On the Effectiveness of Channel Segregation as a Channel Allocation Method in a Variety of Cellular Structures

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***Abstract*—Channel allocation or assignment problems have been studied intensively in the literature for the last 25 years. Current directions of this work appear to be in the area of self-organizing or distributed allocation methods, and the type of cellular arrays involved are moving toward complex mixed or hierarchical structures rather than simple arrays of macrocells or microcells. Channel segregation is a distributed dynamic channel allocation method, which has been shown to work well in simple arrays. Hence we investigate how transportable this approach is to mixed cellular systems. Further, we investigate the gains offered by hybrids of channel segregation and fixed channel allocation and study the stability of the channel segregation approach. Results are given that indicate that channel segregation (or hybrids) is a stable allocation method that performs very well unchanged for certain mixed cellular layouts.**

***Index Terms*—Channel segregation, dynamic channel allocation, hybrid allocation, mixed cellular layouts.**

I. Introduction

OVER the last 25 years, the study of channel allocation (CA) has gradually moved from the fixed channel allocation problem (FCA), where you assign channels in a static way according to cellular layout, measurements, etc., to distributed dynamic channel allocation (DDCA), possibly using power control, inference measurements, specific handoff mechanisms, etc. This development is summarized in Fig. 1.

Alongside the development of CA methods has been an increase in the complexity of the cellular layouts considered, also shown in Fig. 1. The review paper by Katzela and Naghshineh [19] provides a good background to most of these concepts. Other tutorial-type papers can be found in [6], [8], [22], [25], [32]–[34], [38], and [39].

The advantages of DDCA are discussed in [19]. In [38], it is suggested that large performance or capacity gains in cellular systems will only result from the mass deployment of microcells. Hence it is desirable to develop DDCA techniques that can be used in cellular environments containing macro-, micro-, and possibly picocells in a variety of mixed or hierarchical structures. In this paper, we study the channel segregation (CS) technique developed by Furuya and Akaiwa [14] for regular cellular arrays and implemented for a particular umbrella cell system in [13]. In [13], Furukawa and Akaiwa show that CS successfully adapted to the umbrella cell structure to provide good performance. In this paper, we reinforce their results and show that CS is an approach to DDCA that adapts excellently to mixed structures. In addition, we quantify the success of the CS approach by comparisons with several CA benchmarks. Finally, we demonstrate the stability of the CS approach and investigate the gains that can be made through the use of a hybrid of CS and FCA. Throughout this paper, performance is measured by overall blocking probability. Due to the generality of the CA methods and cellular structures considered, we have used simulation for performance evaluation. Commonly used analytic methods include exact approaches based on maximum packing [9], [27] and state space models [2], [3], [16], [17], [20], [28]–[30], approximations based on maximum packing [7], [26], [31] and bounds relative to optimum CA algorithms [9]–[11], [18], [24], [31], [40]–[42]. Unfortunately, no single approach can easily be adapted to analyze the range of systems we consider; hence the adoption of simulation as the performance evaluation tool.

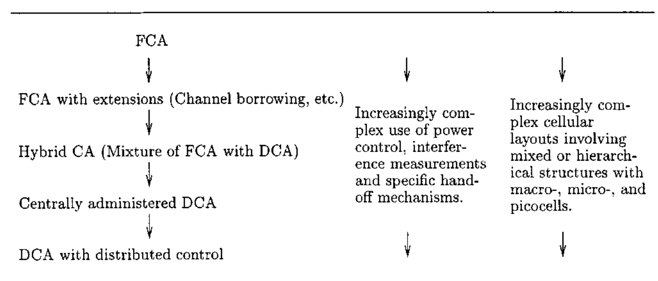

Fig. 1. Development of CA methods.

The organization of this paper is as follows. In Section II, the cellular layouts and simulation parameters are described. In Section III, the performance of CS is compared to various DCA techniques in regular cellular arrays. Section IV extends the comparison to a mixed system, and Section V offers some conclusions.

II. Cellular Arrays

A. Regular Arrays: Simulation Details

The regular arrays considered are the common two-dimensional arrays where the area is tessellated by hexagons [4]. To counter "end effects," we use the approach of [4] and wrap

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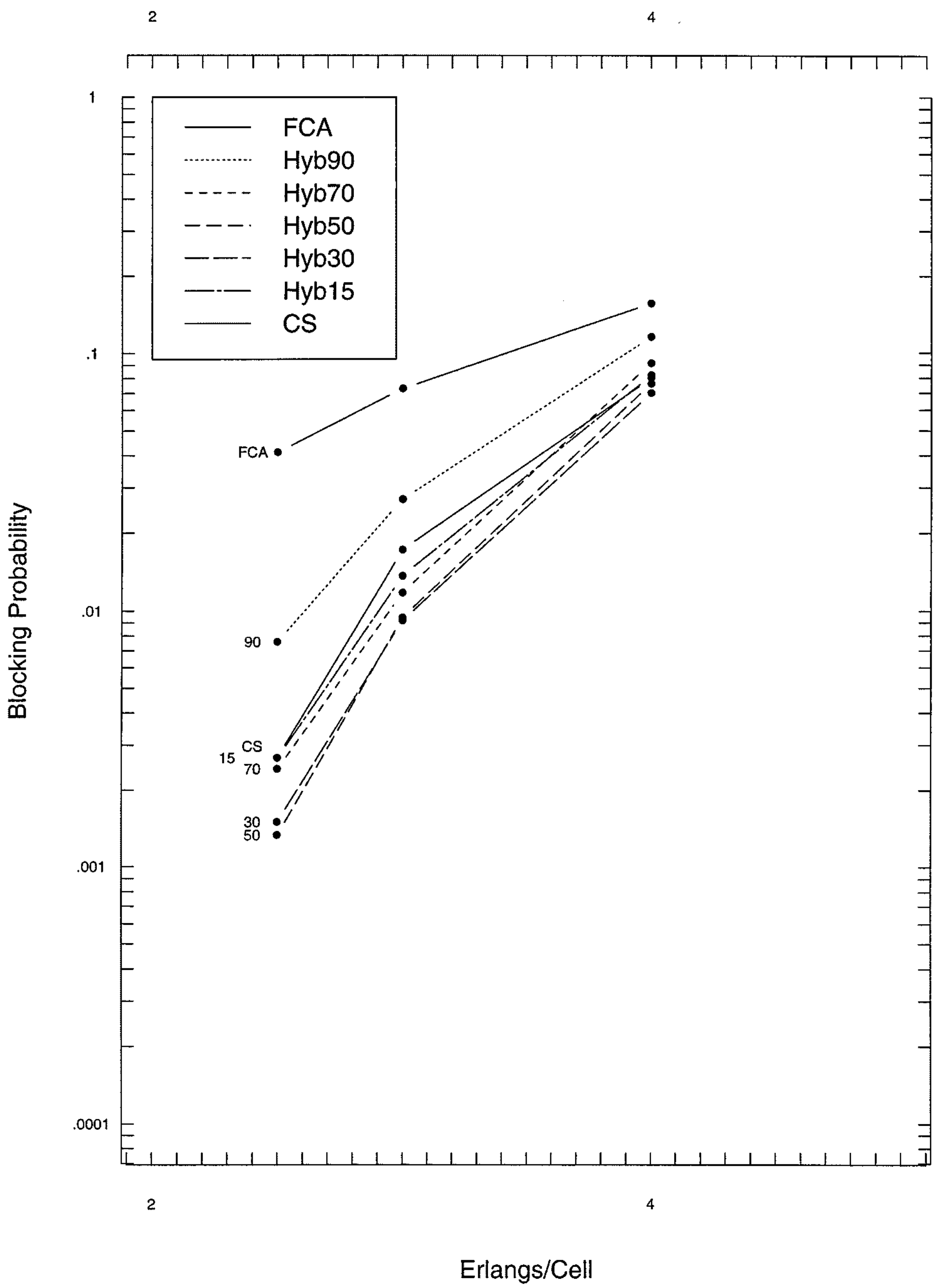

Fig. 2. Comparison of the hybrid algorithm with FCA and CS.

the array around once to form a tube and then again to form a "doughnut" or toroid. A 10 $\times$ 6 array is used for most of the simulations, since checks with a much larger array (20 $\times$ 30) yield similar results. The hexagons have longest diameter set to 200 m. To simulate user motion, we follow the approach of [4] and consider three types of motion: random jumps, where users jump randomly from one cell to any other; random directed motion, where users choose one possible direction at random and continue in that direction for the duration of the call; and random undirected motion, where users choose one possible direction at random and continue until they enter another cell—then the direction of motion is chosen again and the process repeats itself for the duration of the call. For all types of motion, users move a distance D in each cell, where D is chosen either as a fixed distance equal to the cell diameter (200 m) or as a random variable corresponding to entering the cell at a random angle uniform over $[0, \pi]$. When a user's motion results in a cell boundary crossing, then the user applies for a channel in the new cell in exactly the same way as a new user. Hence, no handover priority is simulated. This scenario is also used for the simulation of the mixed systems in Section IV. Call lengths are exponential with mean length set at 1 min without loss of generality, and user speeds are chosen from {0, 10, 50, 100} km/h. Poisson arrival rates of calls are varied and are either homogeneous (constant arrival rate in all cells) or nonhomogeneous where the arrival rates are given by the model described in [15] and [35]. This model gives an arrival rate that decays at rate $10^{-r/20}$, where r is the distance in kilometers from the center of the city.

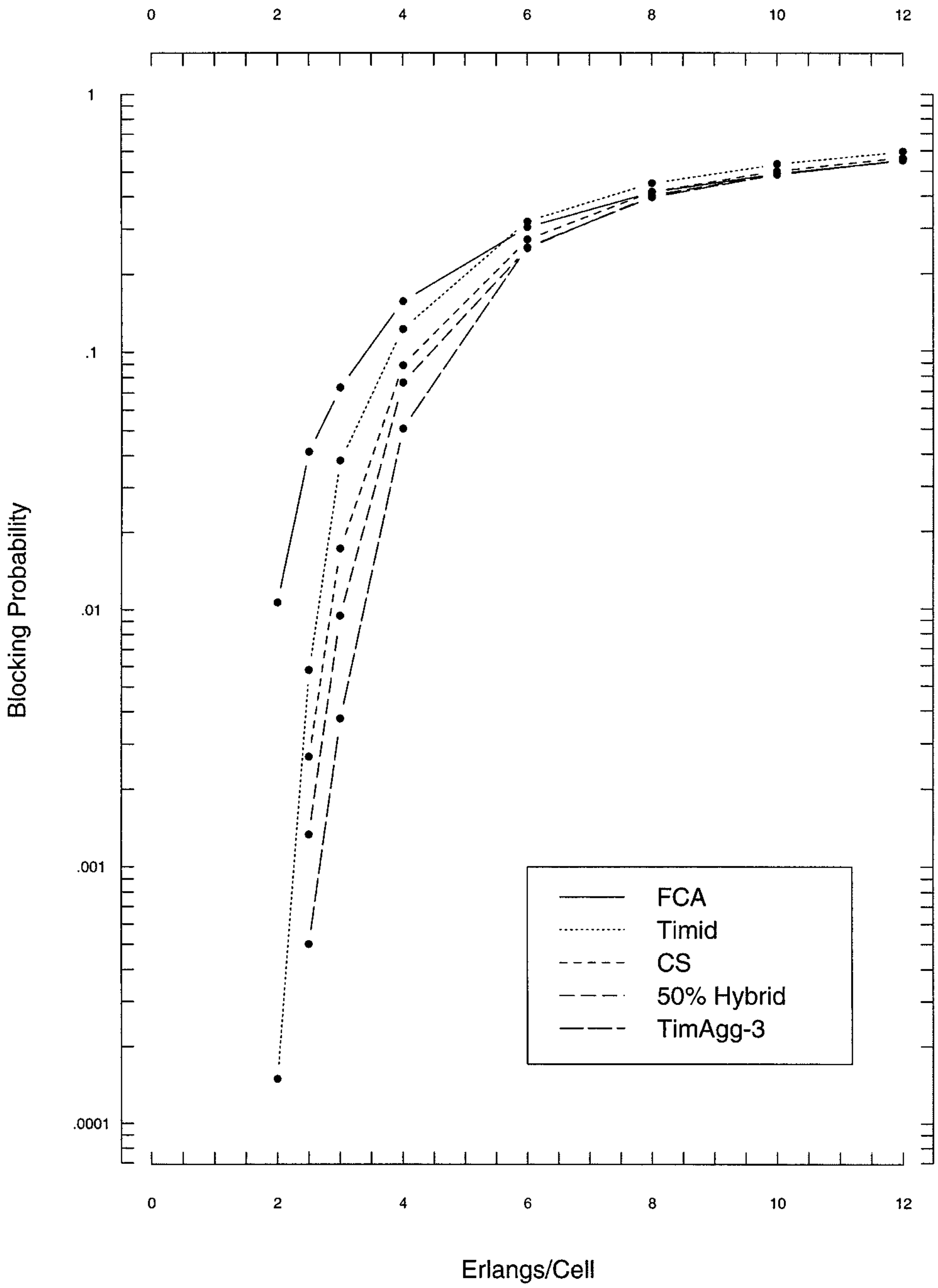

Fig. 3. Comparison of channel allocation algorithms.

The interference constraints used are the simple R-ring constraints [4] with $R = 1$, where channels in neighboring cells are certain to interfere and channels used further away do not. This simple scenario was adopted in preference to more realistic interference models since the focus of the paper is on comparing CA strategies rather than in producing specific results for a particular cellular layout of interest. The total number of channels is set at 24.

A full investigation of all these parameters is beyond the scope of this paper, but further details can be found in [36], where it is shown that several parameters can be fixed since, although they impact on system performance, they do not affect comparisons between CA algorithms, which is the aim here. Hence, we fix user motion as random undirected motion at 100 km/h with a fixed distance ($D = 200$ m) traversed in each cell. Simulations based on these parameters are described in Section III.

B. Mixed Cellular System: Simulation Details

When evaluating CA methods for mixed cellular systems, a fundamental difficulty is the huge proliferation of possible systems. In the literature, attention has focused on microcellular systems with macro umbrella cells to cope with calls not handled by the micro cells [5], [12], [23], [29] or to provide a buffer of channels for handovers [1], [21], [37]. Most of the approaches have a fairly limited dynamic aspect to the CA used and represent a highly specific type of hierarchy. In this paper, our pur-

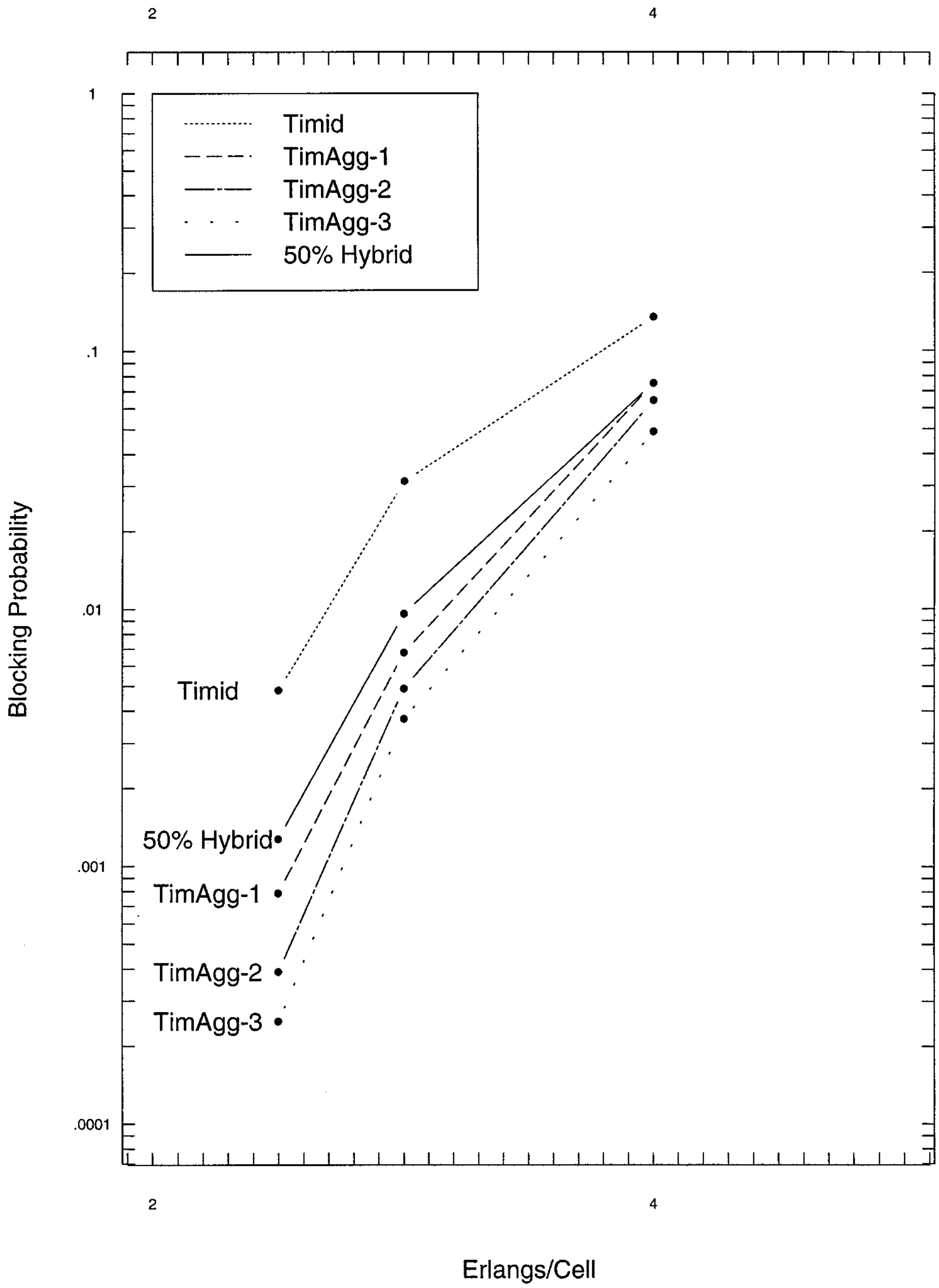

Fig. 4. Varying the number of aggressive iterations.

pose is to evaluate CS as a possibility for mixed cellular systems in general and not to propose a structure for such a system. Hence we have chosen to simulate an idealized mixed cellular system in the same spirit as many researchers consider the array of hexagons as a model for planar systems. The system is described below.

The same grid of hexagonal cells is used as for the regular arrays, but now each cell can be thought of as a macrocell and contains one microcell and one picocell. Cell dimensions are 1 km, 200 m, and 50 m, respectively, for the diameters. User motion is now fairly complicated, but random undirected motion is used between macrocells. Once inside a macrocell, a user can take one of four routes.

Route 1) The user travels through the macrocell only.

Route 2) The user travels through the macrocell and the microcell.

Route 3) The user travels through the macrocell, the microcell and the picocell.

Route 4) The user travels through the macrocell and the picocell.

The routes are chosen with probabilities p_1, p_2, p_3, p_4, respectively. User speeds are set at 50 km/h, 3 km/h, and zero in the macrocell, microcell, and picocell, respectively, and call lengths are exponential with means of 1, 1, and 1.5 min. Fixed distances of 1 km, 200 m, and 50 m are traversed in the three cell types.

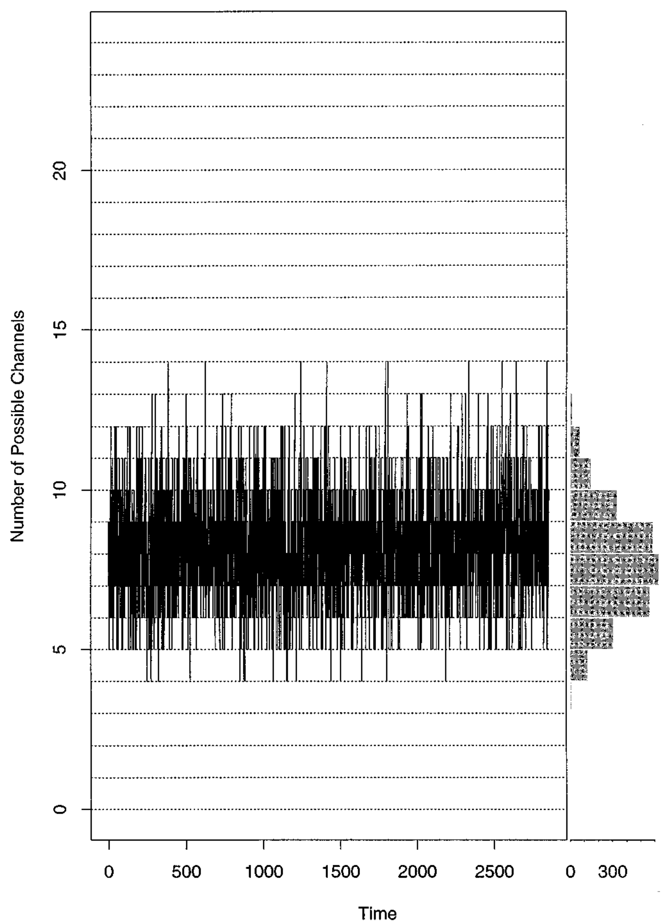

Fig. 5. Local behavior of the 50% hybrid.

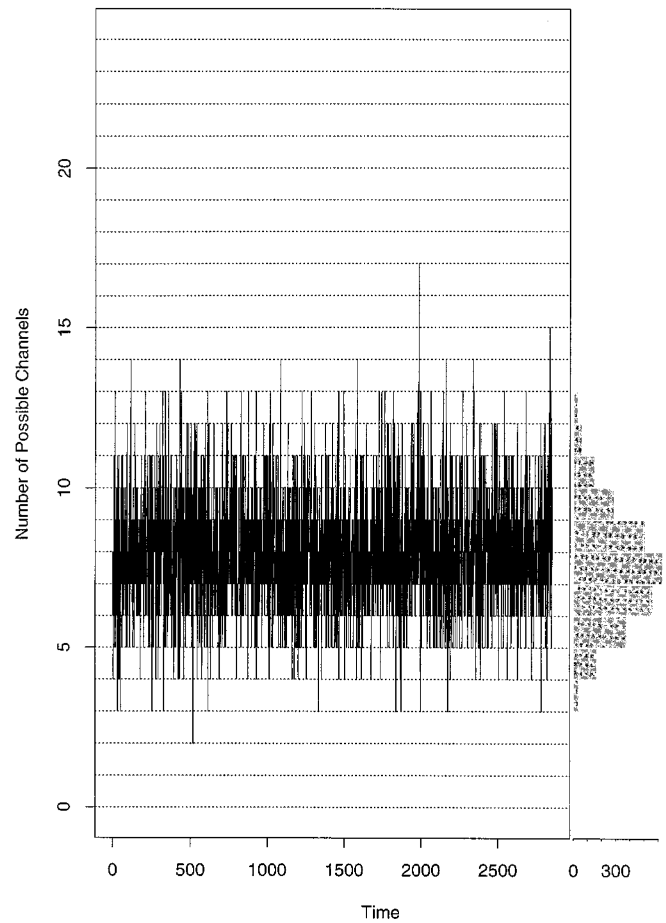

Fig. 6. Local behavior of CS.

Poisson arrivals are simulated with a fixed rate in every macrocell, every microcell, and every picocell in the ratio 3:2:1. The number of channels available is 24.

Interference constraints are a generalization of the R-ring constraint. We assume that a macrocell channel will interfere with its own microcells and picocells and any of the surrounding six macrocells or their microcell and picocells. Channels used in microcells or picocells interfere with any of the macrocells in the group consisting of the mother cell and the six surrounding macrocells. The only interference assumed between microcells and picocells is between the microcell and picocell in the same macrocell.

Simulations based on this particular mixed scheme are given in Section III.

C. Channel Allocation Methods

Five types of CA methods are considered.

1) *FCA:* The traditional fixed channel allocation.
2) *Timid:* A DDCA technique described in [4] that involves no call reconfigurations as only free channels are used.
3) *Timed-Aggressive:* A DDCA technique described in [4] that can involve call reconfigurations since a blocked user will grab a channel in a neighboring cell even if no free channels are available. The user who has had their channel grabbed will then repeat the process, and in principle this sequence of channel grabbing could continue indefinitely.

   In practice, such reconfigurations take time, which limits the number of grabs possible before a call is terminated.
4) *Channel Segregation:* A DDCA technique described in [14] that involves no call reconfigurations and is therefore an extension of the timid approach. CS works by allowing cells to "learn" about channel usage patterns and to choose their own favorite set of channels—essentially a "soft" FCA method. This technique was favorably reviewed in the recent review paper by Katzela and Naghshineh [19].

   Proof of concept of the use of CS in mixed cellular systems has been provided by Furukawa and Akaiwa [13] for a particular macro/microcell umbrella system. They also consider systems where macro/microcells can share channels and show the effective learning of channel patterns achieved by CS. In addition, they provide more detail on issues such as power requirements and interference modeling. In this paper, new contributions are made in terms of mobility simulation, consideration of picocells, blocking hotspots and stability, hybrid CS schemes, and performance comparisons to CA benchmarks.
5) *HCA:* Hybrids of CS and FCA are considered. The notation used is that 75% HCA means 75% of channels are used in FCA and the remaining 25% are administered by CS. Hence 75% HCA means that 18 of the 24 channels are used in an FCA three-cell repeat pattern. The remaining 25% of the channels (six channels) are administered by CS.

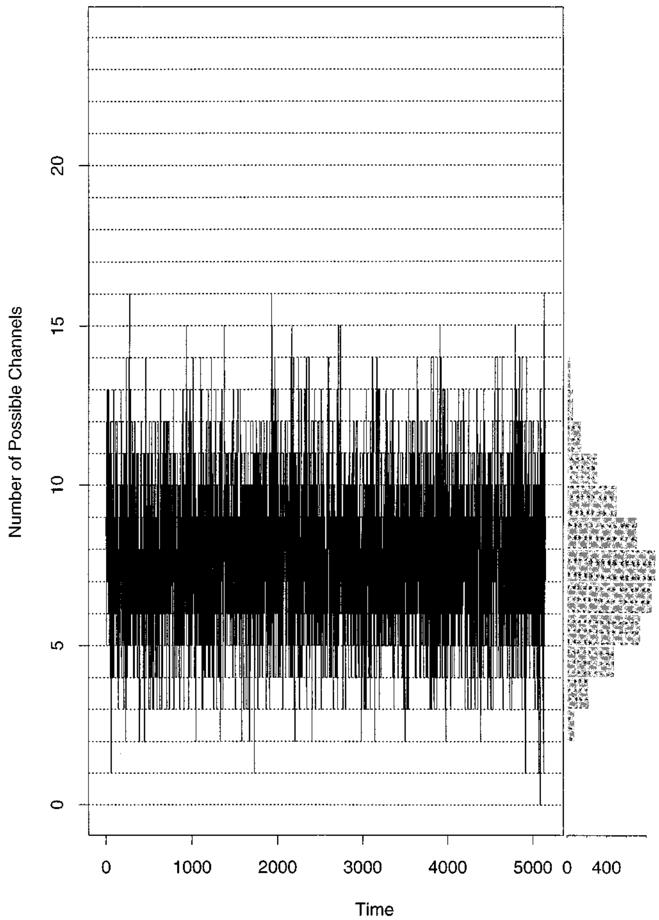

Fig. 7. Local behavior of the timid aggressive algorithm.

In fact, the HCA approach is conveniently administered directly by the CS algorithm. The FCA channels in a cell are given maximum priority in the CS channel priority scheme. Hence these channels are automatically chosen first by new or handoff calls arriving at the cell. Surrounding cells have zero priority given to these channels, and so the hard allocation of the FCA channels is achieved.

The first three methods give us differing baselines with which to contrast the performance of CS. FCA is the established approach but is completely inflexible and is outperformed by DCA at all but exceptionally heavy traffic loads. The timid algorithm is the simplest DDCA approach which involves no call reconfigurations. Comparisons of CS with the timid approach will show the improvement due to the "learning" implicit in the CS algorithm. The timid-aggressive approach is a powerful approach which improves over the timid method by possibly repeated channel grabbing and call reconfiguration. Comparisons of CS with the timid-aggressive approach will show to what extent the "learning" of CS can compete with the more drastic channel grabbing of the timid-aggressive approach.

III. Performance of CS in Regular Arrays

Using the simulation model described in Section II-A, the five CA methods are compared in Figs. 2–4.

Fig. 2 shows the effect of varying the hybrid percentage. As the percentage is decreased, the performance improves over FCA and around 70% reaches the CS curve. Further improvements continue until around 50%, and then performance deteriorates again and returns to the CS curve at 0% HCA. Due to the best hybrid's being around 50%, we now compare this hybrid with the other CA methods in Fig. 3.

Fig. 2 shows an interesting hierarchy of CA methods, which is constant below blocking probabilities of around 0.2. The aggressive method is the best, as expected, at the expense of up to three channel grabs and the resulting call reconfigurations. Very similar performance is achieved by the 50% HCA, which involves only local control and no call reconfigurations. This appears to be a very attractive option. Behind the 50% hybrid are the CS, timid ,and FCA method.

The well-known superiority of FCA for heavy traffic is also shown, but FCA is only marginally better here and only for catastrophically high blocking probabilities around 0.5.

In Fig. 4, the effect of varying the number of channel grabs in the aggressive algorithm is investigated. It is seen that the 50% HCA method achieves a performance roughly equivalent to that of the aggressive algorithm with one channel grab. Hence the hybrid option is again shown to be attractive, as this performance does not rely on any call reconfigurations. The successive gains produced by increasing the number of grabs do decrease but do not reach a limit. This is because in an infinite array, the TimAgg-∞ method can never fail, except in the situation where every call is blocked, which occurs with probability zero.

Next we consider the local behavior of the CA algorithms. The FCA method gives stable and predictable local behavior since each cell has a fixed allocation and thus many users are guaranteed channels. The hybrid is also quite stable, since a fixed number of channels are guaranteed with extra channels available if the dynamic algorithm can supply them. Purely dynamic algorithms, however, offer no "protection" to cells in the sense that a cell could find no channels available at all. This "blackout" situation is the extreme case of poor local behavior, which could conceivably occur with pure DCA. Note that a "blackout" corresponds to a cell's having no calls in progress and no channels available. To investigate this occurrence, we plot the number of possible channels (number of channels used + number of channels available by DCA) available to a fixed cell against time. Results are shown in Figs. 5–7 for the 50% hybrid, CS, and aggressive algorithm. The hybrid has a buffer of four guaranteed channels (50% of eight) and so the number of possible channels available varies above this line. The CS method is similar and only drops to three once. Intuitively, this behavior may be explained by the "hybrid-like" structure of CS, where each cell "learns" a set of favorite channels, which is a form of soft hybridization. The aggressive algorithm shows the worst local behavior and drops to three or below approximately 2% of the time.

IV. Performance of CS in Mixed Cellular Systems

We consider the two best algorithms of Section III (CS and timid-aggressive) and compare them for the simulation model

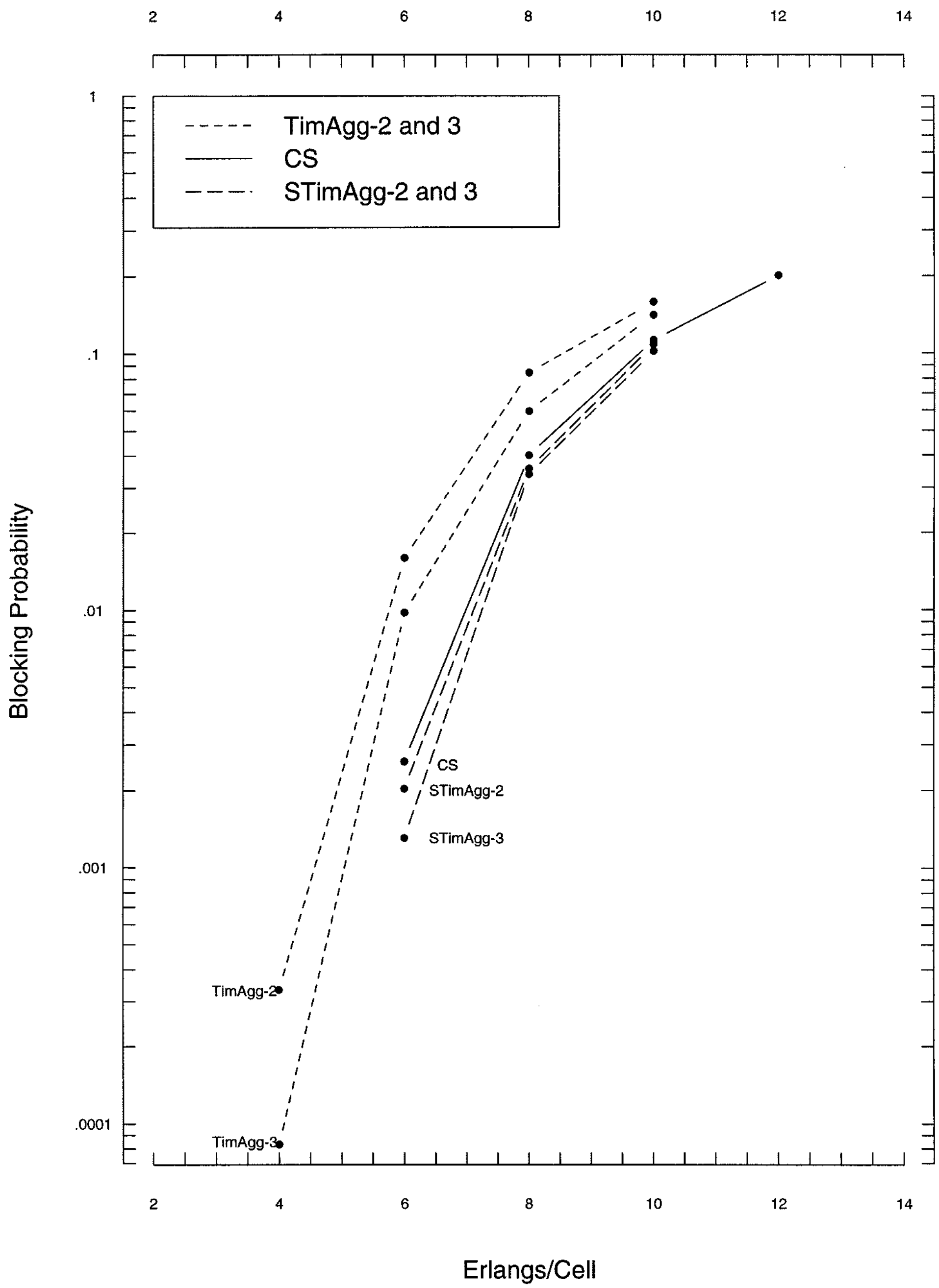

Fig. 8. Results for the mixed cellular layout.

described in Section II-B. The remarkable result, shown in Fig. 8, is that CS outperforms the timid-aggressive algorithm even with up to three channel grabs. The reason for this surprising result is that CS adapts to the mixed structure and learns to allocate channels to microcells and picocells in a close-packed way. This is shown in Fig. 9, which shows a snapshot of the macrocell and microcell channel priorities attached to a cell and two of its surrounding cells. Fig. 9 shows that CS has automatically resulted in a soft partitioning of high-priority channels with microcells reusing high-priority channels in neighboring cells and macrocells avoiding reuse. The picocells show a similar pattern. The fundamental advantage of the mixed system over a regular array is this ability to reuse channels in the microcells and picocells at smaller reuse distances. The CS approach learns this policy and hence performs well with exactly the same algorithm as for the regular array case. This does not occur with the timid-aggressive approach, since the channel grabs are done randomly; this need not result in microcells and picocells' reusing channels, and so the packing of channels is not as close. With sufficient numbers of channel grabs, the timid-aggressive algorithm would still outperform CS, but more than three would be needed. It is clear that brute force channel grabbing is no competitor to the learning of CS. Nevertheless, you can improve over CS with modified versions of the timid-aggressive approach. A smart-timid-aggressive approach is one where all channel grabs first look to take channels from micro- and picocell users. These users then look for replacement channels and can usually reuse channels used

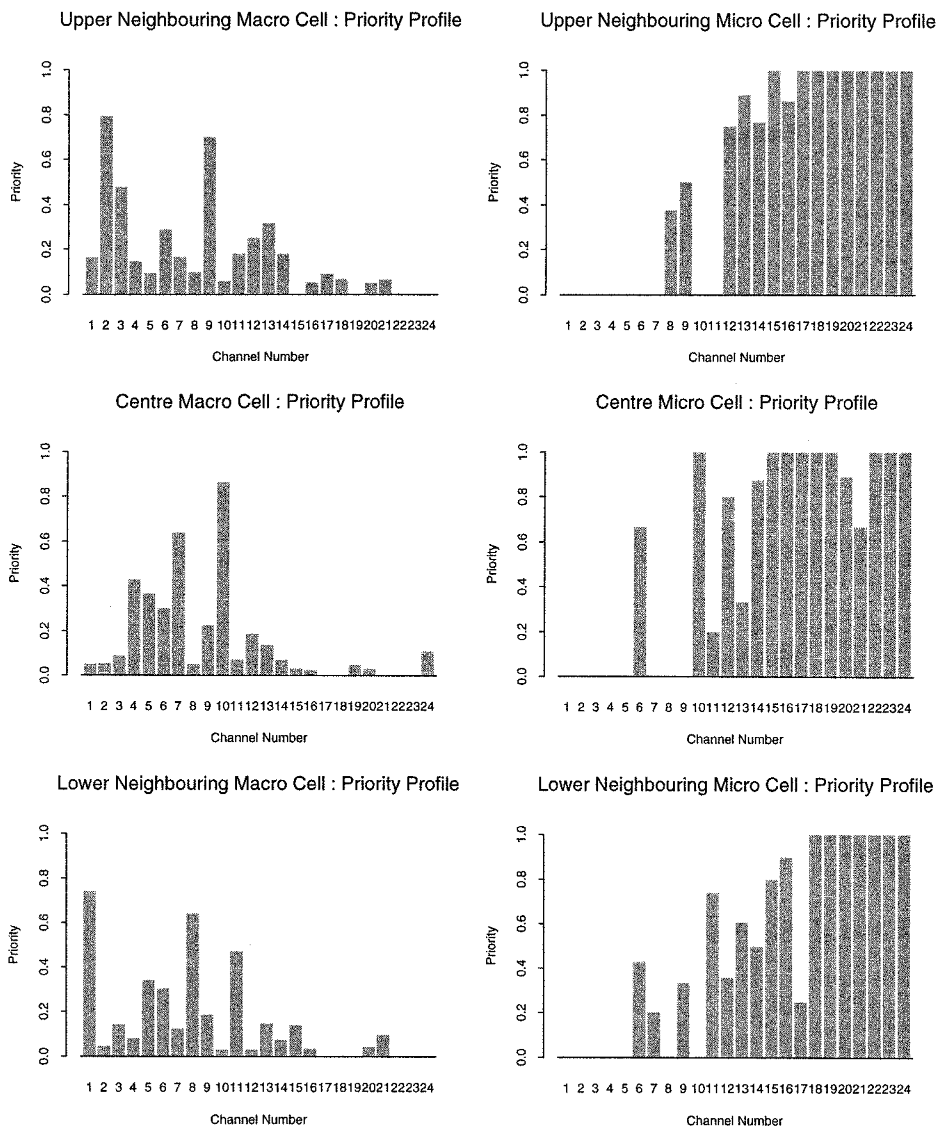

Fig. 9. Snapshot of channel priorities.

in adjacent micro- and picocells. This results in closer packing of channels. The smart-timid-aggressive approach does better than CS, as shown in Fig. 8. The conclusion seems to be that for any particular cellular scenario, it is probably possible to invent better schemes than CS. However, the enormous advantage of CS is its adaptability. The learning capability, which allows it to self-optimize, takes away the need to create new CA schemes for each new layout. Also, the performance of CS, a purely passive CA scheme, compares favorably with the more aggressive schemes, which require substantially more processing overheads. When one considers the simplicity of the CS algorithm, it seems to be an extremely attractive option.

V. Conclusions

The fundamental conclusion is that CS or hybrids of CS and FCA are attractive options for the following reasons.

1) Both CA methods involve distributed control and hence avoid the need for complex centralized control.
2) The 50% hybrid offers performance gains over both FCA and CS and, although requiring no call reconfigurations, achieves similar performance to the timid-aggressive algorithm, which involves a call reconfiguration for each blocked call.
3) The above conclusions are valid over a range of system parameters, including user speeds, types of motion, and distance traversed per cell (shown in [36] and discussed in Section II).
4) Both schemes offer increased stability of local behavior, since purely dynamic algorithms involving call reconfigurations may create pockets of high probability blocking, despite achieving lower blocking probabilities overall.
5) Transportability: the CS approach performed very well unchanged in a mixed cellular system; achieving lower blocking probabilities than the timid-aggressive approach

with up to three channel grabs and performing similarly to the smart-timid-aggressive method.

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