Integrated Dynamic Channel Assignment and Power Control in TDMA Mobile Wireless Communication Systems

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***Abstract*—With the evolution of analog mobile wireless communications systems into digital second- and third-generation systems, there is growing interest in finding more efficient ways of managing the available resources, in particular radio spectrum and power. In the context of time division multiple access (TDMA) systems, this interest has led to the development of a variety of dynamic channel assignment (DCA) and power control (PC) algorithms. Despite the intense activity in both the DCA and the PC arenas and some proposals for combined DCA with PC, not enough work has been devoted to effectively integrating them. In this paper, the integration of DCA and PC is investigated and a family of integrated algorithms is presented. These algorithms, fully distributed and cost adaptive, achieve capacity levels significantly higher than those of a system with only DCA or PC. With respect to a system without any DCA or PC, several-fold capacity increases are obtained. Furthermore, these capacity levels are attained with user mobility included in the analysis.**

***Index Terms*—Admission control, channel assignment, mobility, power control (PC).**

I. INTRODUCTION

THE EVOLUTION of analog mobile wireless communication communication systems into digital second- and third-generation systems, triggered by an ever-increasing need for high capacity, has fueled the interest in finding more efficient ways of managing the resources available to the system, the most important of which are radio spectrum and power. In the context of frequency and time division multiple access (FDMA/TDMA) systems, dynamic channel assignment (DCA) has been a topic of intense research for many years [1]–[5]. DCA allows for more efficient use of the available spectrum and eliminates the burden of costly frequency planning. Power, on the other hand, is both a scarce resource at mobile stations and a capacity-constraining factor in systems inherently limited by interference. This, in turn, has led to the development of a variety of power control (PC) schemes which try to minimize the amount of interference in the system and the power consumption at the mobiles [6]–[9]. Despite the intense activity in both the DCA and the PC arenas, little has been done aimed at trying to integrate them effectively. Some early work in combined DCA with PC was presented in [10], although with a reduced level of integration. Another contribution in [11] addressed important admission control and channel management issues. Additional results can be found in [12]–[15]. In all cases, however, mobility is neglected, and no handoff procedures are considered. With the exception of [11], no channel reassignments are considered either. In this contribution, we investigate the integrated use of DCA and PC in realistic scenarios with user motion.

With the escalating cost of radio spectrum and infrastructure, service providers are demanding extensive capacity on a per channel per base station (BS) basis.[1] We define such capacity as the voice traffic that can be served by a BS at a certain level of quality—measured in terms of blocking and dropping rates—with a given number of channels. For convenience, blocking and dropping are often combined into a single metric, sometimes referred to as grade-of-service (GoS), although that hides the ratio between the two. Since the relative importance of either one is subjective, we prefer to keep them separate, and we consider dropping to be more severe than blocking. On the other hand, we define the "cost" of any algorithm involving DCA as the average number of channel reassignments per call required to achieve a given capacity level.

The impact of user motion on system capacity was investigated in [7] and [17] for fixed channel assignment (FCA) systems. Even within the simplified framework of those investigations, the decrease in capacity proved to be significant. A more thorough study for fixed-power DCA systems was presented in [18], where the impact of mobility on both capacity and cost was quantified. Throughout this paper, pedestrian mobility is included in all analysis and results.

The paper is organized as follows. Sections II and III discuss the separate benefits of DCA and PC focusing on distributed algorithms. Section IV describes the simulation models. Section V presents a class of integrated algorithms which make combined use of DCA and PC to provide distributed admission control and combined channel and power management. Finally, conclusions are summarized in Section VI.

II. DCA

The traditional FCA approach is to establish a reuse pattern determined by a reuse distance selected *a priori* [19]. FCA

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[1] With any wireless access technology, overall system capacity can always be increased almost indefinitely by decreasing BS spatial separation [16].

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does not take advantage of the user distribution, and thus, the channels get assigned to cells and not to users. The reuse distance is conservatively chosen to ensure that any set of cochannel users can coexist with high probability regardless of their location. With DCA, all channels are placed in a common pool and dynamically assigned according to some strategy. DCA algorithms assign channels to different cells depending on their respective loads, and hence, they are able to alleviate traffic hot spots. In addition, these algorithms collect signal and interference measurements that relate to the position of users. By adjusting the reuse distances according to that information, they can push capacity to higher levels. In fact, it can be shown [18] that capacity is maximized when the carrier-to-interference-and-noise ratio (CINR) of every set of cochannel users is balanced around some level no higher than strictly necessary.

The problem of finding the most appropriate channel for a new user can be broken down in two distinct problems.

1) Admission Control Problem: The system has to determine the subset of idle channels on which the new user can coexist with the users already on those channels. To do so, the mutual path gains for the entire set of cochannel users, including the new candidate user, have to be known for every channel. Without PC, this problem can only be explicitly solved by centralized algorithms, which are impractical [20]–[22].

2) Selection Problem: The system has to select—based on some strategy—a channel from those, if any, which meets the admission criterion. Knowledge of signal and interference levels at the new user's location is sufficient, and hence, distributed approaches are feasible.

Notice that with DCA, a valid channel arrangement may no longer be valid as soon as any user moves. Accordingly, the capability to reassign users to a different channel becomes essential. In fact, when motion is considered, emphasis should shift from admission control onto reassignment mechanisms [18]. In principle, the best strategies are those that permit everyone to be rearranged—if necessary—to accommodate a new user. This is ultimately equivalent to solving a new global channel assignment problem every time an admission is requested. Since such schemes would involve a great deal of computation and signaling and a large number of reassignments, practical algorithms only try to rearrange a limited number of users.

A control channel (CCH) facilitates the implementation of DCA and becomes a reference resource for the entire system [3]. It also allows mobiles to locate BS's for initial access and for handoff, especially since the CCH can have fixed power even if the system is power controlled. Additionally, by carefully designing the CCH structure, blind-slot problems can be mitigated [18]. Therefore, we construct our algorithms with the assumption that a fixed-power CCH exists.

In addition, system-wide synchronization is desirable with DCA [3] for several reasons.

- It simplifies the structuring of the CCH.
- Without synchronization, each slot typically experiences interference from portions of two slots instead of only one. The performance is basically determined by the strongest interferer, and a significant penalty is incurred.

Accordingly, synchronization to the slot level is assumed throughout this paper. With that, our analysis holds for both time and frequency division duplexed systems. A traffic channel (TCH) corresponds to a pair of specific carrier/slot combinations for uplink and downlink

A fundamental limitation of TDMA systems lies in the fact that when a mobile is active on a given slot, it cannot monitor other TCH's corresponding to that same slot, and possibly to the adjacent ones [3], without temporarily suspending the active communication. Even worse, the mobile cannot locate other BS's whose CCH is bursting only on those blind slots. This second problem can be solved by an adequate CCH structure [18].

Our system has 128 TCH's organized in 16 carriers and eight slots, three of which are blind to active users. The system architecture as far as modulation, coding, etc. is abstracted by a local-mean CINR level $\gamma_{\min}$ considered sufficient for reliable operation. All signal, interference, and CINR values are local-mean with the fast-fading component averaged out. Calls are set up with directed retry [23]. The mobile scans the downlink CCH and finds the BS with the strongest signal. If the connection attempt fails, the mobile tries again through the next strongest BS and so forth. A total of three BS's are explored, after which the call is blocked and cleared. Handoff is not attempted as long as the current BS remains the strongest one.[2] If a user's CINR (either link) falls below some level γ_{drop} for five consecutive seconds, the call is dropped. While active, a mobile constantly monitors the downlink CCH of neighboring BS's. If one of them exceeds the level of the serving one by a hysteresis margin of 4 dB, a handoff attempt is triggered. If handoff fails, the user stays connected to the old BS, and new attempts are periodically triggered.

Since link quality is basically conditioned by its weakest component, a key aspect of any channel assignment algorithm is the balancing of uplink and downlink. With a few exceptions [3], [24], the issue of achieving balanced link performance has been overlooked in much of the DCA work presented in the literature, where the algorithms usually operate on either uplink or downlink exclusively. In our simulations, all potential sources of imbalance (differences in receiver sensitivity, antenna diversity, etc.) are avoided. With that, the only factors contributing to link imbalance are the following:

- interference asymmetry resulting from the different position and transmit powers of mobiles and BS's;
- the channel assignment algorithms—if the sensing of candidate channels is performed only at one end of the link (either mobile or BS), the resulting assignment will be based only on either uplink or downlink, potentially creating a temporary imbalance; this imbalance can only be avoided by a channel assignment process that is jointly performed by mobiles and BS's.

A proposed implementation of such a balanced algorithm is one where each BS maintains a database with the state of all idle channels, and every time a channel has to be assigned,

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[2] This rule holds for all DCA algorithms, but not for the reference FCA system. Since with FCA there are no reassignment mechanisms, a handoff attempt to the strongest BS is triggered instead if the CINR drops below $\gamma_{\min}$.

a shortlist containing the L best candidates—according to the uplink—is passed on to the mobile, which makes the final selection according to the downlink [3], [24]. Good results are obtained with $L = 6 - 8$ channels [3], with shorter lists tending to favor the uplink and longer ones favoring the downlink. Unfortunately, user motion tends to destroy the balance so painstakingly obtained restoring the (small) natural interference-asymmetry imbalance. Notice that in addition to potential imbalance, too short a list might result in assignment failure if the mobile is unable to find a suitable channel within the database. The longer the list, the higher the probability of a channel being found. Unless otherwise stated, we set $L = 8$, which provides good performance and balance with an acceptable delay.

III. PC

Since DCA algorithms operate on local-mean metrics, we choose to restrict ourselves to slow PC driven also by local-mean values to facilitate embedding PC within the channel assignment and management procedures. Hence, the power updates have to be much slower than the fading rate for the system to be able to obtain reliable local-mean metric estimates. In order to maximize capacity, such PC algorithms should balance the CINR on each channel, and thus they have to be quality based [6], [25]. Additionally, since interference is different for uplink and downlink, closed-loop control is necessary. Therefore, we concentrate on slow closed-loop quality-based PC with a maximum transmit power $P_{\max}$ for every station.

Centralized PC would require the existence of some central processor with continuous access to all mutual path gains, and it is thus impractical [6], [25]–[27]. For either uplink or downlink, a CINR level γ is achievable in a given channel if there exists a power solution $P_i \geq 0$ such that $\gamma_i \geq \gamma$ in every cochannel cell i. It can be proved [9] that—with the $P_{\max}$ constraint—there exists a unique maximum achievable CINR γ'. If γ' is insufficient, one or more users need(s) to be dropped or reassigned to another channel so that the remaining ones can achieve a higher CINR.

In distributed PC schemes, the transmission power for each station is based exclusively on local information and measurements. Since they operate on limited information, such algorithms may be suboptimal from a capacity standpoint, although they also have a much lower signaling load. In order to balance the CINR of every set of cochannel users around some target value γ_t, a very effective dynamic is the one proposed in [28], where the ith user tries to drive its CINR toward γ_t by an amount proportional to its offset from it[3]

$$P_i(n+1) = P_i(n)\,\frac{\gamma_t}{\gamma_i(n)}. \tag{1}$$

Notice how the power at time $n+1$ is directly proportional to the interference measured at time n and inversely proportional to the corresponding path gain. Accordingly, each user simply proceeds to reset its power level to what it needs to be to have acceptable performance when the other users are not changing their power levels. Even though those users are changing their levels, convergence occurs—for each user—every time a solution exists. Otherwise, the powers just keep constantly escalating until they reach $P_{\max}$, as all users try to attain a target which is not feasible.[4] The fact that one or several users increase(s) their powers beyond a certain level can be used as an indicator that the desired performance is not achievable for all users simultaneously. In that case, one or several users have to be cleared and the set rebalanced until γ_t can be achieved [33]. With the inclusion of the power constraint $P_i \leq P_{\max}$, the power update (1) becomes

$$P_i(n+1) = \min\left\{P_{\max},\, P_i(n)\,\frac{\gamma_t}{\gamma_i(n)}\right\}. \tag{2}$$

It can be proved [9] that this distributed algorithm converges to a fixed point $P_i^{(*)}$. The question now is: what is $P_i^{(*)}$? If $\gamma_t \leq \gamma'$, then there exists a feasible power vector that achieves γ_t in which case all links attain γ_t. However, if $\gamma_t > \gamma'$, then there is no power vector such that all links can attain γ_t. In that case, the algorithm tries to support as many links as possible with CINR equal to γ_t.

The distributed constrained PC algorithm starts with powers increasing at every iteration while each station adjusts its power trying to achieve γ_t, until the maximum power constraint comes into effect. For low γ_t values, this might not get to happen, and the target will be achieved for all links. On the other hand, for sufficiently large γ_t, all stations end up transmitting at $P_{\max}$, which is equivalent to operating with constant transmit powers. Therefore, the algorithm is never worse than a fixed-power scheme. In addition, $P_i^{(*)}$ has some interesting properties.

- If user i is transmitting at $P_i < P_{\max}$, then user i has the desired γ_t [34].
- If user i cannot be supported at γ_t, then it is necessarily transmitting at the maximum power level $P_i = P_{\max}$.

Also, it can be proved that the convergence properties hold even when the stations are allowed to have different rates of power updates and when these updates are asynchronous [9], [34].

With user motion, it is crucial that the PC update iterations be fast enough to achieve convergence faster than the rate at which the local-mean path gains change. Otherwise, the PC algorithm will be unable to track the optimal power values as they change along with the path gains. To ensure such convergence, it is desirable to update the power levels as often as possible. On the other hand, it is also desirable to minimize the PC signaling overhead by keeping the update rate as low as possible. In addition, a slower update rate facilitates the procurement of accurate local-mean estimates.

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[3] Throughout the derivations in [28], the path gains are assumed constant; that is, stationary conditions are implicitly assumed. The formulation remains valid as long as convergence is achieved within the coherence time of the local-mean path gains. This problem is addressed in [29]. We further assume continuous transmit power levels, although in practice power is updated at discrete levels. For a detailed study on the impact of such discretization on our PC algorithm, see [30].

[4] In this case, excessive transmit power increases by every station trying to rebalance its CINR result in too much additional interference to all other cochannel stations, which in turn increase their powers excessively and so forth. This is sometimes referred to as the "party effect" [31], [32].

With the PC iterative update of (2) and user speeds up to 60 Km/h at 1.9 GHz, convergence and tracking are satisfactorily achieved—in most outdoor scenarios—with iteration intervals on the order of 100–200 ms [29]. Since we are dealing only with pedestrians, the interval is set to 200 ms in our simulations.

IV. MODELS

A. System Model

All antennas are omnidirectional with two-branch selection diversity (all thresholds are prediversity). BS's do not transmit on idle channels. Good orthogonality between carriers is assumed, and thus, adjacent channel interference is not considered. No limitation in the number of radio transceivers per BS is considered either. The local-mean CINR is defined as

$$\gamma = \frac{C}{I + N} \tag{3}$$

with C the carrier power, N the inband thermal noise, and I the cochannel interference. Mobiles and BS's have equal receiver and transmitter performance with the ratio between $P_{\max}$ and noise floor, such that the average carrier-to-noise ratio at a cell corner—with no interference and the transmit power at $P_{\max}$—is 35 dB. Offered traffic has a uniform spatial distribution with Poisson arrival rates and exponentially distributed holding times with a mean of 100 s.

B. Propagation Model

The local-mean path gain between two stations (identical for uplink and downlink) is modeled [19], [35] as

$$G = K \frac{S}{d^{\alpha}} \tag{4}$$

where K is a calibrated constant for the particular environment, d is the separation distance, α is the propagation exponent, and S is a shadowing log-normal term with a standard deviation of σ dB. This shadowing term, in turn, is modeled as having two independent contributions: a position-dependent one and a link-dependent one [35]. The position-dependent shadowing term varies exclusively with the mobile's location and has a standard deviation of $\sigma_P = 6$ dB, while the link-dependent term depends on both the mobile's location and the serving BS, with a standard deviation of $\sigma_L = 8$ dB. With all these terms log-normal, $\sigma^2 = \sigma_P^2 + \sigma_L^2$ and thus $\sigma = 10$ dB. The spatial autocorrelation function for every shadowing term is a polynomial approximation to an exponential function [36] with a correlation distance $\chi_s = 50$ m.

C. Mobility Model

The mobility model is a random walk controlled by a "directionality" parameter δ which determines how often the mobile makes a turn. When a call is originated, the user speed is assigned, the directionality δ is selected with uniform probability in the range 0–0.5, and an initial direction is randomly chosen. Every 10 s, there is a turning opportunity, and thus the user changes direction or not with probability δ. When a turn occurs, the new direction is chosen from a triangular distribution centered on the old one. This way, small angle turns are more probable than large ones. The speed is maintained throughout the entire call. In order to simulate a microcellular environment with pedestrian traffic, speed is uniformly distributed within 0–5 Km/h.

TABLE I
SIMULATION PARAMETERS AND DATA

BS Separation	850 m
Traffic Channels	128
Propagation Exponent	α=4
Position-dependent Shadowing	σ_p=6 dB
Link-dependent Shadowing	σ_l=8 dB
Total Shadowing	σ=10 dB
Shadowing Correlation Distance	χ_s=50 m
Mean Call Duration	100 s
Antenna Diversity	2-Branch Selection
Maximum Transmit Power (P_{max}) and Noise Floor	Calibrated for Average CNR=35 dB at Cell Corner
CINR Drop-out Level	$\gamma < \gamma_{drop}$=9 dB for 5 consecutive seconds
CINR Minimum (Reassign) Level	γ_{min}=12 dB
CINR Admission Level	γ_{new}=18 dB
CINR Readmission Level	γ_{re}=16 dB
PC Target Level	γ_t=16 dB
PC Update Interval	200 ms
Directed Retry Attempts	3 BSs (total)
Shortlist Size	L=8
Hand-off Hysteresis Margin	4 dB
Confidence Interval	±0.2% at 3% with 99% Reliability
Speed	Uniform 0 5 Km/h

D. Computer Simulations

Simulations are performed on a toroidal universe [37] consisting of a 16 × 16 square grid of BS's with the parameters summarized in Table I. The universe is created prior to the simulations, and thus, the different algorithms are compared on exactly the same scenario. In any given simulation, data collection does not start until the system has been brought to steady state. The confidence interval for all blocking and dropping rates presented is approximately ±0.2% at 3% with 99% reliability.

V. INTEGRATED DCA AND PC

Both DCA and PC techniques can separately achieve large capacity gains with respect to conventional fixed-power FCA. In either case, the common principle is attaining the best possible CINR balance above, but as close as possible to $\gamma_{\min}$. Intuitively, the simultaneous use of DCA and PC has a lot of potential. Nonetheless, because both techniques attempt to balance the CINR, it is also intuitive that there may be a certain degree of redundancy between the two and that therefore their capacity gains might not be additive.

A. Admission Control

With fixed power, the admission control problem could only be strictly solved by centralized algorithms. These algorithms can be extended readily to systems with PC [22]. In addition, with PC-distributed probing schemes with active link protection have also been proposed [11], [38]–[40]. These schemes are based on two basic ideas.

1) Protection Margin: The first idea involves raising the CINR targer slightly above $\gamma_{\min}$ in order to provide a small protection margin to absorb the CINR fluctuations caused by new candidate users trying to gain admission.

2) Controlled Power-Up: The second idea involves forcing every new user to increase its power from zero in progressive steps. If a feasible solution exists for the channel under consideration, its CINR will eventually get to $\gamma_{\min}$, and the user will admitted. Otherwise, its CINR will level out below it, and the user will not be admitted.

However, to ensure that new users do not push admitted users temporarily below $\gamma_{\min}$, the power steps must be made very small, and thus, convergence to the new solution may be intolerably slow. Furthermore, if admission fails, a new candidate channel must be probed, and thus the delays accumulate. A procedure for quick channel probing was proposed in [41] and [42]. This procedure tries to predict—from a few initial iterations—whether the admission process will be successful or not. Unfortunately, this prediction is no longer valid as soon as the system condition experiences any change. With mobility, the system is constantly evolving, and since user motion is unpredictable, it cannot be accounted for. Therefore, quick probing is feasible only with stationary traffic or when user motion is slow. In addition, if the increase in interference caused by new users seeking admission drives an active user up to $P_{\max}$, that particular user will no longer be able to react to further interference increases and its CINR might drop below $\gamma_{\min}$ after all. This problem has no clear solution.[5]

In any case, with mobility, admission control becomes less critical while the ability to reassign users becomes essential. Therefore, we propose a threshold-based approach (Fig. 1) composed of a number of thresholds organized with respect to $\gamma_{\min}$ and inspired by the following ideas.

3) Protection Margin: We not only retain, but we—in fact—extend this margin to absorb both possible CINR fluctuations caused by new candidate users and also CINR fluctuations caused by active user motion. Therefore, the PC target level is $\gamma_t > \gamma_{\min}$, comfortably above the required minimum.[6]

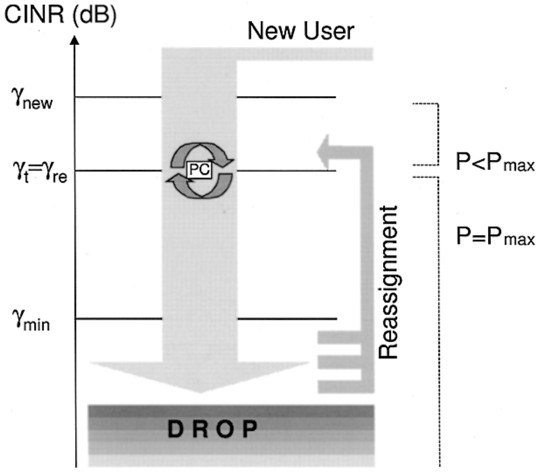

Fig. 1. Threshold-based approach to the admission control problem with PC.

4) Channel Selection: To eliminate the need for time-consuming channel probing procedures, we assign the channel where the user can achieve a given admission threshold with the least amount of combined uplink-downlink power (Section V-B). This is the channel where the new user is least likely to cause excessive interference to other—active—users. With this selection process, we are fully exploiting the channel selection flexibility available to us with DCA, and thus we are effectively integrating the channel assignment process with the admission procedures.

5) Implicit Admission Control: The admission threshold for new users is $\gamma_{\text{new}} > \gamma_t > \gamma_{\min}$ and new users are only admitted if they can achieve such threshold—in both uplink and downlink—with a transmit power $P_i \leq P_{\max}$. With this, new users have to compete with active users at a higher CINR with the same power budget, which implicitly functions as an admission control mechanism. If a set of active cochannel users cannot coexist with the addition of a new one, then it is clear that the transmit power of at least one user would hit the $P_{\max}$ mark in response to the excessive interference. Since the new user has a higher CINR requirement, it is most probably this particular user who will fall short on power and will therefore be denied admission. The higher γ_{new}, the larger the differential between the required CINR for new and active users—with the same power budget—and thus the less likely that an active user may be displaced while a new one is admitted. At the same time, a high admission threshold increases blocking and hence γ_{new} is a compromise value. When a user cannot achieve γ_{new} in the "best" channel, it cannot possibly achieve it in any other channel and thus the user is blocked by the serving BS. If a user is admitted, the PC loop begins to operate immediately. It first reduces power to drive the CINR from γ_{new} down to γ_t, and from then on, it tries to maintain the CINR on target.

6) Channel Reassignment: With implicit admission control, we minimize the probability that an active user may reach $P_{\max}$ in response to new users trying to gain admission. In most cases, the new user—and not an active one—will be the one requiring excessive power. Nonetheless, the threshold differential may occasionally not be enough to compensate

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[5] The solution suggested in [42] is to have a user in those circumstances transmit a distress signal which would abort all ongoing admission procedures.

[6] This margin can be scaled depending on the level of mobility in the system.

for users in unfavorable locations, and thus, a new user may be erroneously admitted causing an active user to power up to $P_{\max}$. In addition, the path gain changes caused by user motion can also cause an active user to reach $P_{\max}$. In both cases, the PC loop is no longer able to respond to further interference increases, and thus, the CINR may fall below γ_t and even approach $\gamma_{\min}$. This is an indication that the channel cannot—at least momentarily—support this set of users in their current positions. Hence, if the CINR of user i (either link) falls below $\gamma_{\min}$ with $P_i = P_{\max}$, a reassignment attempt—within the same cell—is triggered for user i. The readmission threshold on a different channel is γ_{re}, lower than γ_{new} to favor active users versus new users competing for the same channels. If the reassignment fails, the mobile stays on its current channel and new attempts are made—while the condition prevails—until the new user is either dropped or successfully reassigned.

This admission control approach is the result of an integration of DCA and PC which effectively assigns and manages the corresponding resources (spectrum and power). This approach recognizes the dynamic nature of mobile systems, and the impossibility of absolute link protection that results from it. The approach provides for a balance of blocking and dropping that can be controlled by proper threshold scaling. The thresholds chosen for our implementation were obtained by an iterative process and are summarized in Table I.

B. A Class of Integrated DCA and PC Algorithms

With DCA in place, all channels are potentially available, and usually, there may be several meeting the admission criterion ($\gamma_i \geq \gamma_{\text{new}}$ with $P_i \leq P_{\max}$). As indicated in Section V-A, it is desirable—for admission control reasons—to select always the channel where γ_{new} can be met with the lowest possible transmit power and thus with the smallest possible interference contribution to other users. This strategy, which we refer to as power-controlled least-interference algorithm (PC-LIA), attempts to keep the overall interference level as low as possible. It requires that every time an assignment or reassignment is triggered, BS and mobile work together to identify the channel where the least amount of combined uplink–downlink power is needed to meet the admission requirements.

The local-mean path gain between a candidate mobile and any BS can be estimated using the fixed-power CCH.[7] Since $P_{\max}$ is known, the BS can search its database—containing the local-mean interference level on every idle TCH—to identify the channels, if any, where the user could achieve the required uplink CINR with the $P_{\max}$ power budget. The BS compiles a shortlist containing the $L = 8$ least-interfered such channels along with the uplink interference level on each one and sends it over the CCH to the mobile. The mobile monitors the downlink interference on every shortlist channel and determines the ones where the required CINR could be achieved also on the downlink with the $P_{\max}$ power budget. From the pool of shortlist channels where the required CINR could be met for both uplink and downlink, the one with the smallest sum of uplink and downlink interference is selected. If no channel is found, the attempt is blocked by that particular BS.

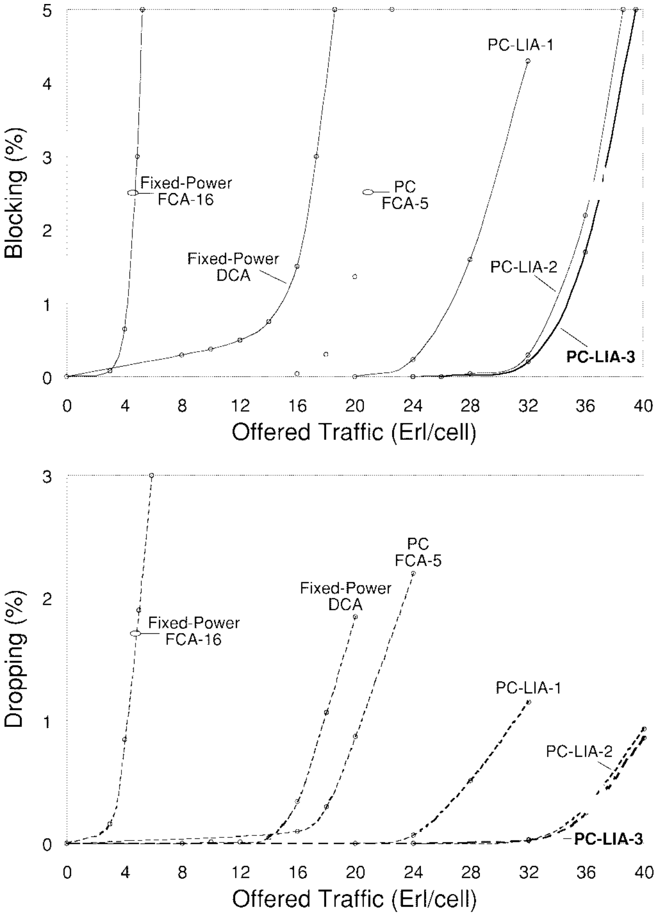

Fig. 2. Blocking and dropping performance of PC-LIA-1, PC-LIA-2, and PC-LIA-3 compared to fixed-power FCA-16, fixed-power DCA, and PC FCA-5.

Channel reassignments and handoffs are performed in a similar fashion, but with a lower admission threshold γ_{re}. In addition, there is no need to utilize the CCH since the path gain can be estimated on the active TCH insofar as the transmitted power is known to the receiving station. Blind-slot channels are unavailable for reassignment and handoff because their downlink interference cannot be monitored. This effect is included in all our simulations. Notice that, upon initial access, there are no blind slots.

1) PC-LIA-1: The basic algorithm within the PC-LIA family triggers a channel reassignment only when a user i becomes compromised ($\gamma_i \leq \gamma_{\min}$ at $P_i = P_{\max}$). The blocking and dropping responses for this PC-LIA-1 algorithm are shown in Fig. 2 compared to reference results for fixed-power FCA with a reuse factor of 1/16 (FCA-16), FCA with a reuse factor of 1/5 and PC (PC FCA-5), and a high-capacity fixed-power DCA algorithm based on adaptive reuse partitioning [18], [43], [44].[8] Reassignment rates are presented in Table II. With the addition of PC on top of the DCA, capacity almost

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[7] Even though instantaneous signal levels on channels more than one coherence bandwidth away are uncorrelated, local-mean values are equivalent within a wide frequency range.

[8] The FCA reuse factors were chosen to provide a reasonable ratio between blocking and dropping.

TABLE II
AVERAGE NUMBER OF PER—CALL CHANNEL REASSIGNMENTS FOR FIXED-POWER DCA, PC-LIA-1, PC-LIA-2, AND PC-LIA-3

Offered Traffic (Erl/cell)	Fixed-Power DCA	PC-LIA-1	PC-LIA-2	PC-LIA-3
20	0.83	0.07	0.17	0.31
24	0.77	0.29	0.61	1.22
28	0.77	0.47	1.28	2.91
32	0.72	0.51	2.98	5.87
36	0.69	0.52	3.29	7.81

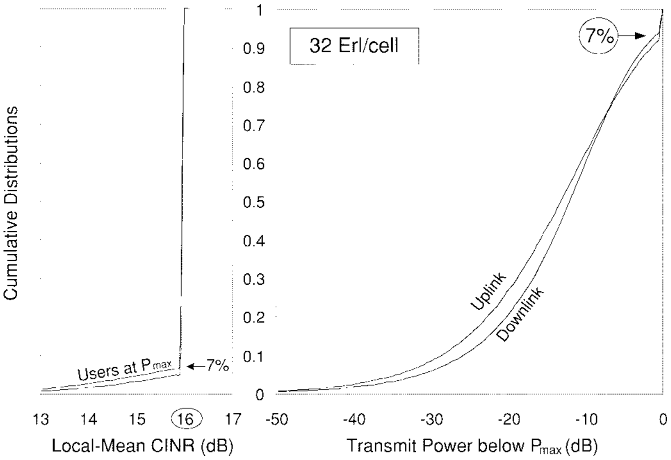

Fig. 3. CINR and transmit power cumulative distributions at 32 Erl/cell with PC-LIA-1.

doubles while the average number of reassignments per call actually decreases. In fact, the reassignment rate is very low, confirming that the admission control mechanisms operate very satisfactorily. With respect to fixed-power FCA-16, the capacity (at 3% blocking) of the PC-LIA-1 algorithm is 6.0 times higher.

Now, in order to further understand how the algorithm functions, we study its behavior with a fixed load of 32 Erl/cell. The CINR and transmit power cumulative distributions corresponding to that load are displayed in Fig. 3 for both uplink and downlink. On the CINR side, notice the precise balance around $\gamma_t = 16$ dB. On the power side, note that even in this relatively congested condition (4.3% blocking), our algorithm is able to power down the transmitters 50% of the time by about 12–13 dB and 20% of the time by about 20–22 dB, which means that—in addition to a large capacity gain—significant power savings may be realized. The congestion is corroborated by the approximately 7% of users with $\gamma_i \leq \gamma_t$ and $P_i = P_{\max}$. Clearly, some users were admitted to their current channel at a time when that channel had spare capacity and, later on, because of user motion or simply because of additional users being admitted, they found themselves in a position where their power was all the way up at $P_{\max}$, and their CINR was still below target. Because of the level of congestion, the system had increasing difficulty in finding alternative channels for those users being compromised.

2) PC-LIA-2: On understanding how the PC-LIA-1 algorithm is limited by those users that get stuck in a position where their PC loop is no longer operative ($P_i = P_{\max}$) and reassignments may not be immediately available, one cannot help but wonder whether it is possible to push capacity even further with some variation of this technique. Clearly, with user motion, the capacity of every channel becomes time variant. In other words, the number of users that can coexist together on a single channel depends on their relative positions and, as they move, those positions change.[9] In isolation, every channel must stay close to its worst-case capacity level[10] to prevent dropping. With increased coordination across different channels, however, they should be able to operate at a higher capacity level. Intuitively, implementing this idea requires constant rebalance of the traffic load across different channels to compensate for capacity variations on individual channels as users move. This balance can be achieved with preventive reassignments. Therefore, we introduce here the PC-LIA-2 algorithm which—in addition to triggering a reassignment attempt whenever a user gets compromised—triggers a reassignment also whenever there is an alternative channel where the user could power down by at least ΔP in both uplink and downlink and still maintain γ_t. In other words, every time there is a channel where the power required to attain γ_t is lower than the user's current power by at least ΔP in both links, the system tries to reassign the user to that channel. With that, the algorithm is constantly shifting the load toward those channels with spare capacity. Evidently, the algorithm's operation is strongly determined by the parameter ΔP. As $\Delta P \rightarrow \infty$, the PC-LIA-2 algorithm becomes PC-LIA-1. On the other hand, as $\Delta P \rightarrow 0$, increased load balance is achieved at the expense of continuous channel reassignments. In order to test the effectiveness of this load-balancing idea, we select a rather aggressive value $\Delta P = 6$ dB.

Next, we analyze the CINR and transmit power distributions of Fig. 3 again in Fig. 4 with the curves for PC-LIA-2 shown next to the previous ones for PC-LIA-1. On the CINR side, PC-LIA-2 achieves an almost ideal balance and reduces the number of users with $\gamma_i \leq \gamma_t$ to virtually zero. On the power side, the cumulatives for both links have shifted toward even lower transmit levels by roughly another 10 dB while the ratio of users transmitting at $P_{\max}$ has dropped from approximately 7% to basically zero. This additional power reduction means that the overall interference level is lower with PC-LIA-2 than with PC-LIA-1 for any given distribution of users. This reduction is due to improved channel allocation at all times, especially with conditions constantly evolving due to motion. Altogether, PC-LIA-2 has turned a congested scenario, at 32 Erl/cell, into a noncongested one. Accordingly, another capacity leap with respect to PC-LIA-1 is expected. And, as seen in Fig. 2, that is indeed the case. The 3%-blocking capacity of PC-LIA-2 is now 7.4 times higher with respect to

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[9] This is another interpretation of the importance of having reassignment mechanisms in place so as to be able to compensate for capacity fluctuations. With stationary traffic, on the other hand, channel capacity is fixed, and thus, strict admission control may suffice.

[10] By worst-case capacity level, we mean the worst possible spatial distribution of users.

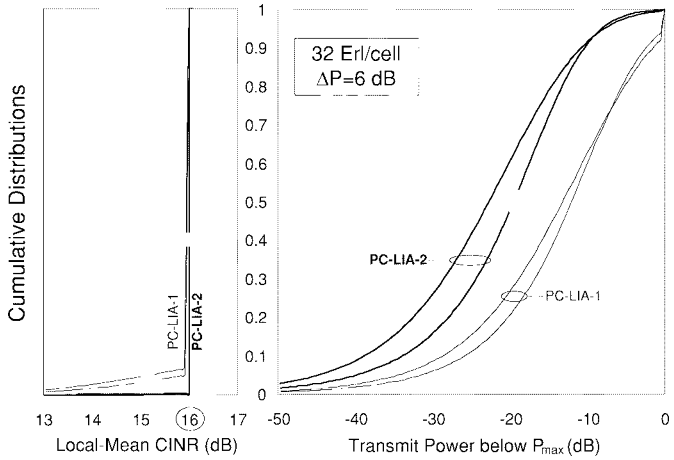

Fig. 4. CINR and transmit power cumulative distributions for PC-LIA-1 and PC-LIA-2 at 32 Erl/cell.

a fixed-power FCA-16 system. This further capacity increase, however, does not come at no cost, for it requires multiple preventive reassignments per call (Table II). By adjusting ΔP, the reassignment rate can be relaxed, and blocking and dropping responses anywhere between the limit cases shown in Fig. 2 for PC-LIA-1 ($\Delta P \rightarrow \infty$) and PC-LIA-2 ($\Delta P = 6$ dB) can be obtained.

The practical implementation of the PC-LIA-2 algorithm is in fact quite simple, although it may consume a significant amount of control bandwidth because of the associated signaling requirements. The BS periodically compares the received signal level on the active TCH with the uplink interference level on every idle TCH in its database and, if the ratio for one of those is higher than the current CINR by at least ΔP, the mobile is notified.[11] In turn, the mobile monitors the candidate channel and compares its downlink interference level against the corresponding received signal level. If the ratio exceeds the current downlink CINR by at least ΔP, the reassignment is completed.

C. PC-LIA-3

Given the success of the load-balancing concept, we attempted to push it to the limit by applying it across BS's in addition to across channels. To that purpose, the conventional CCH-based handoff scheme that has been used thus far is replaced by a TCH-based more aggressive one. In the PC-LIA-3 algorithm, a handoff attempt is triggered every time that a neighboring BS contains a channel where the user could maintain the target CINR while powering down by at least ΔP_H in both uplink and downlink, with ΔP_H a new hysteresis parameter set—for the sake of consistency—to $\Delta P_H = \Delta P = 6$ dB. Preventive reassignments are also performed as in PC-LIA-2. Compared to all previous algorithms, the PC-LIA-3 algorithm can achieve some degree of cell expansion and contraction whereby congested cells shrink their boundaries and allow the neighboring cells to expand and absorb some of their geographical traffic. With that, cells can constantly adjust their boundaries following spatial traffic fluctuations that occur even when the average load is uniform. This feature resembles the so-called code division multiple access (CDMA) "cell breathing" and establishes an interesting link between dynamically controlled TDMA systems and CDMA. Unfortunately, the PC-LIA-3 algorithm would require periodic negotiations involving every active mobile and two different BS's and hence it is not a very practical scheme, although it is theoretically feasible.

TABLE III
AVERAGE NUMBER OF PER—CALL HANDOFF COMPLETIONS FOR PC-LIA-1, PC-LIA-2, AND PC-LIA-3

Offered Traffic (Erl/cell)	PC-LIA-1	PC-LIA-2	PC-LIA-3
24	0.36	0.36	1.07
28	0.35	0.36	2.54
32	0.33	0.36	5.36
36	0.32	0.35	7.58

The blocking and dropping performance of the algorithm is depicted in Fig. 2. Even though the capacity gain over PC-LIA-2 is small (only about 1 Erlang at 3% blocking), the cost in terms of channel reassignment and handoff requirements is enormous, as indicated in Tables II and III. This is a clear case of diminishing returns, which seems to indicate the proximity of some fundamental limit. Nonetheless, capacity at 3% blocking is up to 7.6 times that of a fixed-power FCA-16 system. Altogether, the PC-LIA-3 algorithm is able to serve about 38 Erlangs at 3% blocking with only 128 channels and omnidirectional antennas, which corresponds to a reuse factor slightly below 1/3. Hence, with such a tight reuse, the proximity of a fundamental limit should be no surprise.

Notice also how in Fig. 2 the blocking and dropping responses of the different algorithms show an increasingly gradual slope. Whereas, in FCA systems, capacity is hard limited by the reduced number of channels allocated to every cell, with DCA, capacity is soft-limited by interference well beyond channel constraints come into play. Evidently, this effect is emplasized with the addition of PC, and thus our integrated algorithms display rather "soft" capacity curves with gentle degradation, especially in terms of dropping, confirming one more time the effectiveness of the admission control and reassignment mechanisms in place.

VI. CONCLUSIONS

Conventional FDMA/TDMA mobile wireless communication systems based on FCA and with fixed or quasi-fixed power settings are conservatively designed and do not make effective use of the available bandwidth.[12] This paper has concentrated on the integration of fully distributed DCA and PC. One of the major challenges imposed by a distributed implementation relates to admission control. We have proposed a very effective threshold-based admission control and channel

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[11] Notice that, in most cases, the current CINR is simply γ_t, and thus, the signal level on the active TCH and the interference level on every candidate TCH constitute sufficient information to trigger a preventive reassignment.

[12] Some of these systems evolved from first-generation analog FDMA cellular networks and were constrained by backward compatibility requirements.

management approach embedding PC. A family of integrated algorithms based on this approach has also been presented. These algorithms achieve per-channel per-BS capacities 6–7.6 times higher than a conventional system in pedestrian mobility environments.

It appears that the separate capacity gains of DCA and PC are not additive because of some redundancy between the two. Nonetheless, the potential of their combined use has been demonstrated. Most of this potential can be effectively realized in spite of blind-slot constraints and with imperfect signal and interference estimates [45]. Our integrated algorithms are also very robust at higher degrees of mobility although the "cost" of capacity—in terms of reassignment and handoff rates—does increase with motion.

With an aggressive combination of DCA and PC, TDMA systems can achieve a "soft" capacity similar to that claimed by CDMA. This capacity is upperbounded at every cell only by the total number of channels in the system, in the same way that the capacity of a CDMA system is upperbounded by the number of orthogonal codes. With frequency hopping, which can be considered a form of CDMA, every channel is visited by every user in a random sequence. With deep enough interleaving and powerful codes, performance is determined by some effective CINR—which depends on the system load—rather than by the specific CINR of every individual channel. An "average" performance is achieved for all users. With DCA taken to the limit, every user is also reassigned almost constantly to a new channel, but the sequence of channels visited is not random. Instead, the system tries to keep the user always on the "best" channel. Accordingly, one could speculate that DCA should outperform frequency hopping, at least under ideal[13] conditions. The cost, however, is also higher: with DCA, every reassignment has to be negotiated on the spot because it cannot be anticipated. Furthermore, there is some probability than any reassignment attempt may fail. With frequency hopping, in contrast, every hop is scheduled in advance. Therefore, the question of whether DCA outperforms frequency hopping—everything else being equal—comes down to whether a practical DCA algorithm with a limited number of reassignments per call can achieve a performance close enough to the limit represented by an idealized algorithm executing constant reassignments. Our results indicate that a TDMA system can get close to that capacity limit with a few reassignments per call and that rapidly diminishing returns are obtained with additional reassignments. These results also confirm previous ones indicating that interference-avoidance techniques, such as those provided by DCA, can perform better than interference-averaging techniques [46].

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[13] By ideal conditions, we mean those with no complexity or signaling limitations.

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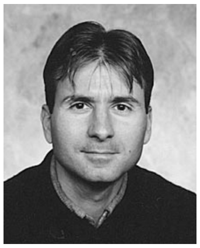

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