while achieving high traffic capacity. The essential difference between ARP and SORP is that ARP always senses the channels in the same order until one is available, while SORP learns which channel is proper for the calling mobile, so it can find a desired channel more quickly [85].

All-Channel Concentric Allocation — In [84] a dynamic channel assignment algorithm called "all-channel concentric allocation" (ACCA) was proposed, which is an extension of the RUP concept. Here, the RUP concept was extended as follows. All radio channels of a system are allocated nominally in the same manner for each cell, as in Fig. 7. Each cell is divided into *N* concentric regions; each region has its own channel allocation. Here, each channel is assigned a mobile belonging to the concentric region in which that channel is allocated, and has a specific desired signal level corresponding to the channel location. Therefore, each channel has its own reuse distance determined from the desired signal level. Thus, ACCA accomplishes effective channel allocation in a global sense, though it is a self-organizing distributed control algorithm. Computer simulations showed that the system capacity at a blocking rate of 3 percent is improved by a factor of 2.5 compared to the FCA. If, in addition, a transmitter power control is implemented on top of ACCA, the system accomplishes a capacity 3.4 times greater than FCA.

Distributed Control Channel Allocation (DCCA) — The recently proposed DCCA [87–89] is a dynamic channel allocation scheme based on the ARP concept. In this scheme all cells are identical, and channels are viewed in the same order, starting with channel number one, by all the base stations in the network. The decision to allocate a channel is made locally based on CIR measurements. The architecture of a cell in DCCA is shown in Fig. 8. It consists of an omnidirectional central station connected to six symmetrically oriented substations. The substations are simple transceivers, and can be switched on and off under the control of the main station. When the traffic density of the cell is low ,all the substations are off and the only operating station is the main station, at the center of the cell covering the entire cell area. Gradually, as call traffic increases, forced call blocking will occur due to an unacceptable level of co-channel interference or the unavailability of resources. In this case, the main base station switches on the nearest substation to the mobile unit demanding access. This in effect relocates the main base station closer to the mobile requesting service; therefore, CIR measurements will now be higher, thus improving the probability of finding an acceptable channel. If the traffic is reduced, the main station switches off a number of substations. The system therefore automatically adapts itself to time-variant call traffic density. As a result, an improvement in both system efficiency and traffic capacity can be achieved. As discussed in [89], the DCCA system results in lower probability of forced termination of calls. Computer simulation showed a drastic reduction in the number of handoffs and almost 50 percent less forced termination of calls compared to the ARP scheme.

All the above schemes can be implemented in a distributed manner. While the methods proposed above do actually increase capacity, they either require a large amount of CIR calculations [38, 81, 82], frequent rearrangement of channels [38, 82], and/or cooperative control among base stations in order to maintain an optimal allocation of channels to different cell zones. The proposed scheme in [38] is a CIR-adaptive but complicated method which showed a potential for producing excellent efficiency. It requires channel reassignment every 5 s for optimal performance and some data communication between base stations. Finally, in [83], the possibility of using Hopfield's neural network to solve the optimal channel assignment problem under the RUP concept was investigated. Although the idea is appealing, it is not practical for present systems. In Table 14, a summary of the important characteristics of channel allocation schemes based on reuse partitioning is provided.



■ **Figure 8.** *DCCA cell structure.*

Other Schemes

Overlapping Cells

Between the extreme schemes based on fixed allocation, there are many possible alternatives, hybrid schemes and schemes such as directed retry (DR) and directed handoff (DH), which take advantage of the fact that some percentage of the mobile stations may be able to obtain sufficient signal quality from two or more cells. With DR, if a call finds its first-attempt cell has no free channels, it can then try for a free channel in any other cell that can provide sufficient signal quality. The DH scheme takes this idea further, in that when a cell has all or almost all of its channels in use, it may, using DH, direct some of the calls currently in progress in its domain to attempt handoff to an adjacent cell . The motivation here is to attempt to redistribute calls in heavily loaded cells to lighter loaded cells [53].

Both the above schemes are expected to improve system performance. This improvement depends on the percentage of calls that could communicate with two or more cells simultaneously or equivalently to the percentage of overlapping between adjacent cells. This percentage has been reported to be as high as 30–45 percent [53], in which the performance of both the above schemes was compared with the MP dynamic scheme which provides an upper bound in the performance of DCA schemes. The conclusions reached by simulations in [53] were that both schemes improve the efficiency of the system. For the DR scheme an increase in the overlapping between cells leads to an increase in the grade of service provided by the system. In addition, the DH scheme has very good sensitivity properties with respect to variation in the spatial traffic profile of the system.

Selective Handover — Another scheme, selective handover for traffic balance (SHOT), is based on the concept of FCA and overlapping cells proposed in [90]. If the traffic of a cell increases temporarily such that the resource utilization rate exceeds a threshold, SHOT hands off some calls to the appropriate adjacent cells. Whenever a call reaches the overlapping area it can be served by the base station of either of the overlapping cells. Therefore, in the case of a temporary traffic increase calls can be distributed to adjacent cells which share the overlapping area. The wider the cell overlapping, the more traffic performance is expected to improve.

Simulation results in [90] show that SHOT improves traffic performance under the condition of uniformly distributed traffic, and enhances the frequency utilization in the time domain through the handoff of mobiles in the overlapped areas of the cell. This method is superior to DCA because it utilizes the conventional intercell handoff function, and no new functions are necessary [90]. The performance improvement achieved by SHOT depends greatly on the algorithm used for selecting a mobile station for handoff from a heavily loaded cell to a new selected cell. In the following, we discuss three algorithms for handoff selection proposed in [90].

SHOT1 — In SHOT1 the algorithm selects the mobile station with the minimum reception level — the mobile further away from the base station. Though it provides very simple selection control which measures only the reception level of the mobile at the base station, the selected mobile station does not necessarily have the required reception level at the new cell.

SHOT2 — In the second algorithm, SHOT2, all mobile stations in the original cell measure the reception level of the adjacent cells which have one or more idle channels. SHOT2 selects the mobile with the maximum reception level. Although the control in SHOT2 is more complicated, it provides better signal quality. Both SHOT1 and SHOT2 do not take into account co-channel interference.

SHOT3 — In SHOT3, all mobile stations in the original cell measure the reception level from the adjacent base stations that have at least one idle channel. The mobile station and the base station that have the highest reception level are selected and called the "first priority pair." Similarly, the "second" and "third priority" pairs are formed. Each selected base station makes its mobile station measure the interference of the candidate handover channel. The same is applicable for the second and third pair. The pair with the least interference is then selected.

As shown in [90], the improvement in traffic handling depends on the required SIR value for channel interference. For the first two methods, as the required SIR increases the frequency utilization gain degrades. Although SHOT3 is a little complex, it provides a performance improvement of about 50 percent. The above results are for uniform traffic; for nonuniform traffic conditions, all SHOT algorithms are expected to perform more effectively. In Table 15 a simple comparison between the three SHOT algorithms is provided. In addition, Table 16 provides a summary of the advantages of the overlapping cell schemes.

Overlaying Macrocellular Scheme

In microcellular systems, frequent handoffs are very common. A channel assignment scheme different from the schemes discussed thus far is the overlay scheme. Here, a cluster of microcells are grouped together and covered by a macrocell [91]. In overlay schemes, the total wireless resource is divided between the macrocell and all the microcells in its domain. In case of congestion, if there are not enough microcell channels for handoff calls, then macrocell channels can be used. Because the macrocell base station covers a much larger area than a microcell, its transmitted power is higher than that of microcell base stations. In the past, different channel assignment schemes for overlay cellular systems based on FCA and DCA schemes have been studied. In [91], a microcellular cluster having contiguous highway microcells, each with its own base station, is considered. Overlaying the microcellular cluster is a macrocell whose base station also fulfills the role of the mobile switching center (MSC) of the microcellular cluster. The macrocell base st ation has X channels at its disposal, composed of X_1 for new calls generated in the macrocell, X_2 for handoffs from other macrocells in the macrocell cluster, and X_3 for handoffs from the microcellular system. A mobile station that is blocked during a handoff attempt due to insufficient channels at a microcellular base station requests a channel from its MSC. If the macrocell has a free channel, it assigns the channel to the mobile station. Later, if an appropriate channel becomes available in a microcell, the macrocell channel is released and the call is handed off to the microcell channel. As shown with simulations in [91], with the use of the above reassignment scheme, the probability of terminating calls is reduced at the expense of an increased number of handoffs.

Frequency Planning

In the previous sections we discussed a number of different channel assignment techniques and evaluated their performance with respect to certain performance criteria. All these techniques assume that a number of channels C is available to the system and try to find the best way of assigning these channels to calls so that the utilization efficiency of the system is increased. Another important question related to the efficiency of the system is the following: Given the traffic profile for a system and a predefined blocking probability, what is the minimum number of channels required to accommodate the traffic?

In [35] the MP concept is proposed, which finds the minimum number of channels required to handle a given number of calls, based on cell compatibility information. Along the same lines, the study in [48] evaluates the minimum number of channels assigned to mobiles under given operating conditions such that given interference conditions are satisfied. The operation conditions refer to the knowledge or lack of knowledge of the location of the mobiles. The interference conditions refer to the acceptable level of interference so that two mobiles will be assigned the same channel. In [48] the minimum number of required channels is evaluated by constructing a matrix, defined as the *compatibility matrix*, of dimension $N \times N$ (N: number of mobiles in the system). Each mobile is evaluated with each other mobile to see if they can use the same channel. A graph is then composed, where each mobile corresponds to each vertex and an edge connects two vertices if and only if the two mobiles are incompatible (i.e., cannot use the same channel simultaneously). A set of graph-coloring algorithms could then be employed to find the minimum number of colors to color the vertices in the composed graph such that no two vertices interconnected by an edge are the same color. Thus, the number of colors is equal to the number of required channels. This problem is equivalent to finding the minimum number of cliques that cover all the vertices in the complementary graph. Because the coloring problem is NP-complete [92], heuristics are used. The heuristic used in [48] is the algorithm proposed in [93], which gives an upper bound on the minimum number of required colors. The results in [48] showed that the MP scheme can reduce the number of required channels almost by a factor of 2 for interference distance 2.0 compared to FCA schemes.

Scheme	Advantages	Disadvantages
Fixed reuse partitioning	Optimum performance Carries more traffic than FCA Afford greater protection to those users that need it most Minimum impact on cell-cite RF architecture	Drawbacks of FCA schemes Difficulty in handling in time variant traffic Difficult implementation in micro-cellular systems Difficult channel assignment planning
ACA RUP	Higher traffic handling capacity than FCA & Higher traffic capacity than DCA Decreases interference Probability Self organized	CIR margin in each Cell Rapid fluctuation in signal level
Flexible reuse partitioning	Improves capacity gain over FCA Self- organized	Requires great deal of CIR measurements Impractical for micro-cellular environment
SORP	Performance superior to DCA Reduces the intra-cell hand-offs Reaches a desired channel quickly Achieves high traffic capacity Same traffic handling as APR Lower Interference probability Less channel senses as APR	
ACCA	Improves system capacity compared to FCA	More complex control
DCCA	Lower call termination than ARP Higher traffic handling than FCA, DCA Lower amount of hand-offs to APR Better traffic adaptability	More complex Requires more hardware Requires complex control coordination

■ **Table 14.** *Comparison of reuse partitioning schemes.*

Power Control

As discussed above, the purpose of all channel assignment algorithms is to assign radio channels to wireless users such that a certain level of CIR is maintained at every wireless terminal. One can also use power control schemes to achieve the CIR level. Power control schemes play an important role in spectrum and resource allocation in cellular networks. The idea behind power control schemes is based on the fact that the CIR at a wireless terminal is directly proportional to the power level of the desired signal and inversely proportional to the sum of the power of co-channel interferers. Thus, by increasing the transmitted power of

Scheme	Advantages	Disadvantages
SHOT 1	Simple selection control	Do not take into account co-channel interference
SHOT2	Moderate selection control Better Communication quality	Do not take into account co-channel interference
SHOT3	Improves traffic handling capacity	Complex selection control

Table 15. *Comparison between the SHOT algorithms.*

Scheme	Advantages
Directed handoff	Has very good sensitivity properties with respect to variation in spatial traffic profile of the system Has the capability to offer a large increase in system performance, if a significant number of calls can hear two or more cells simultaneously
Directed retry	Improves system performance
SHOT	Improves traffic handling capacity Enhances frequency utilization Utilizes the intercell handoff procedure The more cell overlapping, the more traffic improves

Table 16. *Comparison of overlapping cell schemes.*

the desired signal and/or decreasing the power level of interfering signals the CIR level can be accommodated. However, this approach is based on opposing requirements because an increase in the power level of the desired signal level corresponding to a certain wireless station also results in an increase in the interference power level corresponding to a different wireless station using the same channel. The purpose of different power control schemes is simply to find a tradeoff between the change of power level in opposing directions. In a way, power control schemes try to reduce the overall CIR in the system by measuring the received power and increasing (or decreasing) the transmitted power in order to maximize the minimum CIR in a given channel allocation of the system. This can result in a dramatic increase of overall system capacity measured in terms of the number of mobiles that can be supported. Power control can be done in either centralized or distributed fashion. Centralized power control schemes require a central controller that has complete knowledge of all radio links and their power levels in the system [94, 95]. In the distributed approach [96, 97], each wireless terminal adjusts its transmitter's power level based on local measurements. Generally, distributed schemes for power control converge rapidly to a stable state if the system can accommodate all existing links. Otherwise, some of these algorithms can result in fluctuations of the power level and converge to a minimum CIR_i level, which is unsatisfactory. In [98] a set of link admission control algorithms have been introduced, the purpose of which is to avoid such unstable or undesirable conditions in the distributed power control algorithms.

Conclusions

With rapidly growing interest in the area of wireless communications in recent years, the wireless resource allocation problem has received tremendous attention. As a result, a vast amount of research has been done to extend the earlier work as well as to introduce new techniques. Most of the recent work has been in the area of distributed, adaptive, measurement-based, power-control-based, priority-based, and overlay channel allocation schemes. In addition, a vast amount of results have been published which provide an insight into the performance, complexity, and stability of different channel allocation algorithms. In this article, we have provided an extensive survey of the resource allocation problem in wireless networks and presented a detailed and comparative discussion of the major channel allocation schemes. With recent trends in the areas of microcellular networks and wireless access broadband networks where multimedia applications will be extended to end users over wireless links, we are faced with new, interesting, and important challenges to the wireless resource allocation problem. These challenges have arisen as a result of emerging and new technologies, a result of recent advances in the design of low-power handheld wireless terminals, the design of advanced radio modems and antennas, and, finally, recent developments in the area of spread-spectrum systems. These emerging new areas will introduce a new set of constraints in the resource and channel allocation problems. The solution of these problems will play an important role in providing ubiquitous access to multimedia applications in personal communication networks.

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