Title
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*Resource Allocation in Wireless Networks**

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Abstract

Wireless services are one of the strongest growth areas in telecommunications today. Dynamic channel allocation schemes have garnered a considerable amount of attention as methods for achieving efficient use of system resources. Various combinations of permanent channel assignment, channel borrowing, shared pools of channels, channel ordering, channel reassignment, and dynamic adjustment of parameters have been suggested. In this paper, we suggest a categorization of dynamic channel allocation policies. We hope that this categorization will help distill the concepts involved and encourage the research that is necessary to extend these concepts to future integrated service wireless systems.

I. Introduction

Wireless services are one of the strongest growth areas in telecommunications today. Cellular voice is well established as a high-end service in most areas, but demand is increasing rapidly. Personal communications services (PCS) are expected to be introduced in the next few years as a mass market phone service. Wireless data services are appearing in the form of cellular digital packet data (CDPD), wireless local area networks (LANs), and wireless modems. Capacity, however, is now a critical issue for all of these services.

The current cellular system transmits analog voice on dedicated bandwidth. This bandwidth is split into several (typically 7) segments permanently assigned to small geographical regions called cells. Ideas for expanding capacity include:

- Cell Splitting: By creating smaller geographical cells, better use can be made of the existing spectrum allocation via a higher degree of spatial reuse. There is a minimum cell radius, however, and in some areas this limit has already been reached.

- Allocation of New Spectrum: Additional frequency spectrum is being auctioned in the Emerging Technologies Band (ETB). This spectrum is expected to spur new services such as PCS.

- Alternative Multiple Access Architectures: By transitioning from analog to digital transmission, it is expected that a significant increase in capacity will be realized. There are disagreements as to the best multiple access scheme and its resulting capacity gain.

- Dynamic Channel Allocation: Currently, the existing cellular frequency band is strictly divided among cells. This use of the existing spectrum is inefficient. Capacity can be increased by adding complexity and relaxing channel allocation rules.

These alternatives are not mutually exclusive. Cell splitting has been the principal method of increasing capacity in the current cellular system. Carriers are now following a multipronged approach: purchasing additional spectrum, evaluating dynamic channel allocation schemes, and designing the next generation digital system.

Research in this area has followed suit. In the multiple access area, vigorous debate is occurring between time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA) proponents, all trying to push these methods to their limits. In the dynamic allocation area, a flurry of schemes have been suggested.

II. A Brief History of Dynamic Channel Allocation

In cellular systems, the geographical region is split, using a regular topology, into cells, each containing one base station. The most common cell shape in 2 dimensions is a hexagon (Figure 1). A mobile wishing to initiate a call must request a channel from the base station in the cell in which the mobile currently exists. The base station must assign a channel that is not currently used within some specified “reuse distance”. In Figure

1, we assume the reuse distance is 2 cell diameters. The set of cells that interfere with a given cell is called the “interference region” of that cell. For certain regular topologies (including those of interest), there exists a smaller set of cells called a “cluster” such that the reuse constraint can be satisfied only if the total number of calls active within each cluster does not exceed the total number of system channels.

The existing cellular system was proposed by Schulte [1] in 1960. Called fixed channel allocation (FCA), it partitions the available spectrum into channel sets (A-G in Figure 1). The reuse distance constraint is satisfied by assigning these channel sets to the cells in each cluster in a manner determined by a graph coloring problem (c.f. [20]). A base station is allowed to transmit to and from mobiles in it’s cell only on channels in it’s assigned channel set.

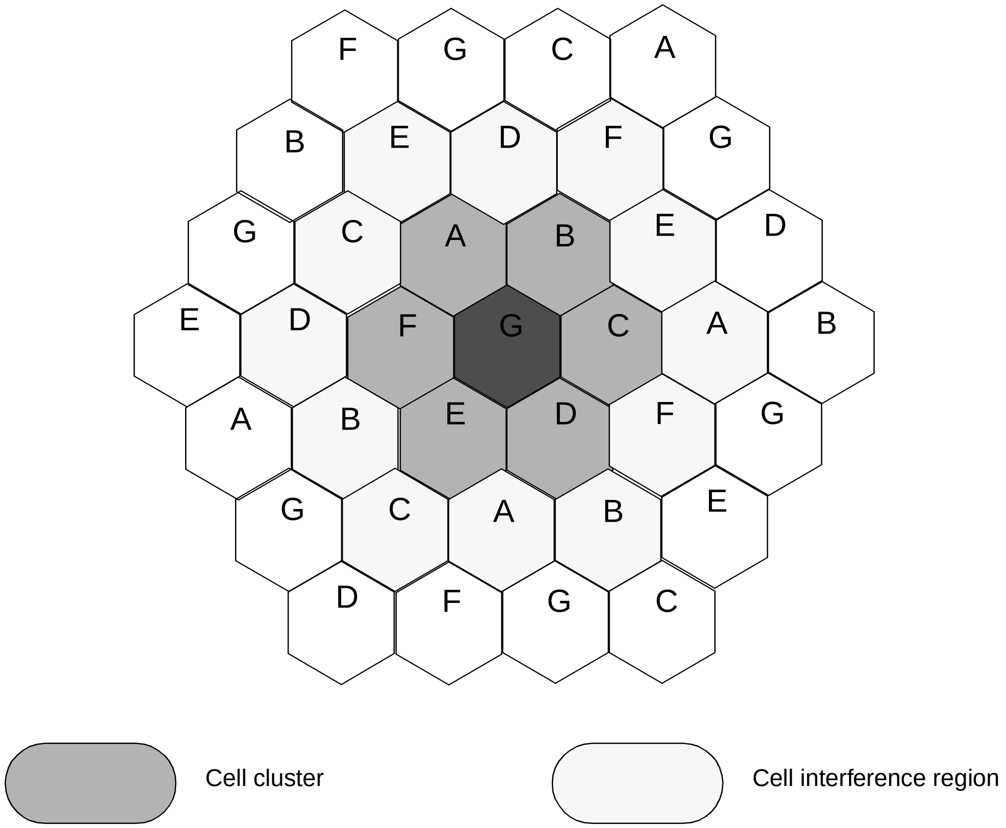

Figure 1 A cell cluster and interference region.

In Figure 1, a mobile attempting a new call while in the center cell must obtain a channel in segment G of the spectrum. This FCA policy clearly is *sufficient* to insure that no other mobile uses the same channel within the reuse distance, since channels in G can not be reused within the interference region of the center cell. However, the policy is not *necessary* to guarantee the reuse constraint is satisfied. To demonstrate this, suppose that all channels in G are currently used in the center cell, that no other mobiles are placing calls within the region in Figure 1, and that one additional mobile in the center cell wishes to initiate a call. Under FCA, this mobile must use a channel in segment G, and hence it’s attempt would be blocked. A channel *could* be found, however, in say segment A, that is not used anywhere in the interference region of the center cell. Assigning this channel to the new call would thus not violate any reuse constraint. The realization that FCA is overly restrictive has inspired all other channel allocation policies.

In the late 1960s and early 1970s, a number of alternatives were suggested. Araki [2] introduced the original dynamic channel allocation (DCA) policy, which assigns to a new call *any channel* that is unused in the originating cell's interference region. Cox [3,4,5,8] introduced the concepts of keeping channels in an order (channel ordering), assigning channels based on information about channel usage just outside the interference region (channel assignment), and reassigning existing calls when a call completes to maintain good channel usage (channel reassignment). Engel [6] introduced the concept of initially assigning channels using the FCA policy, but then allowing a base station to borrow a channel from a neighboring cell if it has none available (channel borrowing). A plethora of policies have followed from the late 1970s through today. A partial list appears in table 1:

Name	Acronym	Citation
Fixed channel allocation	FCA	[1]
Dynamic channel allocation	DCA	[2]
DCA - nearest neighbor	DCA-NN	[3]
DCA with channel ordering	DCA-CO	[4]
DCA - ring	Ring	[5]
DCA - orthogonal nearest neighbor	DCA-ONN	[5]
Simple channel borrowing	SB	[6]
Anderson I	A1	[7]
Anderson III	A3	[7]
DCA - ring with reassignment	HCAR	[8]
Hybrid	HCA	[9]
Borrowing with channel ordering	BCO	[10]
Maximum packing	MP	[11]
Forced borrowing channel assignment	FBCA	[12]
Locally optimized dynamic allocation	LODA	[13]
Borrowing with directional channel locking	BDCL	[13]
MaxAvail DCA	Max	[14]
ReMax1 DCA	ReMax1	[14]

Table 1: A partial list of dynamic channel allocation policies

Name	Acronym	Citation
ReMax2 DCA	ReMax2	[14]
Dynamic resource acquisition	DRA	[15]
Markov allocation	MA	[16]
Ordered DCA with reassignment	ODCAR	[17]
Aggressive DCA	ADCA	[18]
Polite aggressive DCA	PADCA	[18]
Persistent polite aggressive DCA	PPADCA	[18]
Weighted DCA	WDCA	[19]

Table 1: A partial list of dynamic channel allocation policies

These dynamic channel allocation schemes involve various combinations of permanent channel assignment, channel borrowing, shared pools of channels, channel ordering, channel reassignment, and dynamic adjustment of parameters. Questions remain. How does each dynamic channel allocation scheme produce its capacity gains? What are the basic trade-offs that are occurring? What is the effect of unequal cell loads upon various dynamic channel allocation schemes? Why do some only work well under certain traffic patterns? Can they be combined? What is the value of additional information about the state of nearby cells?

In this paper, we suggest a categorization of these dynamic channel allocation policies. We hope that this categorization will distill the concepts involved in a manner that will help others to answer some of the questions posed above.

III. Categorization

In any TDMA or FDMA system, a basic frequency reuse constraint is imposed to guarantee that any channel is not reused within a specified distance. In addition, some systems assign a channel to a call if, in addition, that channel satisfies a minimum carrier to interference (C/I) ratio. The simplest policy to insure the reuse constraint, FCA, simply segments the available spectrum among all cells within a cluster (whose radius is determined by the reuse distance). A call request is thus accepted if and only if there exists a free channel within the channel set assigned to the cell in which the call originates.

This policy is simple but restrictive, since it may deny a call request when there is a free channel available within the reuse distance, but when there is no free channel in the channel set of the originating cell. Alternatives to FCA can achieve higher efficiency at the cost of higher complexity and greater regional state information.

The most complex alternative is maximum packing (MP) [11]. MP accepts a new call if there is any possible reassignment of channels to calls in progress which results in a channel that is free within the interference region of the new call's cell. This policy requires complete knowledge of all existing channel assignments in the entire system, and may potentially reassign all existing calls.

Alternative policies generally fall in between FCA and MP in one or more of three categories: admission control policy, channel assignment strategy, and packing algorithm.

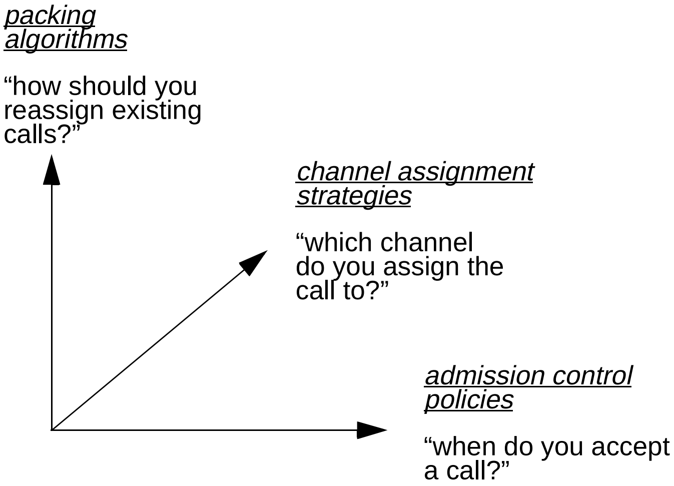

Figure 2 A categorization of dynamic channel allocation schemes

An admission control policy answers the question "When do you accept a call?". FCA accepts a call iff there exists a free channel in the corresponding cell's channel set. MP accepts a call iff there is any possible reassignment of calls that obeys all reuse constraints.

A channel assignment strategy answers the question "Which channel do you assign the call to?". FCA spreads each channel set over the spectrum to avoid adjacent channel interference, but otherwise assigns channels randomly. MP assigns a channel based on knowledge of all other channel assignments in the system.

A packing algorithm answers the question "When and how should you reassign existing calls to new channels?". FCA never reassigns an existing call to make room for a new call. MP will reassign every active call in the network, if necessary, to be able to accept a new call.

How a scheme addresses each of these three questions is usually not independent. Which channel a new call is assigned to may affect whether the next new call can be accepted. To what extent the scheme is willing to reassign existing calls affects the ability to accept new calls. Under what conditions a scheme accepts a new call affects the distribution and pattern of channel occupancies.

In the following sections, we explain where each of the above listed dynamic channel allocation policies fits using this categorization. We then address the concepts used to place different schemes between FCA and MP along each of these three dimensions. Finally, we explain the variation of performance along each axis.

IV. Admission control policies

To define intermediate policies between FCA and MP with respect to admission control of new calls, we define the state of the system as $x = (x_1, \ldots, x_N)$, where N is the total number of cells in the system and x_i is the total number of active calls in cell i. The frequency reuse constraints impose restrictions upon the values the state x can take on, and hence define a state space "Z". For an appropriate choice of the minimum reuse distance, these constraints for the state space Z are:

$$\sum_{j \in C_i} x_j \le M \qquad \forall C_i \tag{EQ 1}$$

where C_i are overlapping clusters over the state space Z and M is the maximum number of channels available to each cluster [11].

The Maximum Packing strategy accepts a call request if and only if there exists a global reassignment of the existing calls and the new call to satisfy the frequency reuse constraints. Since this policy shares all channels among all cells, we will alternatively call this policy Complete Sharing (CS) to stress the resource usage. MP is equivalent to accepting a call if and only if the resulting state remains in the state space $Z_{CS} = Z$ as defined in (EQ 1) [11].

Fixed channel allocation, on the other hand, accepts a call request if and only if there is a free channel among the subset of channels permanently assigned to the corresponding cell. Since this policy permanently divides all channels among cells in a cluster, we will alternatively call this policy Complete Partitioning (CP) to stress the resource usage. FCA is equivalent to accepting a call if and only if the resulting state both remains in the state space Z as defined in (EQ 1), and satisfies:

$$x_i \le \frac{M}{C} \qquad \forall i \tag{EQ 2}$$

where C is the number of cells per cluster. (EQ 2) defines a reduced state space $Z_{CP} \subset Z_{CS}$. (See Figure 3).

All proposed dynamic channel allocation policies in table 1, except for FCA, HCA, and HCAR, allow any call to potentially access any channel, subject only to channel assignment rules to be discussed below. The hybrid (HCA & HCAR) policies reserve some channels for each cell, and share the remainder. A hybrid policy that reserves R channels for each cell allows the state to enter a state space given by Z_{CS} intersected with constraints of the form

$$\sum_{j \in C_i, j \ne i} x_j \le M - R \qquad \forall C_i$$

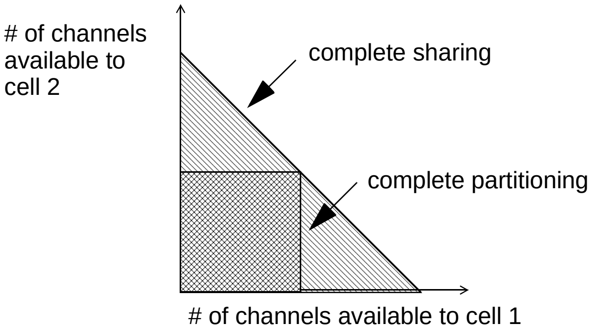

Figure 3 The state space Z for CS and CP policies.

A. Performance

Many studies have suggested that the optimal point along the spectrum from FCA to MP is dependent upon the load in each cell. Most of these results compare dynamic channel allocation policies that differ in more than one dimension. Early results from Cox [8], however, found that HCAR was often superior to both FCA and DCA (the “ring” version[5]), if the number of channels reserved, *R*, was chosen appropriately. Kahwa et. al. [9] provided additional evidence when they introduced HCA without reassignment, and found that when the cell loads were equal the optimum number of reserved channels varied from *0* at low loads to *M/C* at high loads. The optimal hybrid policy, under equal loads, therefore progresses from DCA to FCA as the cell load increases, under the conditions of random channel assignment and no packing (in the other two dimensions).

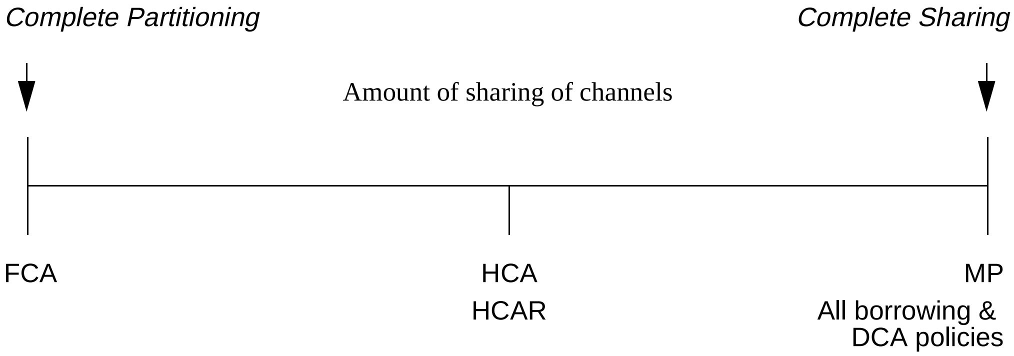

Figure 4 The admission control spectrum

These results were strengthened in [21]. These papers considered all possible admission control strategies, under the conditions of MP in both channel assignment and packing. They found that the optimal policy’s state space (for a system with linear cells) under equal cell loads was of the form Z_{CS}, intersected with constraints of the form:

$$x_i \le K \qquad \forall i$$

(EQ 3)

These type of constraints do not reserve a set of channels for each cell, as do hybrid policies, but instead limits the number of calls any single cell can serve. The optimal value for *K* varied from *M* at low loads to *M/C* at high loads. The resulting optimal policy, therefore, also varies from CS to CP as the load increases.

The analysis in [21] lends insight into why the optimal admission control policy follows this pattern. As observed in previous studies, DCA without packing allows the system to reach configurations in which single cells accumulate a large share of the system capacity. Since each such greedy cell blocks new calls in every cell in it's interference region, these configurations are undesirable. Furthermore, these undesirable configurations become more likely as the system load increases. The optimal policy does not allow the system to achieve these states, by imposing constraints of the form of (EQ 3). A new call is accepted if and only if it results in an *average increase in the number of calls accepted in the whole system*. The maximum number of calls any single cell is allowed is decreased as the system load increases. The resulting optimal policy accepts all calls when there are many idle channels, and *blocks calls when one cell is occupying too large a percentage of the cluster's capacity*.

Results on the performance of admission control policies under *unequal* cell loads are more scarce. Early studies [22,9] found that HCA and DCA strategies are significantly less sensitive to load imbalances between cells than FCA. The effect of load imbalance upon optimal admission control was investigated in [23]. It was found that the optimal policy (in a system with linear cells) is similar in form to (EQ 3), but allows for different values of *K* for cells with different loads. FCA becomes congested when any cell's load reaches it's allocated capacity. HCA and DCA, however, are able to shift capacity to cells with instantaneous high demand. As a result, they become congested only when a cluster's total load reaches the number of channels in the system.

V. Channel assignment strategies

Once the system has decided to accept a new call request, as discussed in the previous section, it must choose which channel to assign the new call to. These two tasks may well be integrated in a dynamic channel allocation policy, since the system must determine that there exists at least one available channel in order to accept a new call. However, for the purposes of discussion, we segment these tasks.

The simplest strategy is again given by FCA, which spreads each channel set over the spectrum to avoid adjacent channel interference, but otherwise assigns channels randomly. Within the constraints of FCA's admission control policy, the particular channel assignment doesn't matter. Any other policy requires more information about channel usage in the neighborhood of the cell in which the call originates.

A. Interference region information

The first DCA policy [2] assigns a randomly chosen channel among those unused in all channels within the interference region of the originating cell. This requires information about channel usage within this region. As discussed above, in regular topologies the interference region is a set of layers of cells (rings in two dimensional systems) around the originating cell. We denote the number of such layers composing one interference region as IR.

The performance of a strategy is a function of the intelligence of that strategy, which is in turn partially a function of the amount of information available for the channel assignment decision. We therefore categorize strategies by the information used, in Figure 5, for each policy in table 1. For each strategy, we show the number of layers of cells, around the originating cell, for which current channel usage information is necessary in order to make the channel assignment decision.

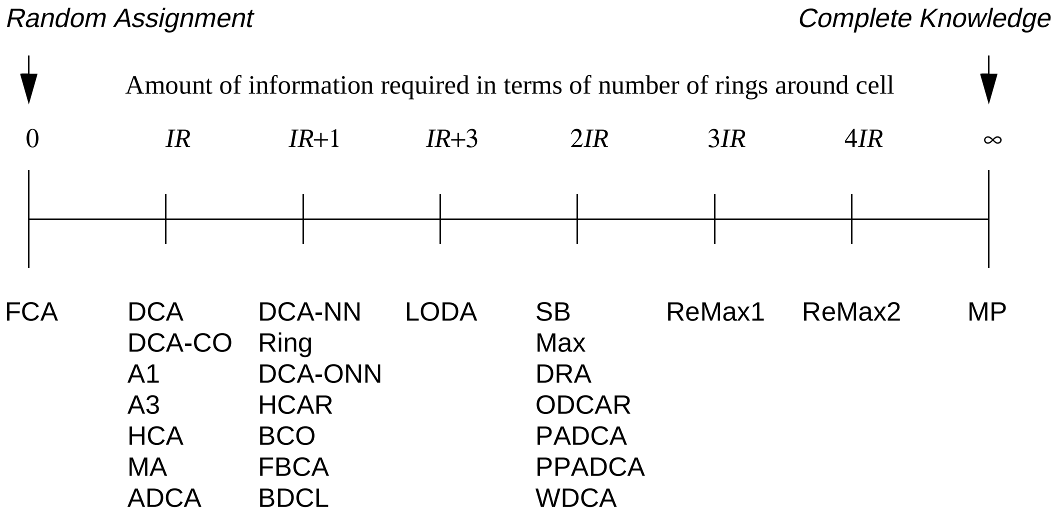

Figure 5 The channel assignment spectrum

B. Maximum packing

The channel assignment strategy affects the future ability of the system to accept new calls. Most strategies try to maintain “good” system configurations in terms of channel usage. The upper extreme is given by MP, which assigns a channel based on knowledge of all other channel assignments in the system. Since it is willing to perform as many channel reassignments as necessary, it accepts any call that could possibly be accepted.

C. Channel ordering

Early DCA policies were recognized to suffer at high loads, in part due to persistent undesirable system configurations. One solution is admission control, as discussed above. A second approach, however, is an intelligent channel assignment strategy.

One approach, suggested by Cox [4] in 1972, is for each cell to maintain a list of the channels unused within the interference region in an ordered list, by channel number, and to choose the lowest numbered such channel. This strategy (DCA-CO) packs calls into lower numbered channels, and as a result tends to result in configurations in which channels are reused in a minimum distance.

The original DCA scheme, and variations such as DCA-CO, HCA, and MA, require no additional information beyond IR layers.

D. Nearest neighbor strategies

A second approach, also suggested by Cox [3], is to explicitly choose, among channels available within the interference region of the cell in which a new call is initiated, the channel that is in use nearest the originating cell (but outside it's interference region). Such a strategy (DCA-NN) results in a lower average reuse distance for a given channel than DCA with random channel assignment, and therefore achieves a higher system throughput and lower new call blocking probability.

The nearest neighbor strategy, and variations such as Ring and DCA-ONN, require one additional layer of channel usage information in order to choose among those channels used just outside the interference region.

E. Channel borrowing

A third approach, suggested by Engel [6] in 1973, is to assign “nominal” channels using a FCA policy, and then to let a cell “borrow” a channel from a nearby cell when it has no free nominal channels. This borrowing strategy (SB) also results in a lower average reuse distance for a given channel less than DCA with random channel assignment.

The original borrowing scheme, SB, borrows the channel that maximizes the minimum available nominal channels in corresponding nominal cells within the interference region. This requires knowledge of nominal channel availability from loaner cells IR layers out. Furthermore the loaner cells must know about channel usage within *their* interference regions, so the total information required comes from cells within $2IR$ layers around the borrowing cell. Borrowing can be accomplished using less information. Variations A1 and A3 use heuristics such as borrowing a channel from the neighbor with the maximum number of channels to loan. This requires no additional information beyond the interference region.

Some more complex borrowing strategies such as BCO and BDCL require little additional information, but use more intelligence in tracking which cells are blocked from using the borrowed channel. Others such as

LODA, Max, DRA, ODCAR, and WDCA attempt a more complex impact minimization by considering the channel configuration in the interference region of each cell that is within the IR layers around the originating cell. These strategies generally offer superior performance to SB or BCO, but at the cost of $2IR$ layers of information.

Finally, there are some policies, to be discussed in more detail in the next section, that perform a limited amount of channel reassignment of existing calls to choose the channel to assign to a new call. These strategies, including ADCA, PADCA, PPADCA, ReMax1, ReMax2, and MP, require an amount of information proportional to the distance over which the reassignments occur.

F. Performance

We expect that performance of channel assignment strategies should be increasing with the information available to them. However, while MP represents the optimal policy using a complete sharing admission control policy, the evidence for this claim through the remainder of the spectrum is mainly empirical.

VI. Packing algorithms

Once the system has decided to accept a new call request, and assigned a channel, it need not allow that call to remain on the channel through the entire connection. Changing the channel assignment “on the fly” is attempted in all cellular systems whenever a mobile crosses into a neighboring cell. Some dynamic allocation schemes also attempt to reassign existing calls at other times to move the system into a more desirable configuration.

The simplest strategy is again given by FCA, which never reassigns existing channel assignments except for mobile handover from one base station to another. The first dynamic channel allocation scheme (DCA), and some variations (e.g. DCA-NN and HCA), did not reassign existing calls either.

A. Reassignment at call termination

Engel [6] and Cox [8] introduced the concept of reassigning an existing call *at the time that another call terminates*. Cox’s HCAR scheme partitions channels into “fixed channels” which are dedicated to cells as in FCA, and “dynamic channels” which are shared among all cells as in DCA. When a call on a fixed channel terminates, if there is a call in the same cell on a dynamic channel, it is reassigned to the just vacated fixed channel. This algorithm packs calls into the fixed channels, which tends to combat the problems DCA otherwise encounters at higher loads.

Engel’s Simple Borrowing scheme similarly initially partitions channels, as in FCA, among cells. These channels are known as “standard” or “nominal” channels. A cell, however, if it has no standard channels available for a new call, can borrow a channel from a nearby cell. In this case, the channel is considered a “nonstandard” or “borrowed” channel to the borrowing cell. When a call on a standard channel terminates, it was suggested that the channel could be reassigned to any call in the same cell currently using a nonstandard channel. This option increases the number of channels that can be borrowed in the future. Unlike reassignments in Cox's algorithm, it was noted that one such reassignment can free standard channels in other cells, and therefore spur additional reassignments at those locations.

Reassignment can be attempted at call termination not only to encourage use of fixed or standard channels, but also to preserve channel ordering. Schemes using channel ordering maintain lists of available channels in each cell. Channels are numbered and the list is maintained in increasing channel order. When a new call is accepted, the lowest numbered channel is assigned (perhaps among channels satisfying additional constraints). The initial versions of DCA using channel ordering (e.g. DCA-CO) did not reassign channels at call termination to preserve this ordering. Later borrowing schemes (e.g. [10,13]), however, suggested that when a call terminates, the vacated channel should be reassigned to the call using the highest numbered channel in the cell. This algorithm packs calls into the lowered numbered channels, which further accomplishes the aims of channel ordering as discussed earlier.

More recently, Kuek [17] introduced a variation of SB in which channels are reassigned at termination or handoff in order to encourage use of standard channels and in an ordered fashion. This algorithm provides superior performance to SB, at a cost of about twice the number of channel reassignments per call.

B. Reassignment at call setup

The performance of a strategy is in part a function of the number of reassignments it requires. We categorize strategies by the number and type of reassignments in Figure 6, for each policy in table 1.

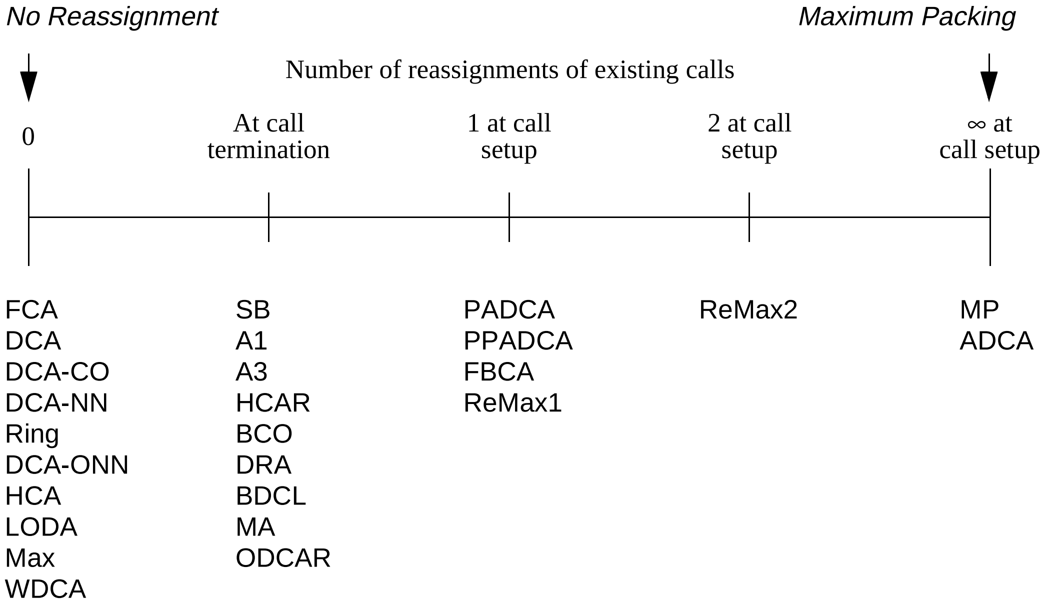

Figure 6 The packing spectrum

Engel [6] introduced the idea of reassigning existing calls not at call termination, *but instead at call setup*, in order to accept a call that would otherwise have to be blocked. Everitt [11] carried this concept to it's extreme in the maximum packing scheme (MP). In this algorithm, if no channel is unused within the interference region of the cell in which a new call request is issued, the call is not necessarily blocked. The system tests to see if accepting the call would result in a system state that still satisfies (EQ 1). If so, then it rearranges as many existing channel assignments as necessary to free a channel within the originating cell's interference region. This algorithm may require an unbounded number of reassignments (in an infinite cell 2-dimensional system).

Sekiguchi [12] suggested a more moderate scheme. FBCA proceeds as a simple borrowing policy. If no nominal or borrowable channels can be found, however, it borrows an occupied channel from a neighboring cell if that cell can in turn borrow a free channel from another nearby cell to compensate. If no such neighbor can be found, then the new call is blocked. This process was found to result in a superior performance to SB, especially under non-uniform loads. The algorithm requires up to one call reassignment at call setup, in addition to the reassignments it may require at call termination.

More recently, schemes have been proposed that may require more than one reassignment at call setup. Sivarajan's ReMax1 algorithm [14] is a variation of DCA-CO, and is willing to accept a new call to an occupied channel if that existing call can be reassigned to a free channel. A second algorithm, ReMax2, was proposed in which this process is repeated. A new call is accepted and assigned an occupied channel if the displaced call can grab another occupied channel whose call can find a free channel. As a result, this algorithm may require up to two call reassignments at call setup. In addition, it requires knowledge about channel usage in a greater number of cells, as noted above.

Cimini et. al. [18] recently proposed a set of policies that display how algorithms might span the spectrum. Their "aggressive" algorithm (ADCA) assigns any channel not currently used in the cell in which a new call originates. If one or more cells in the corresponding interference region were already using that channel, they simply grab other channels unused in those cells. These reassignments propagate, as in MP, but do not necessarily result in one additional call carried by the system. A more moderate version is their "polite aggressive" algorithm (PADCA). In this scheme, a new call attempts to find a channel unused within the interference region. If unsuccessful, then it will attempt to grab the first channel it finds that has only one interferer. If the interfering cell can find an unused channel, the new call is accepted at the cost of one reassignment; otherwise the new call is blocked. A variation in which all channels with a single interferer are investigated, PPADCA, is similar to FBCA.

C. Performance

In general, we expect that the capability to perform additional reassignments, if necessary, should result in increased performance. Some empirical evidence of this claim is known. MP achieves the maximum performance for any algorithm using a complete sharing admission policy. In addition, Sivarajan [14] and Cimini [18] each found this to be true within those policies investigated.

VII. Conclusion

We have suggested a categorization of dynamic channel allocation schemes in terms of how they answer three questions:

- When do you accept a new call?
- Which channel do you assign the call to?
- When and how do you reassign existing calls to new channels?

We call the answers to the these questions the admission control policy, the channel assignment strategy, and the packing algorithm of the dynamic channel allocation scheme. We find that admission control policies differ in the amount of sharing of channels they allow. Furthermore, some evidence suggests that the optimal amount of sharing decreases with the cell loads. We find that channel assignment strategies differ in the amount of information required from neighboring cells. Empirical evidence suggests that increased information generally results in increased performance. Finally, we find that packing algorithms differ in the number of reassignments of existing calls they allow. Empirical evidence suggests that increased reassignments generally results in increased performance.

We hope that this categorization will help distill the concepts involved and encourage the research that will be necessary to extend these concepts to future integrated service wireless systems.

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