Measurement-based Band Allocation in Multiband CDMA

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Abstract—**Multiband (or multi-carrier) CDMA is a promising approach to increasing the capacity of CDMA networks, while maintaining compatibility with existing systems. This paper investigates a family of algorithms for allocating new calls to bands based on measured path gains, or alternatively, on estimates of the users' positions. By separating strong and weak users into separate bands, this approach reduces the other-cell interference on the uplink. This is shown to reduce the number of calls in soft handoff, which reduces the hardware requirements at the base stations. Under a range of conditions, it also provides significantly lower outage than alternative algorithms. An additional benefit of this approach is a reduction in the dynamic range required for uplink power control.**

Keywords— **Multiband CDMA, hybrid FDMA/CDMA, resource allocation, cell tiers, non-uniform power allocation.**

I. INTRODUCTION

CODE division multiple access (CDMA) allows multiple users to transmit in the same spectrum at the same time without precise synchronisation requirements. Users interfere with each other, but as long as the total transmission bandwidth is much larger than the signal bandwidth of an individual user, users' signals may still be recovered. However, in some CDMA systems, only certain subsets of users interfere with one another. For example, hybrid frequency division multiple access (FDMA)/CDMA systems [1–4] do not spread users' data across the entire available spectrum, giving several frequency channels, or bands. Users in a given band interfere with each other, but not with users in other bands. In time division duplex (TDD) CDMA systems [5], several time slots are allocated to uplink transmissions and several timeslots are allocated for the down link. Users in different timeslots again cannot interfere with one another, again giving a "multiband" CDMA system.

This paper investigates the uplink performance of a multiband system consisting of N bands of equal bandwidth. The bands will be assumed to be completely independent, but statistically identical.

One of the keys to getting good performance from a multiband system is the selection of which calls, and how many calls, use which band. As there is an overhead in reallocating the band of an existing call, this paper will consider only the case that a call must remain in the same band for its entire duration. This provides a lower bound on the achievable performance.

This case has already been addressed in [1], where it was suggested that new calls be allocated to the band with the fewest current connections. This was found to provide a significant improvement in the outage performance. Other approaches are suggested in [6]. One is to use separate bands for macro- and micro-cells, which yields lower capacity than random allocation. The other is to co-ordinate the allocation to macro- and micro-cells from a common set of bands, which yields higher capacity than random allocation.

An algorithm integrating band allocation with iterative power control is proposed in [7] for the case when bands may be reallocated freely.

This paper investigates an alternative approach to the task of band selection, Measurement Based Allocation (MBA), based on path gain measurements. MBA attempts to group calls with a high path gain together in one band, and to group calls with a low path gain in another band. Most other-cell interference is caused by users with a low path gain to their own base station, and hence a high transmit power. It is thus desirable for users with a low path gain, which are unable to tolerate excessive interference, to use a different band from that used by the users with a low path gain in the neighboring cells. The users with a high path gain can then be received at a higher power to overcome the greater interference they experience. Fluctuations in path gain due to mobility and shadowing cause the segregation of strong and weak users to be imperfect. However, the results presented in this paper demonstrate that even partial segregation improves performance.

This approach is not limited to multiband CDMA systems, but can be applied to any system with inter-cell interference and mutually non-interferring bands within a cell. For example, a band may correspond to one or more timeslots in a time division multiple access (TDMA) system with frequency reuse.

After a brief description of multiband CDMA in Section II, Section III describes the principles behind MBA band allocation. Section IV then specifies the simulation environment in which the numerical results of the following sections were obtained. Section V considers the case of a wireless local loop (WLL) application in which users remain stationary throughout a call. Numerical results are presented in Section VI under the assumption that a call may not change its band but that the propagation environment changes due to user mobility. The issue of partial soft handoff is addressed in Section VII, where it is shown that MBA reduces the number of calls in soft handoff at a given time, thereby reducing the cost of base station hardware.

II. MULTIBAND CDMA

There are several ways to use the increased spectrum required for next generation CDMA systems. The most obvious approach is wideband CDMA (WCDMA), which simply increases the spreading factor. However there are many other alternatives.

The approach studied in this paper is hybrid FDMA/CDMA [1–4], also called *multiband CDMA*. Like FDMA, multiband CDMA divides the available spectrum into distinct bands, and allocates each connection to a single band. However, several connections are spread over each band, so that each band is a miniature CDMA system. This hybrid retains many of the advantages of CDMA over FDMA, such as frequency reuse of 1. Moreover, the guard bands separating the data bands can be much smaller than for pure FDMA. Another fundamental advantage of multiband CDMA over wideband CDMA is the ability to accommodate a non-contiguous spectrum allocation. (Note that multiband CDMA is sometimes called multicarrier CDMA. That term is not used here to avoid confusion with OFDM/CDMA [8,9], which is also called multicarrier CDMA.)

In the cdma2000 third generation standard, 5 MHz bands may be divided into three bands of 1.25 MHz for compatibility with IS-95A [10]. This instrinsically leads to a multiband structure. However, the capacity of a cell can always be increased by allocating two or more bands, even if it is not explicitly required by the standard.

There are complexity tradeoffs in multiband CDMA and wideband CDMA. For example, a wider bandwidth requires more accurate synchronisation, whereas having multiple bands may complicate functions such as cell search, for which WCDMA algorithms exist [11]. These are beyond the scope of this paper.

It is generally accepted that WCDMA has a slight capacity benefit over multiband CDMA. This is due to increased multiplexing gain [1] and increased multipath resistance [2–4], albeit at the expense of increased rake receiver complexity [4]. The challenge is thus to maximize the capacity of a multiband system, while maintaining its advantages of backwards compatibility and hardware simplicity.

III. MEASUREMENT BASED BAND ALLOCATION

In measurement-based band allocation (MBA) [12–15], the area of each cell is partitioned into “tiers”, according to the path gain from the base station to each point. If shadowing is neglected, these form concentric rings around each base station; two possible arrangements are shown in Figure 1. Allocating a single band to each ring was proposed independently in [12] and [14]. Both of these investigated the performance without soft handoff, and with only static users. Kim and Prabhu [15] proposed a system, called here “two-tier MBA”, in which cells in a three-band system are partitioned into two geometric tiers. Two bands were used in the inner tier, and the remaining one was used in the outer band, as shown in Figure 2. The three choices of band for the outer tier give rise to three “types” of cells. It was suggested that this frequency reuse may be particularly beneficial when the load on cells is non-uniform. The results of that work are not directly comparable with this paper, as we consider the uplink rather than the down link. More importantly, [15] neglects shadowing and both [14] and [15] ignore the problem of limited multiplexing gain, which results in random numbers of users in each tier. Both of these degrade performance significantly. This paper will study the effectiveness of the “two tier” approach on the uplink, under more realistic conditions, and compare it with “pure MBA”.

“Pure MBA” [12], [14] is similar to “two tier” MBA. In this scheme, each tier was allocated its own band, in concentric rings around the base station. It was shown in [12] that very significant performance gains can be made for one-dimensional arrays of cells, such as those studied in [16].

The scheme of [12] was analysed in [13] under the assumption of many calls per cell, which implies that users are uniformly spread throughout the system. It was shown that all users receive equal signal-to-interference ratio (SIR), α, when

$$\left(\frac{G}{\alpha k_T}\right) P = [A(I+F)]P, \tag{1}$$

where $k_T = \sum_i k_i$ is the total number of users per cell, $P = (p_0, \ldots, p_{N-1})^T$ is the vector of received powers and G is the spreading factor. Matrix $F = (f_{i,j})$ is the (non-negative) matrix of other-cell interference, which depends on the geometric arrangement of cells, and also the assignment of bands to rings within each cell, and $A = \mathrm{diag}(a_0, \ldots a_{N-1})$ where a_i is the proportion of the cell area covered by ring i. Thus for all users to have equal SIR, P must be an eigenvector of the matrix $A(I+F)$, and for rings of equal size, it is also an eigenvector of F. The present paper considers the case when the number of users is low; this causes the approximation of users being uniformly spread across space to break down, and these results do not apply.

A. Power control

The near-far problem in CDMA systems describes the phenomenon where a user located near the base station has a strong received signal, and can entirely mask the signal of a user located further from the base station. This is usually overcome by using power control to ensure that all users in a given cell are received at the same power level, irrespective of their path gains [17–19]. However there are several drawbacks to this approach. Firstly, users who have a low path gain are typically near the boundary of a cell, and thus their high transmit power causes excessive other-cell interference. Also, power control often requires the mobile transmitter to have a very large dynamic range, up to 80 dB [20], to counter the wide variety of fading conditions. As an additional consideration, users with low path gains will suffer reduced battery life and the other adverse affects of excessive transmit power.

Multiband CDMA with MBA provides the opportunity to address the near-far problem more directly while improving the adverse aspects of power control. Allocating “near” users with high path gain to a separate band from “far” users with lower path gain reduces “power competition”, rendering a lower received power acceptable from “far” users. This translates to a lower transmit power, which reduces other-cell interference and saves battery power. Also, the dynamic range of the transmitter could be reduced when the maximum transmission power needed is lower.

B. Coordination of band allocations

In this paper, a group of users within a cell allocated to the same band will be called a “ring”, since the distance-dependent component of path gain causes them to lie approximately in concentric rings around the base station. The rings containing users with high path gains will be referred to as the “inner” rings while those with lower path gains are referred to as “outer” rings.

We now consider how frequency bands should be assigned to different rings for a network of cells. As an example, in a two band system, if band 0 is always assigned to the inner ring and band 1 to the outer ring for all cells in the system, the multiple bands are not exploited to reduce other-cell interference throughout the network. Instead, the inner and outer rings should be assigned different frequency bands for different cells such that users in the outer ring interfere with inner ring users in adjacent cells. In a two band system, this can be achieved by introducing two types of cells: type 0 with band 0 as the inner ring and type 1 with band 1 as the inner ring. These types of cells can then be arranged to minimize other-cell interference.

The arrangement of types of cells has similarities with the frequency planning problem [21], [22]. The chosen arrangement for a two band system is shown in Fig. 1(a), where the fewest possible neighboring cells of the same type is two. A symmetric arrangement is possible for three bands, as shown in Fig. 1(b). It is not clear that the symmetric arrangement is optimal, although it is intuitively appealing and gives good performance, as shown in [12]. Also, it has been shown in [23] that this spatial subdivision of cells is optimal for capture driven packet access (CDPA) systems with multiple carriers, which share similarities with MBA. (In CDPA, users transmit at random powers in the hope that one user will be sufficiently much stronger than the others to allow successful decoding.) Figure 1 assumes distance-dependent path gain without shadowing, which allows the ring boundaries to be drawn as lines. In a real system with shadowing, boundaries would not be so clearly defined in space.

C. Band selection

Neglecting the short timescale effects of Rayleigh fading, which can be partially compensated by rake receivers [24], the path gain of a user can be represented as

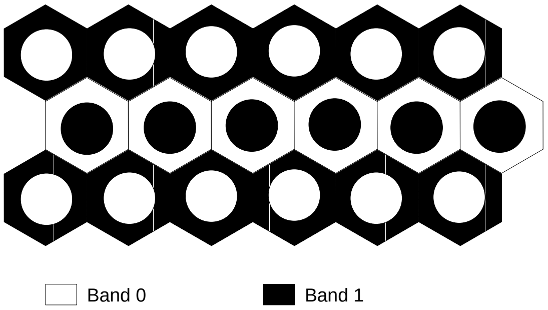
$$y = r^{-m}10^{\zeta/10}x,$$

where y is the received power, x is the transmitted power, r is the distance from the user to the base station, $m \approx 4$ describes the geometric component of the path gain, and $10^{\zeta/10}$ is a log-normally distributed shadowing term,

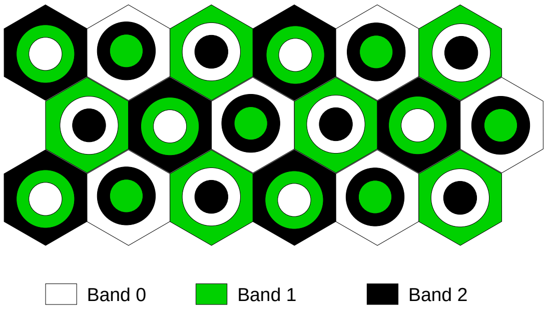
$$\zeta \sim \mathcal{N}(0, \sigma^2). \tag{2}$$

In the absence of log-normal shadowing, grouping users by average path gain is equivalent to grouping them in order of distance from the base station. (Note that the required distance information will be available in many systems since the US government has ruled that mobile phones must be able to determine their location to within 125m 67% of the time to assist with e-911 emergency calls [25,26].) However, with shadowing, the two approaches are not equivalent, and MBA bases allocation on path gains.

In this paper, the following five distinct band allocations will be compared.



(a) two bands



(b) three bands

Fig. 1. Symmetric arrangement with two and three bands in two dimensions

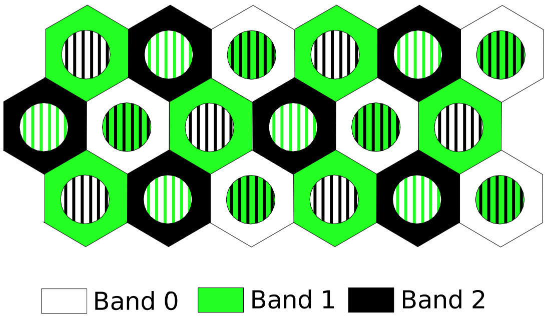


Fig. 2. Two-tier MBA with three bands.

Random. In the benchmark scheme, the band allocated to an arriving call is chosen uniformly and independently of all other choices.

Least load (LL). Under “least load” allocation [1], no physical measurements are required, and the new call is allocated to the band with fewest current users. Ties are broken randomly. This minimizes the variance of the number of users in each band, thereby minimising the probability of the tail events which cause outage. This counters the loss in multiplexing gain incurred by using multiple bands.

Pure MBA. An n-band pure MBA system uses n tiers, with each tier allocated to one band. For two- and three-band systems, the tiers are arranged as in Figure 1. For four-band systems, there are four types of cells, with the bands cyclically permuted among the tiers. If cells are sectorized, the optimal arrangement of bands will depend on the interference between adjacent sectors of each cell. If this interference is sufficiently small, the same band allocation can be used in each sector. Otherwise, further optimisation would be necessary. The numerical results in the paper are for single-sector cells.

If the bands are offered equal load, pure MBA results in very large differences between bands, in terms of receive power and outage. A key finding of this paper is that, although MBA does not adapt the thresholds between bands to the current occupancy, an overall reduction in outage can be achieved by setting the tier boundaries to allocate more users to the bands with either lower receive power or lower outage. Aside from the analysis of high-capacity systems in [13], the optimal loading of tiers has not yet been studied in detail. In this paper, loads are selected heuristically, as follows.

The heuristic specifies the "middle" of the cell. For two-band systems, the "middle" is simply the threshold between the two tiers. For four-band systems, it is the threshold between the second and third tiers; tiers one and two are allocated equal load, as are tiers three and four. Three-band systems are more complicated; the inner tier covers two thirds of the calls closer than the "middle" of the cell, the outer tier covers two thirds of calls with lower gain than the "middle", and the central band covers the remainder. In this paper, the "middle" will not be expressed as an actual path gain, but instead as θ, the fraction of the cell in which users' path gains would be above the threshold, in the absence of shadowing; thus $\theta = 50\%$ represents equal loading, and values less than 50% correspond to overloading outer bands.

In general, it was found that optimal performance in the presence of shadowing occurs when the outer bands (with lower SIR requirements) are offered more traffic. This is probably due to the blurring of cell boundaries caused by soft-handoff. With no shadowing, the reverse is true, and it is marginally better to move some traffic to the inner bands, thereby increasing the protection offered to the outer bands. The capacity of systems with three or more bands is increasingly sensitive to large deviations from the optimal threshold; however the optimal threshold becomes less sensitive to other system parameters (spreading and shadowing). In contrast, the optimal threshold for two-band systems varied systematically with both spreading and shadowing.

For two bands, it was necessary to adjust the threshold, θ, to depend on both the variance of the log-normal shadowing, σ in (2), and the spreading gain, G. Typical values for these parameters are $0 \leq \sigma \leq 12\,\mathrm{dB}$ and $128 \leq G \leq 3200$ [27], and so it was decided to numerically optimize an ad hoc parametric form of θ for this range of conditions. The log-normal nature of other users' interference suggests an exponential-quadratic form, $\theta \propto \exp(A\sigma^2 + B\sigma + C)$ when G is large. The optimal threshold decreases to a plateau as G increases, which suggests setting $\theta \propto (1 + D\sigma)^{E/G}$. Numerically optimising $A,\ldots,E$ yielded a suitable threshold

$$\theta_{2,\sigma} = \exp(-0.00015\sigma^2 - 0.018\sigma - 0.63)(1 + 0.04\sigma)^{-64/G}. \tag{3}$$

There is no theoretical justification for this formulation, and better performance may be obtained with optimized thresholds. However, MBA using this threshold outperforms systems not using MBA.

For three and four bands, the degree of spreading was less important. This paper used $\theta_{3,0} = \theta_{4,0} = 0.5$ when there is no shadowing, and $\theta_{3,8} = 0.4$ and $\theta_{4,8} = 0.44$ for three and four bands with 8 dB shadowing.

Two-tier MBA. For three-band systems, the two-tier scheme is as described in [15] and illustrated in Figure 2. Each cell has two tiers, with the load offered to the outer tier being half that offered to the inner tier. There are three types of cell. In cells of type i, calls in the outer tier are allocated to band i, while calls in the inner tier are randomly allocated to one of the two remaining bands.

There are several ways to generalize the two-tier MBA scheme to four bands. Three of these are investigated here. In "two-tier 1", the outer tier is allocated one third of the load of the inner tier, and all calls in the outer tier of a cell of type $i = 1, 2, 3, 4$ are allocated to band i, while calls in the inner tier are randomly allocated to the other three bands. In "two-tier 2", the two tiers are equally loaded, and calls in the outer tier are allocated to bands i and $i + 1 (\mathrm{mod}\ 4)$. "Two-tier 3" is really a three-tier arrangement; the loads of the tiers have ratio 1:2:1, and the middle tier is allocated two bands, while the others have one each.

Two-band two-tier MBA reduces to pure MBA.

Hybrid MBA. Hybrid MBA is a variant of two-tier MBA, in which the random choices of bands are replaced with least load allocation. The allocation of bands to tiers is the same in "Hybrid 1, 2 and 3" as in "two-tier 1, 2 and 3"; the only difference is how calls are allocated in tiers containing multiple bands. Hybrid MBA aims to achieve the multiplexing gain of least load for the majority of calls, while providing MBA's protection against interference for the vulnerable outer-most calls.

IV. SETTING

The channel assignment algorithms described in Section III were simulated with discrete calls for the case of two, three and four bands. Mobiles were placed on a 6×6 regular hexagonal toroidal grid of base stations. Call attempts were made according to a Poisson process in time and space, with a uniform distribution of users over the grid. Call times had a negative exponential distribution, and calls were never dropped or blocked.

Shadowing, when present, was modeled as log-normal with a standard deviation of $\sigma = 8\,\mathrm{dB}$. The standard assumption was made [27], that half (4 dB) of the shadowing was due to clutter local to the user, which affects the path gain to all base stations. Shadowing was varied throughout each call. In Section V, the variation was such that the correlation between the shadowing at the start and end of an call of average duration was 0.5. In Section VI, the variation was proportional to the speed of the user, such that a call of average duration from a user traveling at speed 1 had a correlation of 0.5 between initial and final shadowing. Fast (Rayleigh) fading was averaged over. Power control was assumed to be ideal in that there was no tracking error in the control loop. Before outage was calculated, the transmit power of each user was calculated to try to achieve a target SIR of 6.5dB. The maximum transmit power was 58 dB higher than the effective thermal noise level, and a call was declared to be in outage if it was transmitting on full power and had less than 6dB SIR. Factors such as Doppler spread were not considered in defining outage, since the band allocation scheme does not alter

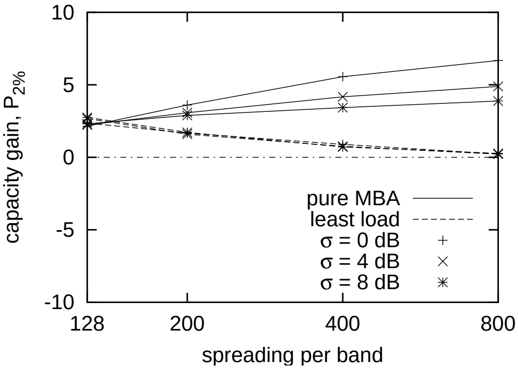


Fig. 3. Increase in capacity of a two-band system at 2% outage relative to random assignment as a function of spreading.

the robustness of the modulation scheme, and SIR is the measure of signal quality most affected. The combined power and cell-site selection algorithm of [19] was used, with best-of-three decoding. Since only the uplink was considered, there was no interference from a pilot signal.

Band allocation was based on the user's path gain, which was assumed to be known exactly, rather than the position. Voice activity was 100%, and antenna sectorisation was 1.

The performance measure used was, $P_{2\%}$, the capacity gain at 2% outage, relative to random band allocation. For each allocation scheme, the load was dynamically adjusted to $\lambda_{2\%}$, the level which gives an outage of 2%. The load which yields 2% outage with random band allocation is denoted $\lambda_{2\%,rnd}$. The capacity gain is then

$$P_{2\%} = \left(\frac{\lambda_{2\%}}{\lambda_{2\%,rnd}} - 1 \right) \times 100\%. \tag{4}$$

V. STATIC USERS

There is considerable interest in the wireless local loop [28], which replaces the copper access network by a cellular radiotelephone system with users fixed in space. Such systems are ideally suited to MBA, since users' signal strengths remain approximately constant throughout a call. This section investigates the capacity gain from using MBA in this context.

A. Gain vs. spreading

Soft handoff is modeled by decoding each user by that base station, out of the three nearest, which requires the least transmit power to achieve its target SIR [19]. This base station also power controls the user. (Similar results are obtained by selecting to maximize the path gain [27] instead of to minimize the transmit power.) Figure 3 shows the performance of MBA and least load allocation for spreading gains of 128 to 800, with log-normal shadowing with variance $\sigma = 0, 4, 8$ dB, and with band selection threshold given by (3).

Neither LL nor MBA provides as much benefit in this case as for hard handoff, which was studied in [12]. MBA is particularly affected, because its main effect is to reduce the other-cell interference, which is already reduced by soft handoff. MBA performs best for low shadowing, σ. Shadowing can cause a user to have a high path gain to multiple base stations. When that happens, the user will be connected to an "unprotected" (inner) band of its home base station. However, this band will be a "protected" (outer) band of a neighboring base station, and the user will still cause considerable interference.

Least load allocation and MBA also show opposite trends as the spreading increases. Least load improves performance by reducing the variance of the interference in each band; as spreading increases, the variance automatically decreases, and so the benefit of LL decreases. Conversely, the benefit of MBA increases.

Results for a three-band system are shown in Figure 4. Note that two-tier MBA is consistently less effective than pure MBA. The hybrid least-load/measurment-based approach ("hybrid MBA"), using load balancing on the inner bands, increases capacity for low spreading, since it provides greater multiplexing gain than pure MBA, while still protecting weak users from strong ones.

When four bands are available, the number of ways of allocating bands increases. In particular, hybrid MBA can be of type 1, 2 or 3, each of which must be evaluated. Figure 5 shows the performance improvement for a four-band system. Two-tier MBA is again outperformed by hybrid MBA, and has been omitted for clarity. These results show that hybrid-2 MBA is the optimal strategy for realistic spreading factors. This is because both tiers benefit from load balancing, while retaining MBA's ability to segregate users of different path gain.

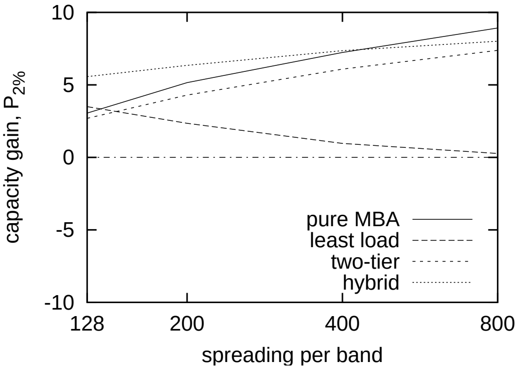
The results of Figure 5(b) rely heavily on the appropriate choice of the load balancing parameter, θ. The variation of $P_{2\%}$ with θ is shown in Figure 6 for four and two bands, for spreading of 128 and 400 and $\sigma = 8$ dB. This shows that the impact of θ is greater when there are more bands. Indeed, if $\theta = 50\%$ had been used in Figure 5(b), the pure MBA would actually have performed worse than random assignment for low spreading. However, the common trend is that, in these shadowing conditions, the optimal value of θ is slightly less than 1/2. This results in more users being placed in the outer bands than the inner bands.

The results of this section show that the benefit of least load over random channel assignment decreases as the multiplexing gain increases, while the effectiveness of MBA increases significantly under those circumstances. For a substantial range of spreading values, both pure MBA and LL are outperformed by the hybrid approach of protecting the outermost users while equalising the load on the bands used by the remaining users.

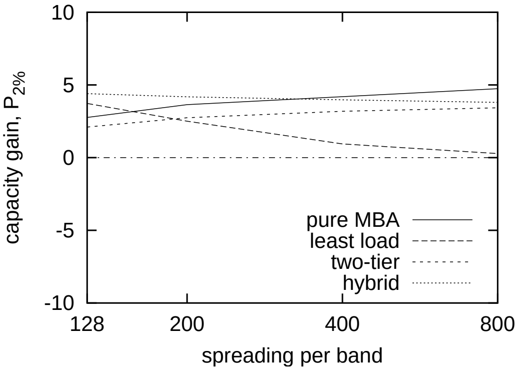
Note that it is the mean number of users in each band, not the spreading, which determines the quality of the "uniform users" approximation of [14], [15]. If the spreading were halved and the required SIR per user were halved, the results would be unchanged. Having a mixture of high-rate and low-rate users, with different SIR requirements, will yield results between those of the systems containing only high- or only low-rate users.

B. Gain vs. quality of service

Experiments were conducted to determine the change in capacity gain as the permitted level of outage was varied between 0.5% and 10%. There was a small but clear dependence on the outage level. The ranking of each scheme was unchanged, but the spread in the gains increased slightly as the level of outage

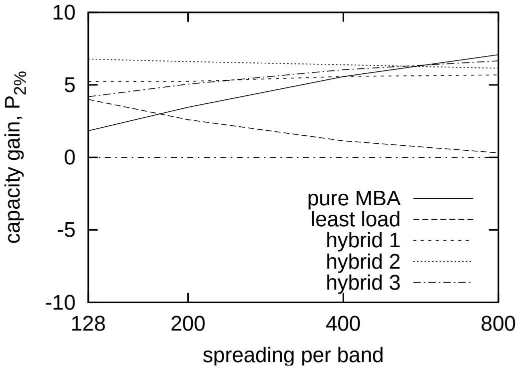


(a) No shadowing

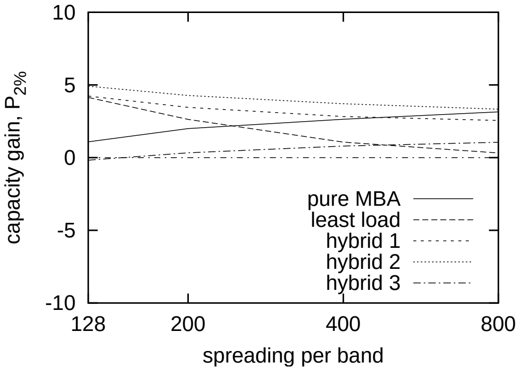


(b) $\sigma = 8\,\mathrm{dB}$

Fig. 4. Increase in capacity of a three-band system at 2% outage relative to random assignment as a function of spreading.



(a) No shadowing



(b) $\sigma = 8\,\mathrm{dB}$

Fig. 5. Increase in capacity of a four-band system at 2% outage relative to random assignment as a function of spreading.

increased.

As the permitted outage increases, the behavior of the system is increasingly governed by the mean interference levels, rather than the tail events. This causes the trend with increasing outage to be similar to the trend with increasing spreading: the gain due to MBA increases, while that due to least load decreases.

VI. Dynamic Users

It is inevitable that users' path gains change during a call. This will adversely affect MBA. The impact of changes in path gain was investigated by studying mobile users, whose signal strength to all base stations changes, and who undertake soft handoff. As in the previous section, calls were not permitted to change bands once established, and thus only intra-band soft handoff is performed. The performance could be increased at the expense of increased complexity by allowing inter-band handoff.

In the scenario studied here, a fraction, m, of users were moving at constant velocity, while $1 - m$ were stationary. The directions were selected at random, and the speeds were exponentially distributed. Speed was measured in normalized units, with speed 1 being the speed required to travel between neighboring base stations in one mean call holding time. These results were taken for large systems (spreading 800 per band) to isolate the effects of mobility from those discussed in the previous section.

The results, in Figure 7, show that a small proportion of mobile users do not cause much degradation in the performance of MBA. If a majority of users are moving, then even quite slow motion can cause the effectiveness of MBA to drop dramatically. However, as the average speed of mobile users decreases, the proportion of mobile users becomes less important.

VII. Partial Soft-Handover

So far, soft handoff has been considered in its most extreme form, where users are permanently connected to the three nearest base stations, and decoded by the one with the highest SIR. A user in soft handoff consumes resources at each of the base stations to which it is connected. Thus real systems use "partial" soft-handoff, where users are only connected to multiple base stations if propagation conditions require this. This section will derive an expression for the probability that a call will be "in soft handoff" in the case of best-of-two soft handoff with two bands using MBA. In this study, all calls permanently have a soft hanodff set consisting of two base stations, and a call is deemed "in soft handoff" only if it is currently being decoded by a base station other than the nearest. The cells are assumed

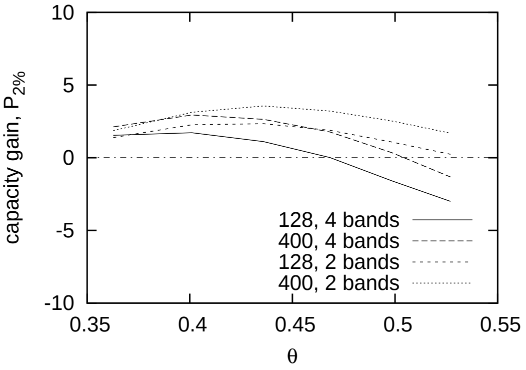


Fig. 6. Increase in capacity at 2% outage relative to random assignment as a function of load balancing, for spreading of 128 and 400, and two or four bands.

to be hexagonal, while the boundaries between rings are circular. The outer ring has a target receive power of p, and the inner ring has a target receive power of 1. This scenario is depicted in Figure 8. Each user connects to the base station which requires it to transmit at the lowest power. Thus the probability that a call in the outer ring of cell 0 is connected to base station 1 is

$$\begin{aligned}
\Pr(\text{soft}) &= \Pr\left(\frac{1}{r_1^{-m}10^{b\xi_1/10}} < \frac{p}{r_0^{-m}10^{b\xi_0/10}}\right) \\
&= \Pr\left(\xi_1 - \xi_0 > \frac{1}{\beta b}\left[m\log\frac{r_1}{r_0} - \log p\right]\right) \\
&\approx \Pr\left(\xi_1 - \xi_0 > \frac{m}{\beta b}E\left[\log\frac{r_1}{r_0}\right] - \frac{\log p}{\beta b}\right) \\
&= 1 - \Phi\left(\frac{mE[\log r_1/r_0]}{\beta b\sqrt{2}\sigma} - \frac{\log p}{\beta b\sqrt{2}\sigma}\right),
\end{aligned}$$

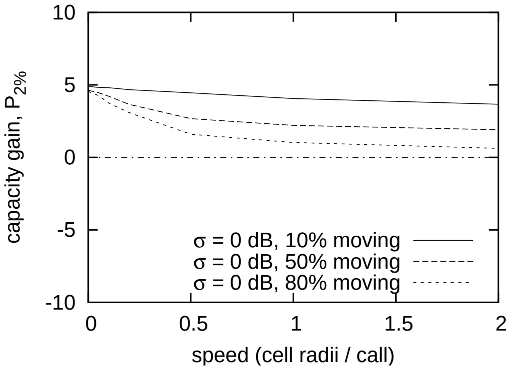
where $\beta = \log(10)/10 \approx 0.23$, $\xi_i \sim \mathcal{N}(0, \sigma^2)$, $i = 0, 1$, are the independent "far field" components of shadowing between the user and base stations 0 and 1, and $b^2 = 0.5$ is the proportion of the total shadowing due to the far field [27]. The expectation $E[\log r_1/r_0] \approx 0.315$ is taken over the sixth of the outer ring closest to base station 1 (Figure 9), and $\Phi(z)$ is the cdf of a zero mean, unit variance Gaussian. Using the values $m = 4$ and $\sigma = 8$ dB gives

$$\Pr(\text{soft}) = 1 - \Phi(0.685 - 0.543\log p). \tag{5}$$

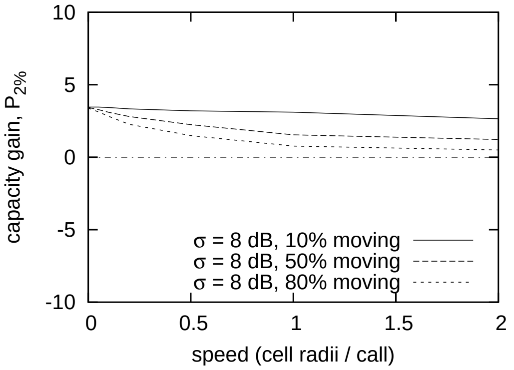
Band allocation schemes which ignore path gain will typically have $p \approx 1$, whereas MBA gives much smaller values. For best-of-two soft handoff, the Monte-Carlo simulation of [12] gives $p \approx 0.86$. Thus the probability of these outer users being in soft handoff drops from $1 - \Phi(0.685) \approx 0.247$ to $1 - \Phi(0.767) \approx 0.222$, a reduction of 10%. This reduction in the number of users in soft handoff is a result of the ability of MBA to decode outer-ring users with a lower received power than conventional schemes.

A. Simulation Results

To investigate the performance of band allocation with partial soft handoff, the system was simulated for the case where a user was only connected to the second-nearest base station if the signal from the nearest base station was below a threshold. This threshold was varied in the range $[0, \infty)$ to alter the proportion of calls in soft handoff. Note that as the threshold increases, this becomes best-of-two soft handoff, rather than best-of-three as is used in the rest of this paper.



(a) No shadowing



(b) $\sigma = 8$ dB

Fig. 7. Increase in capacity of a two-band system at 2% outage relative to random assignment as a function of the average speed of mobile users.

Figure 10 shows the outage probability against the percentage of users not decoded by their nearest base station ("% soft handoff") for two bands, spreading of 128 per band, and a total load of 30 Erlangs. For a given number of users in soft handoff, the outage is consistently lower using MBA than either random or least-load assignment for most levels of outage.

As the soft handoff threshold was increased (more soft handoff), all of the algorithms produced lower outage, but the measurement based approach is consistently the best.

These simulations gives $p \approx 0.85$, and so (5) again predicts a reduction of around 10% in the number of calls in soft handoff compared with $p = 1$, in the limit of unrestricted soft handoff. This is compatible with the simulated values of around 15% soft handoff for MBA and 17% for position independent allocation. This validates the approximations in the derivation of (5).

VIII. CONCLUSION

This paper has investigated a measurement-based approach to the task of assigning new calls to bands in a multiband CDMA

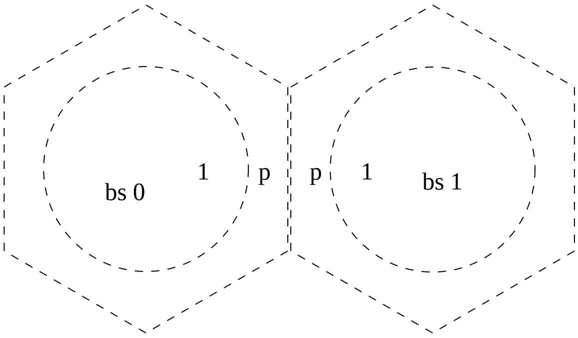


Fig. 8. Scenario for soft handoff analysis. Cells have two bands; the target receive power in the inner band is 1, and in the outer band is $p < 1$.

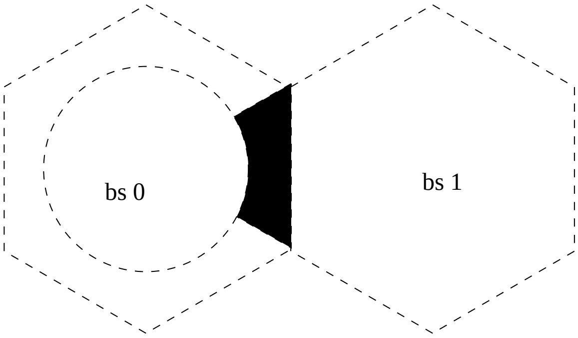


Fig. 9. Region in which soft handoff from base station 0 to base station 1 is considered.

system, based on measured propagation conditions. By separating strong and weak users into different bands, the near-far problem can be attacked directly, reducing the amount of power control, increasing the system capacity and reducing amount of soft handoff needed by around 10%.

The gain in capacity increases as the number of users per cell increases, asymptoting to a constant corresponding to the traditional model of users smeared out in space. In contrast, the gain due to least load allocation decreases as the user density increases.

It has been shown that load balancing between the bands becomes increasingly important as the number of bands increases, and that there should be slightly more users classified as "weak" than "strong".

Ways have been proposed to combine MBA with the least load algorithm for systems with more than two bands. It has been shown that, for moderate user density, these hybrids outperform either technique by itself.

IX. ACKNOWLEDGEMENT

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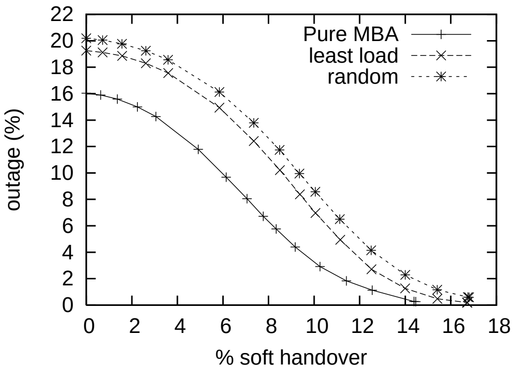

Fig. 10. Outage against percentage of calls connected to non-nearest base station for partial soft-handoff, for a load of 15 Erlangs per band (30 Erlangs total).

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