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Dynamic Channel Allocation in Interference-Limited Cellular Systems with Uneven Traffic Distribution

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***Abstract*— Most recently proposed wireless dynamic channel allocation methods have used carrier-to-interference (C/I) information to increase the system performance. Power control is viewed as essential for interference-limited systems. However, the performance of such systems under an imbalance of load among cells, as may occur often in microcells, is largely unknown. Here, we study a typical interference-limited dynamic channel allocation policy. Calls are accepted if a channel can be assigned that will provide a minimum C/I, and power control and intracell handoffs are used to maintain this level. We focus on the relationship between system performance and the amount of imbalance in load among neighboring cells. Previous studies for systems that do not use C/I information have found that dynamic channel allocation (DCA) outperforms fixed channel allocation (FCA) in all but heavily loaded systems with little load imbalance. We present two principal new results. First, we find that with use of C/I information, the difference in performance between FCA and DCA (in terms of throughput or blocking probability) is increasing with load imbalance. DCA was found to be more effective in congestion control at the cost of a slightly lower call quality. Second, we find that use of power control to maintain a minimum C/I results in two equilibrium average power levels for both DCA and FCA, with DCA using a higher average power than FCA, and that while DCA's power is increasing with load imbalance, FCA's average power is decreasing with load imbalance.**

***Index Terms*—Cellular systems, cellular system capacity, channel allocation, dynamic channel allocation.**

I. Channel Assignment and Allocation Under Varying Loads

THE GROWTH of the wireless market has increased the need for capacity. In response, a large number of channel assignment and allocation policies have been proposed. All such dynamic channel allocation (DCA) policies use additional information or complexity to obtain increased efficiency of the allocated spectrum. In any time-division multiple-access (TDMA) or frequency-division multiple-access (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 require that the channel satisfy a minimum carrier-to-interference ratio (C/I). The simplest policy to insure the reuse constraint, fixed channel allocation (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 segment of the spectrum assigned to the cell in which the call originates, perhaps subject to a minimum C/I.

FCA 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 spectrum segment of the originating cell. Alternatives to FCA can achieve higher efficiency at the cost of higher complexity and greater regional state information. Alternative policies generally differ from FCA in one or more of three manners: admission control policy, channel assignment strategy, and packing algorithm. An admission control policy answers the question "When do you accept a call?" FCA accepts a call if there exists a free channel in the corresponding spectrum segment. A channel assignment strategy answers the question "Which channel do you assign the call to?" FCA spreads each segment over the spectrum to avoid adjacent channel interference, but otherwise does not address this question. 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.

Proposed *admission control policies* vary along a spectrum from FCA to classical dynamic channel allocation, which accepts a call whenever a channel can be found that satisfies the basic frequency reuse constraint. FCA represents a complete partition of the channels among cells in a cluster. DCA represents a complete sharing of the channels. Intermediate policies differ in the amount of resource sharing they allow and include hybrid strategies [4], adjustment of parameters according to load [7], and channel borrowing [2], [8]. Proposed *channel assignment strategies* vary along a spectrum from random assignment, which randomly assigns any free channel satisfying the admission control policy to a new call, to global assignment, which uses information about all existing channel assignments in the entire service region to assign a channel that will in some sense minimize the system-wide detrimental effects. Intermediate policies differ in the amount of information required and include hybrid strategies [4], channel borrowing [2], [8], aggressive channel assignment [29], and heuristics to minimize impact upon neighboring cells [1], [3], [8]. Proposed *packing algorithms* vary along a spectrum from no reassignment, as in FCA, to maximum packing, which will reassign as many calls in the entire service region as necessary to accommodate a new call. Intermediate policies differ in the number of reassignments they allow and

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include channel ordering [25], [26], simulate annealing [24], and aggressive channel assignment [29].

Most recently proposed policies have used C/I information and power control to increase system performance. Policies using C/I assign channels based on the interference present on individual channels at the cell cite or at the mobile (see, e.g., [14]–[17]). This approach is consistent with the goal of *distributed* channel assignment, which becomes more important as the number of cells increases, which renders centrally administered methods useless. Power control is used to improve the call quality at the mobile position and to minimize interference (see, e.g., [11], [19], and [20]). In addition, power control may be explicitly used in call admission [29] at the expense of rearrangements of the calls already in progress. Systems with power control may also cause more call rearrangements than constant power systems [15]. Since these extra rearrangements more densely pack existing calls in the system [29], power control combined with an appropriate channel assignment algorithm may constitute a packing algorithm that rearranges calls in progress in order to accommodate a new call.

Most of the analysis of these proposed policies, however, has been conducted under the assumption of equal average load across the geographical service region. Cellular loads are often not equal across cells. In addition, when smaller cells are employed, as may occur in a personal communication system (PCS), we expect greater variation in traffic among cells. It is precisely this variation that presents FCA and DCA schemes with their critical challenge. It is of importance, therefore, to investigate such allocation policies in scenarios where the average load varies significantly across the coverage area.

When cells are presented with identically distributed numbers of call requests, it has been recognized that at low loads maximum packing (MP) is an optimal policy, while at high loads FCA is nearly optimal [3], [6]. Furthermore, the optimal policy lies on a continuum between these two, and the optimal amount of sharing is a decreasing function of the uniform cell loads [21]. Research into the performance of dynamic channel allocation techniques under unequal cell loads has been relatively scarce. A few early papers presented single examples of nonuniform traffic under DCA [5], [27], [28]. Everitt [3] investigated MP in the situation in which mean cell loads were i.i.d. normal random variables. Zhang simulated one unequal load configuration, with proportional increases, for some channel borrowing schemes [8], [23]. Two recent studies have investigated packing algorithms and their effect upon unequally loaded cells in dynamic channel algorithms which attempt to accomplish MP [25], [26].

In a recent paper [22], Khan and Jordan investigate the variation of the optimal channel allocation strategy with variations in the traffic pattern. They found it helpful to consider patterns that consist of lightly loaded cells and heavily loaded cells. Two quantities were used to define the variability of the traffic: spatial imbalance, defined as the percentage of cells that are heavily loaded, and load imbalance, defined as the ratio of "heavy" to "light" load. It was found that classical dynamic allocation (with global assignment and maximum packing) achieves a higher total throughput than fixed allocation for all but heavily loaded systems with small load imbalances. Furthermore, it was found that the optimal policy only achieves a small increase in total throughput over dynamic allocation and that this gain occurs principally at moderate loads in systems with a high degree of spatial imbalance.

The effect of the use of C/I information and power control in DCA under load imbalance, however, remains largely unexplored. In this paper, we consider a typical interference-limited dynamic channel allocation policy. Calls are accepted if a channel can be assigned that will provide a minimum C/I, and power control and intracell handoffs are used to maintain this level. We focus on the relationship between system performance and the amount of imbalance in load among neighboring cells. In Section II, we present the system considered, including the attenuation model and call acceptance and handoff procedures. In Section III, we analyze the effects of load imbalance upon interference-limited FCA and DCA. We present two principal new results. First, we find that with use of C/I information, the difference in performance between FCA and DCA (in terms of throughput or blocking probability) is increasing with load imbalance at the cost of a slightly lower call quality. Second, we find that use of power control to maintain a minimum C/I results in two equilibrium average power levels, for both DCA and FCA, with DCA using a higher average power than FCA and that while DCA's power is increasing with load imbalance, FCA's average power is decreasing with load imbalance.

II. System Description

A. Layout and Traffic Model

The system under study consists of a rectangular 12.8 by 11-km area, covered by 64 equal-size hexagonal cells. The cell diameter is 1.85 km, and there are a total of 252 channels available. Since our primary goal is to study the effects of nonuniform traffic on the performance of the system, a percentage of the aggregate incoming traffic is distributed uniformly in a narrow 200-m strip running across the center of the geographical region (Fig. 1), while the rest of the incoming calls are uniformly distributed across the whole coverage area.

There are two types of mobiles: cars and pedestrians. Cars move in a straight line (N, S, E, or W) and may change direction every 600 m. Pedestrians move in uniformly distributed direction (0°–360°) and change direction after a uniformly distributed distance (0–20 m). 40% of the mobiles are pedestrians moving at 0.8 km/h, 40% are cars moving at 24 km/h, and 20% are cars moving at 40 km/h.

The population of mobiles in the service area is finite, and call originations per mobile form a Poisson process with an average of two calls per hour. The duration of a call is exponentially distributed with a mean of 100 s. Each mobile thus generates 0.055 Erlangs of traffic. For example, for a cell diameter of 1.85 km, traffic volume of 30 Erlangs per cell approximately corresponds to 13.5 Erlangs/km^2.

The size of the system is as large as systems typically considered in simulation studies and large enough to model an actual system. In addition, other systems of smaller or

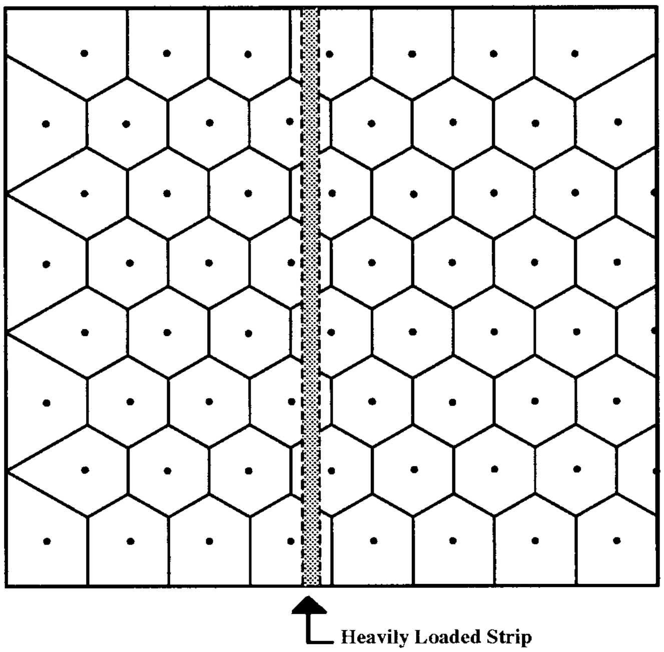

Fig. 1. Simulation coverage area layout.

greater size have been considered in test runs. The present system is large enough to have essentially the same statistics as larger systems. Finally, the highway imbalance scenario is a representative case and can also be encountered in actual systems.

B. Attenuation Model

The average received power in cellular systems is usually assumed to be proportional to the transmitted power, attenuated by an inverse power of the distance between receiver and transmitter. Existing models differ in the choice of this power factor and some adjustment parameters. It can be assessed from [13] that the choice of the attenuation model has a minor effect upon the qualitative system performance. We use in this study the most widely used attenuation model in analog cellular, the Hata attenuation model [9], to calculate the signal strength at mobiles or cell sites. According to the Hata model, the decibel attenuation of the signal for an urban area is given by the empirical formula

$$L_p = 69.55 + 26.16 \log f_c - 13.82 * \log h_b - a(h_m) + (44.9 - 6.55 * \log h_b) \log(d) \quad (1)$$

where

- f_c frequency in megahertz (820–830 MHz);
- h_b cell site antenna height (30 m);
- h_m mobile antenna height (1.5 m);
- $a(h_m)$ 3.2 $(\log 11.75\, h_m)^2 - 4.97$ (correction factor for large city);
- d distance in kilometers.

The numbers in parentheses indicate values used in this study. The term $a(h_m)$ provides a correction factor for large cities.

In addition, the path loss is adjusted for a suburban area [9]

$$L_{ps} = L_p(\text{urban area}) - 2(\log(f_c/28))^2 - 5.4. \quad (2)$$

Omnidirectional antennas are used, and the background noise is assumed to be −128 dBm. In addition, only cochannel interference is considered, and adjacent channels are never used in the same cell, either in FCA or DCA.

Signal shadowing is not included in the model, since our main purpose is to compare the average throughput of different channel allocation techniques. Shadowing is expected to increase forced termination and handoff rates. It has been reported that the different attenuation models do not alter the qualitative performance of the system [13], [31]. Shadow fading would increase the handoff rates and power level to a small degree. This does not affect relationships between the performance of different system configurations (i.e., range of load, channels per cell). We have established with additional simulations that results presented here are qualitatively insensitive to shadow fading. On the other hand, shadow fading plays an important role when different power control or channel assignment algorithms are compared, as we discuss in [30].

C. Call Initiation

When a new call is attempted, the cell with the strongest received signal at the mobile is selected. Mobiles are assumed to listen on a separate control channel on which there is no power control. The strongest cell's signal is determined by the Hata distance-attenuation model, thus, the cell borders are not predefined, but rather determined at the mobile location. The base station (BS) scans all channels of the cell, if using DCA, or its allocated channels if using FCA. In FCA, channels are allocated to each cell according to a seven-cell reuse pattern with 36 channels/cell. The numbers of the three channels with the least interference at the cell site are passed to the mobile, which selects the one with the least interference at its location. The minimum transmitter power level is chosen among 6.3, 15.8, 39.8, 100, 251, 630, and 1584 mW (taken from AMPS standards [11]) to achieve a resulting C/I of at least 20 dB. If no channel can be found that can achieve this minimum C/I at maximum power, the call is blocked. When a new call enters the system, the cochannel interference is updated both at cell sites and mobiles, as shown in Fig. 2.

The channels are assumed to be full duplex [10], [11], so that the cochannel interference at a mobile is simply the sum of the signals of all interfering calls that use the same channel, and vice versa.

The call admission algorithm allows for an incoming call to acquire a channel even when interference is present. The channel selection process is distributed in the sense that there is no knowledge at a BS about the channels that are used in cells in the same cluster. Since power control is used to control the C/I of the channel, it is possible that after a call admission an arbitrary number of channel rearrangements (intracell handoffs) will be performed, so that the interference in the system is minimized.

D. Handoffs

Handoffs are attempted either to find a better cell (intercell handoff) or to find a better channel at the current cell (intracell handoff). Intercell handoffs are requested whenever a cell with

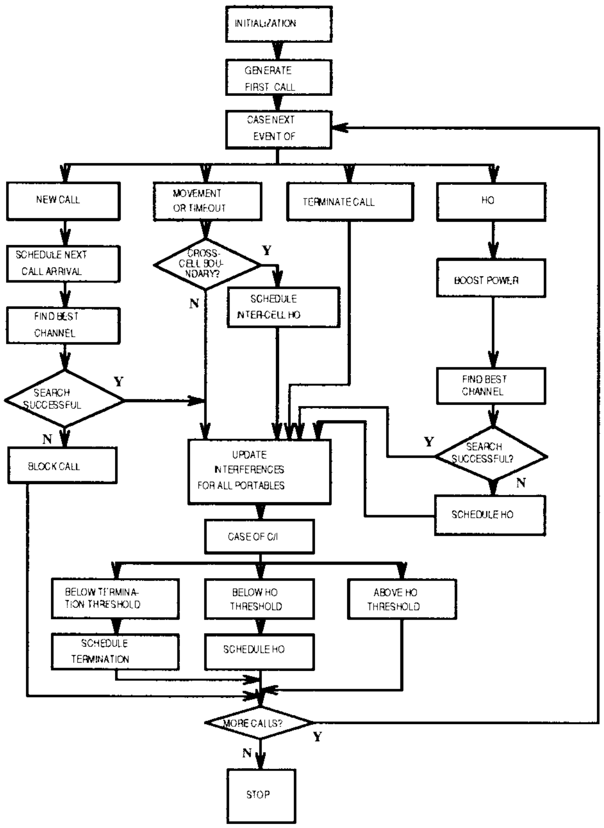

Fig. 2. Simulation model flow diagram.

a stronger signal is detected at the mobile. If the request is successful, the same channel search procedure as in call initiation is followed. It is thus guaranteed that mobiles are always locked onto the strongest cell. Note that cells are taken to be interference limited, and cell boundaries are stochastic rather than deterministically given.

Intracell handoffs are requested whenever the C/I ratio drops below 17 dB. The mobile boosts the power level immediately to the minimum power level which yields a C/I above the minimum level for call initiation (20 dB). It then scans the available channels at the cell for one that has less interference than the current channel. If no such channel exists, the handoff is blocked and the mobile may request another handoff. Typically, there is a time interval between successive handoff requests in order to avoid multiple "ping-pong" handoffs; we assume a 3-s delay.

If at any time during a call a mobile's C/I remains below 10 dB for 3 s, the call is dropped (forced termination). The completion time of the handoff is uniformly distributed between 2–4 s. It has been found that this time is load dependent [12], but for simplicity, independence is assumed here. If during a handoff procedure the call quality falls below the termination threshold before the handoff procedure is complete, the call is dropped. If on the other hand, the call quality improves above the handoff threshold, the handoff is cancelled.

III. RESULTS

FCA and DCA are compared under several cases of load imbalance, corresponding to heavily loaded strip traffic equal to 0% (no imbalance), 5%, 15%, and 30% of the total traffic. We use new call and handoff blocking probabilities as performance measures of the system. Calls in progress are given priority over new calls in the sense that they are allowed to boost their power level when their C/I is poor, even though this may prevent new calls from entering the system. Since signal fading, which would produce possible points of poor coverage in a cell, is not modeled, the probability of forced termination is virtually zero in all cases. In the following sections, we analyze the ability of DCA and FCA to cope with load imbalance in an interference limited system.

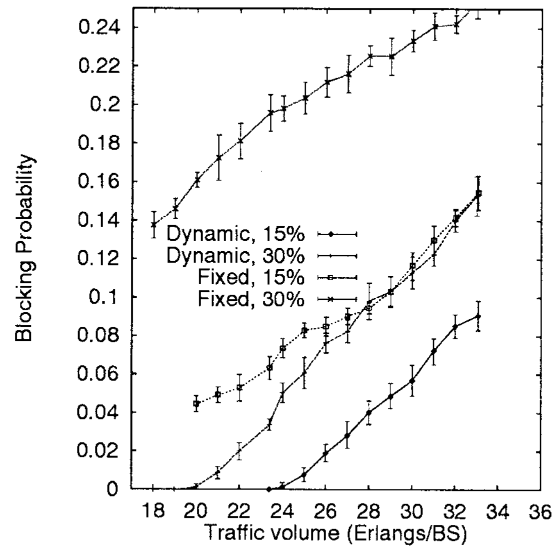

Fig. 3. Blocking probabilities, 95% confidence intervals.

A. Blocking probabilities

The blocking probabilities for FCA and DCA are plotted against load, under 15 and 30% load imbalances, in Fig. 3. The vertical bars represent 95% confidence intervals. The blocking probabilities are in all cases increasing approximately linearly with load in the range of intermediate loads and low blocking. As expected, DCA outperforms FCA at all loads and both load imbalances.

Of greater interest, the difference between DCA's and FCA's performance, at a fixed load, is an increasing function of load imbalance, as observed in Fig. 3. To understand this result, we focus on estimating the "knee" of each curve, the average load at which the blocking probabilities in each system start becoming significant. FCA reserves 36 channels for each cell. The blocking probability is thus dominated by the heavily loaded cells and starts increasing rapidly when the loads in these cells approach their capacity. This occurs near an average of 18 Erl/cell at 15% high-load region traffic and near an average of 12 Erl/cell at 30% high-load region traffic (see Appendix).

DCA, however, only operates under the constraint that the number of calls within a cluster not exceed the total number of channels. Its average blocking probability, therefore, is dominated by the clusters surrounding the high-load region and starts increasing rapidly when the *total cluster load* approaches the cluster's capacity. In our model, a high-load region cluster

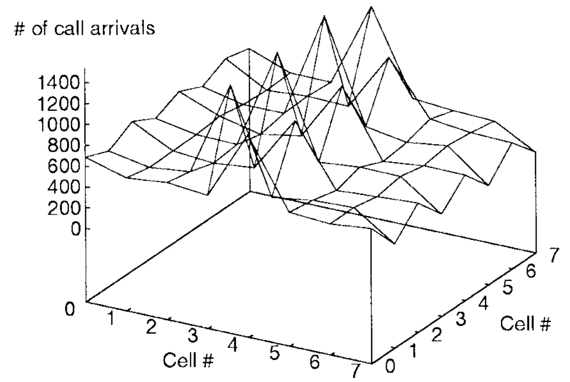

Fig. 4. Load profile (15% imbalance, 27 Erlangs per cell average load).

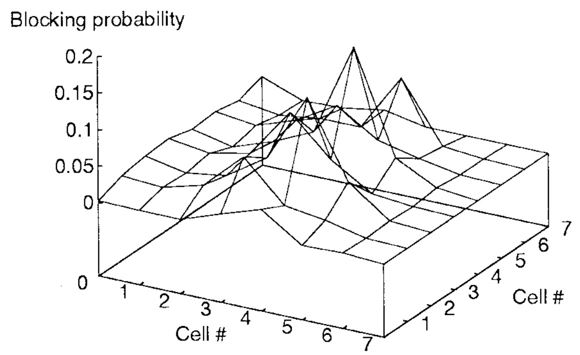

Fig. 5. Blocking probability profile (dynamic allocation, 15% imbalance, 27 Erlangs per cell average load).

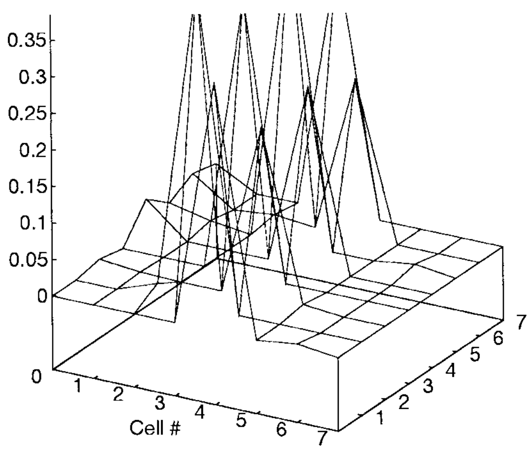

Fig. 6. Blocking probability profile (fixed allocation, 15% imbalance, 27 Erlangs per cell average load).

contains three high-load cells and four normal load cells. A high-load region cluster's load approaches the number of channels near an average of 26 Erl/cell at 15% high-load region traffic and near an average of 21 Erl/cell at 30% high-load region traffic (see Appendix).

The difference in congestion point between DCA and FCA is clearly visible in Fig. 3. At very light average loads (less than 15 Erl/cell at 15% or less than 10 Erl/cell at 30%), only DCA achieves negligible blocking. At moderate loads (24–30 Erl/cell at 15%, 20–24 Erl/cell at 30%), DCA still achieves moderate blocking, while FCA is clearly unacceptable. Furthermore, the difference of blocking rates between the two methods becomes larger as the load imbalance increases,

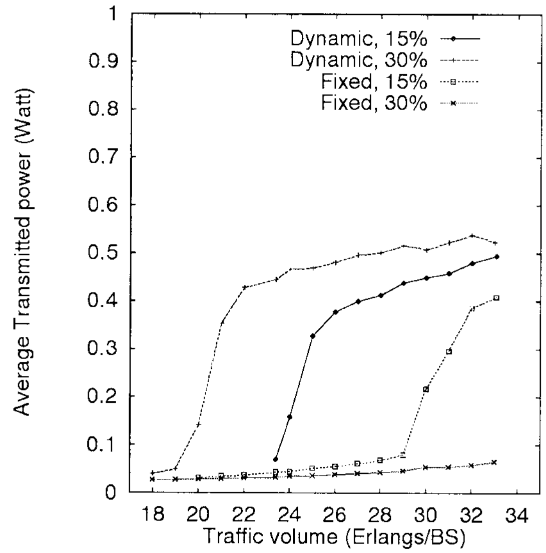

Fig. 7. Average transmitted power (W).

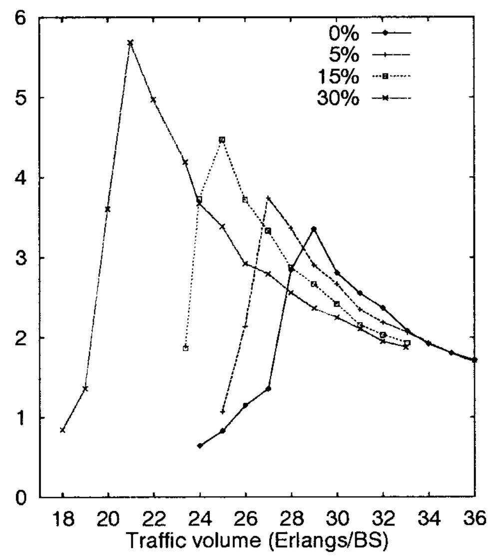

Fig. 8. Average number of channel changes, DCA.

which indicates that dynamic allocation responds better by reallocating resources to meet increased demand.

This ability of DCA is best observed in Figs. 4–6. In Fig. 4, the spatial profile of the offered load, in the case of 27 Erlangs per cell average load and 15% load imbalance, is presented. The effect of the high-load region is shown as an increase in the offered load in the center cells.

It can be observed from the spatial profile of the system blocking (Fig. 5) that DCA tends to "spread" the blocking from cells with higher load to their neighbors. On the other hand, blocking for FCA is extremely high for the cells with the increased load, as shown in Fig. 6.

B. Average Transmitted Power

The average transmitted power for FCA and DCA are plotted against load, under 15% and 30% load imbalances, in Fig. 7. In each case, the curves are almost piecewise constant, with two "equilibrium" power levels. The system operates at a low-power level at low loads, and the power

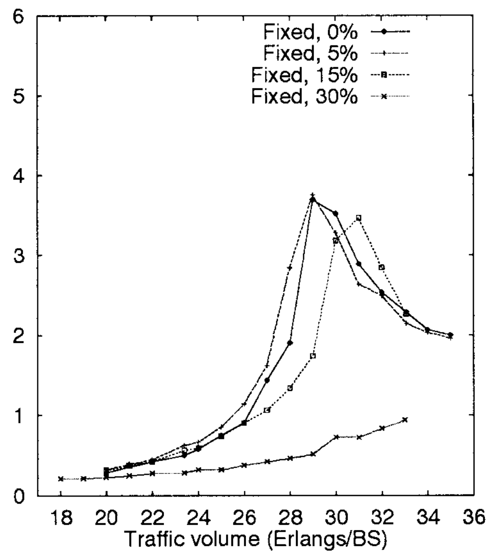

Fig. 9. Average number of channel changes, FCA.

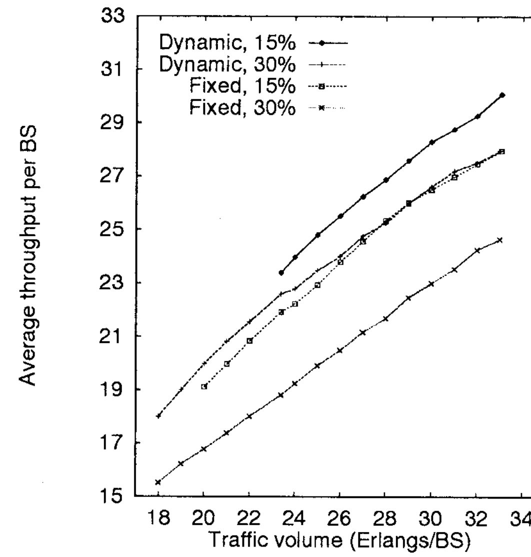

Fig. 11. Average throughput per cell.

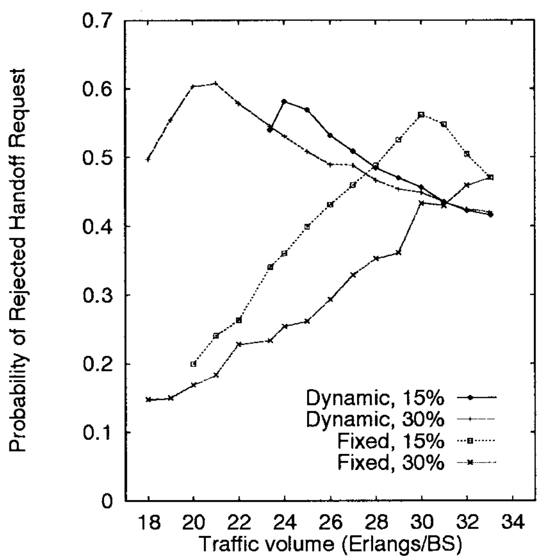

Fig. 10. Handoff blocking probabilities.

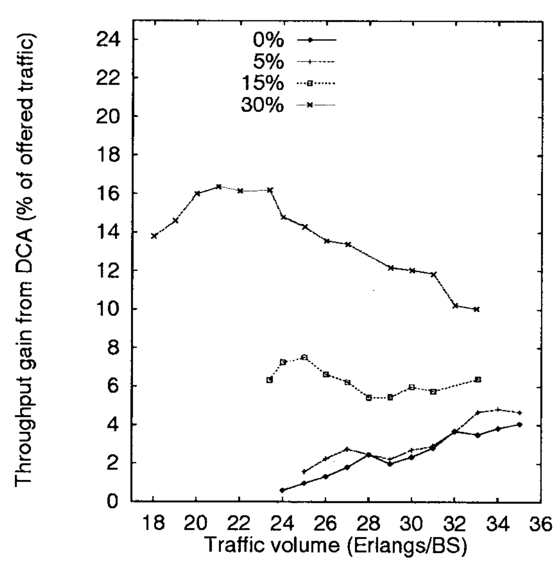

Fig. 12. Average throughput gain from the use of DCA as a percentage of the input traffic.

is slightly increasing with load. This slow increase is due to the increase in the number of rearrangements, or intracell handoffs, required in order to accommodate more calls in the system. As new calls enter the system, they cause interference to existing calls. If an existing call's C/I falls below 17 dB, that call momentarily boosts its power level to improve its quality. It holds the higher power until it is assigned a channel with less interference. If such a channel cannot be found, the call maintains the higher power level, forcing cochannel calls to do the same. If the handoff blocking probability is sufficiently high, this will create a chain effect throughout the entire system, driving the average power to a new level where further increases are unproductive.

At each load imbalance, DCA uses a higher transmitted power than FCA. The *threshold* at which the system is driven to the higher equilibrium power level (Fig. 7) depends on the allocation policy and on the load imbalance. A perhaps surprising result is that while under DCA the threshold is decreasing with load imbalance, under FCA the opposite holds. To understand this effect, we again focus on the congestion points for each policy.

In DCA, the threshold occurs at the load where the blocking probability curve has its *knee*, namely, near 26 Erl/cell at 15% high-load region traffic and near 21 Erl/cell at 30% high-load region traffic, as mentioned above. In FCA, however, increased blocking from increased imbalance tends to be confined within the cells with the excess load. The extent of the power adjustment chain effect is thus limited, since new call arrivals tend to be controlled by the cap on the maximum number of calls per cell. Meanwhile, in the normal load cells, channels are available to serve new calls, even when the high-load region cells have high-blocking probabilities. As a result, the total average power level will be increased only when the load in these normal load cells reaches a critical point. The general system trend is thus to boost power levels when the *total*

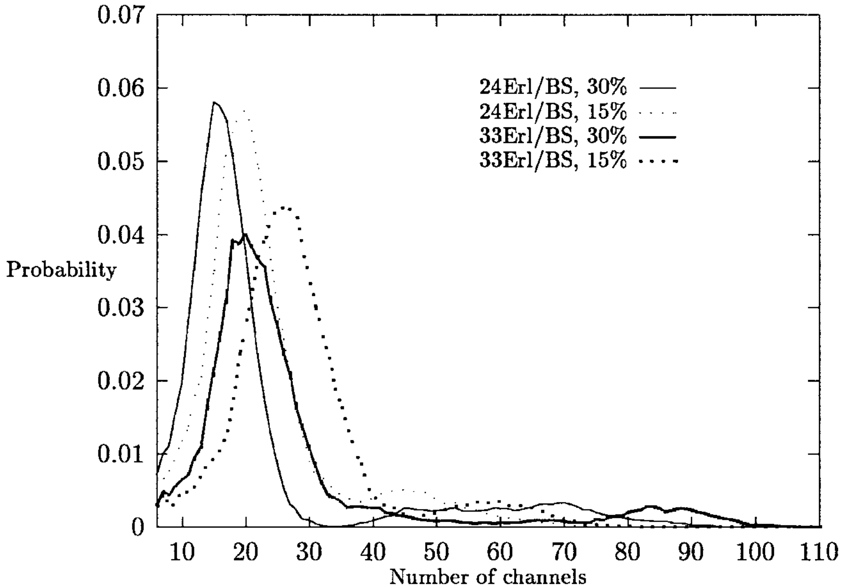

Fig. 13. Probability density of channel utilization at cell, DCA.

throughput reaches a critical level, and under FCA, this occurs at higher average loads for higher load imbalances.

C. Handoffs

In Figs. 8–10, the average number of channel changes per call for DCA and FCA and the blocking probability of handoffs requests are plotted, respectively. The channel changes are consistent with the average power levels plotted in Fig. 7. If a mobile A boosts its power level, any cochannel call, e.g., B, will detect the increased interference. If the resulting C/I is unacceptable, B will immediately boost its power level and scan the available channels at its current cell for a channel with less interference. If such a channel cannot be found, the higher power level is maintained by B, and this will trigger a similar sequence of actions for other cochannel calls. High-channel request blocking rates thus occur when there are abrupt changes in average transmitted power. Handoff rates follow a similar trend. The effect occurs sooner with increasing load imbalance in DCA, while the opposite holds for FCA.

D. Throughput

The trends in blocking are also reflected in the system throughput, defined as the average number of calls in the system, shown in Fig. 11. DCA outperforms FCA, and the difference between the two is increasing with load imbalance since DCA is less sensitive to this measure. Within each policy, the difference between the throughputs in the two load imbalances is mainly due to calls lost in high-load cells. This difference is slightly increasing with average load, since high-load cells' loads proportionately increase.

The curves for DCA are slightly concave, since they are a combination of cells that operate close to their capacity and cells that carry very light load. The curves for FCA show a considerable loss in call-carrying capacity in the presence of load imbalance. The FCA curve for 30% high-load traffic is almost linear for the range plotted, indicating that high-load cells are operating at their capacity, while the throughput for normal load cells is increasing linearly due to their light load.

From Fig. 12, it can be assessed that the higher the imbalance, the higher the gain from the use of DCA. At low imbalance ratios (5% and 15%), the gain in throughput is an increasing function of the traffic for the range studied. In the case of 30% imbalance, the difference in throughput is decreasing with increasing traffic load (Fig. 12).

In Fig. 13, the probability density function of the average throughput at a cell is plotted, averaged across all cells in the coverage area, for DCA only under two loads and two load imbalances. There are two local maxima on each curve: the lower maxima corresponds to low channel usage in normal load cells, and the upper maxima corresponds to higher channel usage in high-load cells. The curves for lower loads have more probability mass at lower channel usages as expected. The upper maxima's location is increasing with load and with load imbalance. Even for the case that yields the highest blocking probabilities, however, it is obvious that DCA does not make full use of all 252 channels in a single cell. We conclude that a hybrid allocation scheme which would allocate a number of channels in between that of FCA and DCA could achieve the same throughput as DCA, while at the same time reducing cell installation costs.

E. Call Quality

Finally, the resulting call quality, in terms of C/I, is shown in Fig. 14. The cost of increased throughput or lower blocking probability is lower call quality, so these curves are in inverse order from those in Fig. 11. Under each policy, however, the average call quality remains well above the minimum call admission requirement of 20 dB.

In an interference-limited system, the total interference is an increasing function of the channel throughput. Since the aver-

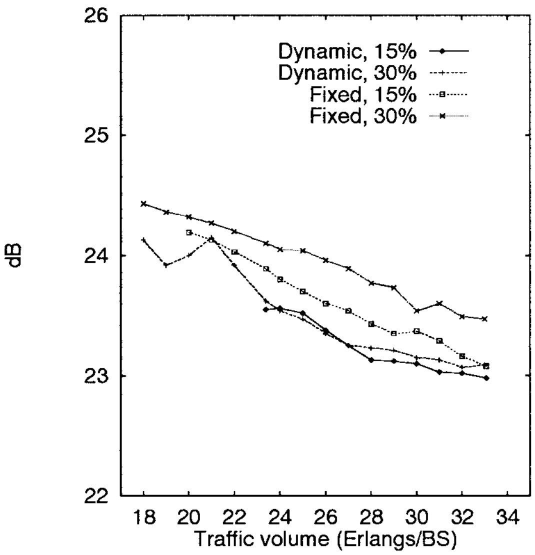

Fig. 14. Average call quality (C/I) in decibels.

age throughput is increasing with load, the average call quality is decreasing with increasing load. Call quality is independent of the average transmitted power in the system. The curves in Fig. 14 are thus not affected by the transition of the system from the lower to the higher power equilibrium level.

IV. Conclusions

The performance of FCA and DCA schemes using C/I information and power control were studied in the presence of significant load imbalance. Most recently proposed dynamic channel allocation policies have included use of C/I and power control, yet little information is available concerning their performance in systems with variations in cell loads. Since these variations may become more common in microcells, it is critical that their effect be understood. It was found that the difference in performance between FCA and DCA (in terms of throughput or blocking probability) is increasing with load imbalance at the cost of a slightly lower call quality. We also found that use of C/I and power control results in two equilibrium average power levels, for both DCA and FCA, with DCA using a higher average power than FCA and that while DCA's power is increasing with load imbalance, FCA's average power is decreasing with load imbalance.

When the system moves from a low-power equilibrium to a higher power equilibrium, there is an excessive number of handoffs, particularly for DCA. One way to control this effect is to consider alternative power control algorithms, such as decreasing power level when C/I is significantly high, which has not been considered here. Analyzing strategies for smoothing out this transition, as well as studying the dynamics of movement between the two equilibria, may yield useful insights into system design and are topics for future research. Additionally, assessing separately the gains for DCA obtained from increased channel availability and power control will be useful in determining their individual impact for a given load imbalance scenario.

Appendix

Denote by p the imbalance percentage, as defined in Section II, and by ρ the average offered traffic per cell. The average traffic load in a cell of the heavily loaded strip ρ_h is given by

$$\rho_h = \rho \times \left[(1-p) + p\frac{K}{K_h}\right] \tag{3}$$

where K is the number of cells $(= 64)$ and K_h is the number of cells on the heavily loaded strip $(= 8)$. The traffic load in a lightly loaded cell ρ_l will then be

$$\rho_l = \rho \times (1-p). \tag{4}$$

In DCA, the blocking increases rapidly when the total load per cluster ρ_c approaches the capacity of the cluster, which is the total number of available channels N. In the configuration studied here, there are in the worst case three high-load cells per cluster. The blocking probability becomes significant when

$$\rho_c = 3\rho_h + 4\rho_l = N. \tag{5}$$

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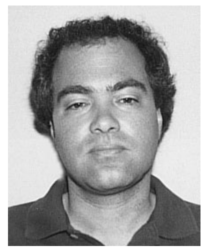

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