Power-control-based Band Allocation in Multiband CDMA

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***Abstract*— Multiband CDMA is useful for constructing DS-CDMA (CDMA) systems over a non-contiguous spectrum. The method by which users are assigned to their respective frequency bands, termed 'band allocation', is an important part of assuring good performance in multiband CDMA systems. This paper proposes a novel approach to band allocation based on the transmission power as it is adjusted by power control. We investigate one such power-control-based algorithm that makes use of quality-based power control to switch users to another band when they reach the maximum transmission power. This algorithm is shown to provide a significant increase in capacity for high QoS requirements when compared with both wideband CDMA systems and other proposed band allocation algorithms for multiband CDMA. The capacity gain provided by the investigated algorithm substantiates our claim that power-control-based algorithms are a viable option for band allocation in multiband CDMA.**

I. Introduction

Third generation cellular systems aim at satisfying the demand for increased capacity by the use of greater spectral bandwidth than that of IS95 systems. The most effective way of using this additional bandwidth is under consideration, and numerous possibilities exist. One obvious approach is wideband CDMA, in which the spreading factor is increased from that of the IS95 standard.

In some cases, portions of available bandwidth are not large enough to accomodate wideband CDMA, and in these cases, future generation systems instead propose the use of multiband CDMA. The greatest advantage of multiband CDMA systems is the ability to make use of a non-contiguous spectrum [1]. The available spectrum is divided to create multiple CDMA channels and each call operates over one of these channels. Multiband CDMA systems implement frequency reuse by alternating band assignments between base stations, and cochannel interference is decreased [2]. Multiband CDMA offers additional advantages over wideband CDMA, including backwards compatibility with IS95 and simplicity in hardware, both discussed in [3]. However, there are disadvantages to using multiband CDMA in place of wideband CDMA. Due to the use of smaller portions of bandwidth, multiband systems are more suceptible to frequency selective fading than wideband systems [4]. Also, if users are not permitted to change bands during a call, the trunking efficiency of multiband systems is lower than wideband systems, since there are fewer users on each band. This problem may be avoided if users may change bands freely. Despite these drawbacks, multiband CDMA is invaluable to systems with a non-contiguous spectrum, and it is thus necessary to improve performance as much as possible.

Good performance in multiband CDMA relies on the band allocation algorithm used. Various algorithms have already been considered. One approach is to assign users to the band with the fewest current connections, termed 'least load' allocation [5]. The approach suggested in [6] is to assign different channels to microcells and macrocells initially and to switch to alternate bands in sequential order if the quality requirement is not met. In [3], it is proposed that bands be assigned according to measured path gains, or alternatively, the position of the mobile.

A new method for band allocation based on the results of power control is proposed in this paper. We consider a power-control-based algorithm that uses constrained quality based power control to balance the received carrier to interference ratio (CIR) of all users. Each base station orders the bands from the preferred band down to the most protected band. Initially users are connected to the preferred band, and those that are unable to achieve their required CIR are switched to a protected band. Users that have already cycled through all available bands are denied service. The concept of using power control to switch users to different channels is adopted from the algorithm proposed in [7], where it is suggested for use in narrowband systems.

Power-control-based band allocation offers the possibility of improved performance over other band allocation schemes, and we demonstrate this improvement by the performance of the algorithm investigated. Our assumption that users can change bands during a connection eliminates the problem of a lower trunking efficiency than wideband systems, and this contributes to the performance improvement. Also, the suggested algorithm provides a method of handling users that reach the maximum transmission power in quality-based power control. In the sections that follow, the proposed scheme is further elaborated upon and then evaluated by snapshot simulation of the uplink.

II. Power-control-based Band Allocation

A. Distributed Constrained Power Control

An integral part of the investigated algorithm is the Distributed Constrained Power Control (DCPC) algorithm proposed by Grandhi, Zander and Yates [8]. DCPC was developed with the goal of equalizing CIR among all connections, thereby providing maximum capacity for a given link quality requirement. Here the CIR of the i^{th} user as measured at the base station it connects to (before despreading in the case of a CDMA system) is expressed as [8]

$$\gamma_i = \frac{P_i G_{ii}}{\sum_{j=1, j \neq i}^{M} P_j G_{ij} + \nu}, 1 \leq i \leq M \quad (1)$$

where P_i is the transmission power of the i^{th} user, G_{ij} is the path gain from user j to base station i, ν is the receiver thermal noise, and M is the number of users operating on the same band. Here it is assumed that the allocated bands are sufficiently spaced such that there is no interference between bands. 'CIR balancing' is achieved by adjusting mobile transmitter powers through use of a feedback loop between the base station and mobile. As in [8], at the n^{th} iteration, the transmission power of the i^{th} mobile is

$$P_i^{(n)} = \min\left\{P_{\max}, \gamma_t \frac{P_i^{(n-1)}}{\gamma_i^{(n-1)}}\right\} \quad (2)$$

where $P_{\max}$ is the maximum transmission power in the system, and γ_t is the target CIR. Results in [8] show that the algorithm converges after five iterations for a system with ten users operating over two channels in ten different cells.

The performance of DCPC is shown to be nearly optimal: it supports the maximum number of users with CIR greater than or equal to the target. However, the algorithm does not provide an alternative for users required to transmit at maximum power. Multiband CDMA with the proposed band allocation algorithm provides such an alternative. Upon reaching $P_{\max}$, connections are switched to another band, the transmission power is lowered to that at call initialization, and the power continues to be adjusted by DCPC.

B. Initial Band Usage Layout

To make proper use of the additional bands, users should be assigned to different bands at setup. This could, for example, be based on the path gain to the base station: users close to the center of the cell are assigned to one band and users located further away to another band. To evaluate the simulated algorithm we assign all calls to the same band initially and move the ones that experience poor communication quality as described above.

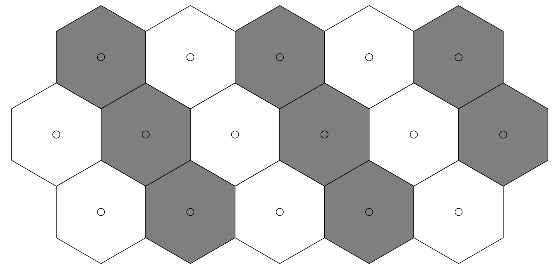

Fig. 1. Initial band allocation layout for two bands

In similar fashion to frequency planning, the initial band assignment is made according to which base station the call connects to. An initial band usage layout that minimizes same-band interference is used, as shown for the case of two bands in Fig. 1. All users connecting to the same base station initially utilize the same band according to the shading in the figure. As the power control iterates some of them will be switched to the other bands in such a way that all cells use all of the available spectrum. Users at the borders will not have as many interferers in neighboring cells as they would in a system without this initial band allocation strategy.

C. Band Allocation Algorithm

At connection, a user is assigned to its initial band in the manner discussed above and begins transmitting at nominal power P_0, where P_0 is the same for all users. The DCPC algorithm is then run through five iterations so that users reach their approximate required transmission power. Next, all users that attempt to transmit at $P_{\max}$ are identified. One fourth of these are chosen at random and switched to a protected band. In the case of a two band system, users switch to the only protected band available to them, and for a system with more than two bands, users are switched to the next protected band according to a pre-determined ordering of all bands available in that cell. After switching bands, these users continue transmitting at power P_0. At this point, all users that attempt to transmit at $P_{\max}$ and have cycled through all available bands are removed from the system. The algorithm then returns to DCPC iterations, and it completes when DCPC has converged and no user is using the maximum transmission power. Thus we iterate until all users in the system have reached the target CIR, γ_t, or we have decided to not support them (those we define to be in outage). The algorithm can be simply described in five steps.

1 **Initialization:** Users are assigned to a base station and begin transmitting on the initial band for that base station at transmission power P_0.
2.1 **Power Control:** DCPC algorithm is run through 5 iterations for all users.
2.2 **Band Switching:** 25% of users transmitting at $P_{\max}$ are chosen randomly and switched to the next sequential band.
2.3 **Call Dropping:** Users transmitting at $P_{\max}$ that have cycled through all bands are dropped from the system.
3 **Algorithm Completion:** Repeat from step 2.1 until no users are transmitting at power $P_{\max}$ and DCPC has converged.

III. EXPERIMENTAL SCENARIO

The investigated algorithm was evaluated by snapshot simulation of the uplink, i.e., users were placed in fixed locations and all started running the power control algorithm at the same time, with no mobility, handovers, arrivals or departures. Simulations were performed for the case of two bands as well as the wideband case. For comparison, a least load algorithm with two bands was also simulated. In our snapshot simulations, we model a 'steady state' least load algorithm, where half of all users in each cell are allocated to each band. A spreading factor of 256 was used for the wideband simulations and 128 was used for the two band systems, such that the total bandwidth occupied in all cases was the same, corresponding to 2.5 MHz. A total of 28 cells were used in the simulation, and a wraparound technique was used to eliminate edge effects. The antenna sectorization was one (omni-directional antennas) and the cell radius was 1 km.

The number of users was assumed to be Poisson and they were distributed uniformly over the area. As we consider only the uplink, we model soft handover as users connecting to the base station with the maximum path gain.

All users began transmission at a nominal power P_0 of 4 dBm and the maximum transmission power $P_{\max}$ was 34 dBm. The path gain is modelled as [9]

$$G_{ij} = \frac{A}{r_{ij}^{\alpha}} 10^{X_{ij}/10} \tag{3}$$

where A is a gain constant determined by the carrier frequency and antenna heights, r_{ij} is the distance in meters between user j and base station i, α is a propagation coefficient determined by the environment (urban, rural, etc), and X_{ij} is a zero-mean, uncorrelated, normally distributed random variable corresponding to shadow fading. These propagation parameters were chosen to reflect an urban environment. The propagation coefficient α was set to 4 and the gain coefficient A was set to -23.3 dB, corresponding to a carrier frequency of 2GHz, base station antenna height of 26.5 meters, and a user antenna height of 1.5 meters. Also, a standard deviation of 8 dB was used for the log-normal shadow fading. We assume the system to be well designed, meaning that a user transmitting at $P_{\max}$ at the edge of a cell experiences a signal-to-noise ratio of 30 dB in the absense of shadow fading. Then the noise ν is

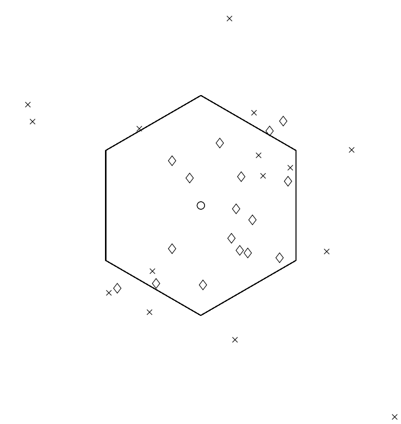

Fig. 2. Band allocation as a result of algorithm: users remaining on initially allocated band are shown as $\diamond$ and users switched to protected band are shown as $\times$.

$$\nu = P_{max} \frac{A}{1000^{\alpha} 10^{(30/10)}} \tag{4}$$

The target CIR for DCPC after despreading, γ_t, was set to 7 dB, and we assume that the algorithm has converged when the power adjustment between iterations is not greater than 0.1μW. Calls were deemed to be in outage if they required transmission power $P_{\max}$ on every band, and they were subsequently dropped from the system.

A practical example of the effect of this algorithm in the case of two bands is shown in Fig. 2. The position of many users in the system relative to the cell they connect to is shown, and those remaining on the initially allocated band are contrasted to those that are switched to the protected band. Here it should be noted that mobiles connect to the base station for which they receive the strongest signal, as opposed to the closest base station. Thus, a user located outside of the hexagonal boundaries of a cell can be connected to that cell, as occurs in this example. As seen from the figure, most users located close to the base station remain on the initially assigned band, as it is unlikely that they will need to transmit at maximum power. Near and outside the borders of the cell, however, most users are switched to the protected band as they reach maximum transmission power. This eliminates interference from those located close to the base station and allows the users to achieve desired quality.

The performance measure for the proposed algorithm was the outage probability. This value was estimated by averaging the observed outage over many snapshots. At each average load per cell λ_c, the estimated outage probability was modelled as

$$\theta_{\lambda_c} = \frac{\frac{1}{N}\sum_{i=1}^{N} x_i}{L\lambda_c} \quad (5)$$

where N is the number of snapshots, x_i is the total number of users in outage in the system in snapshot i, and L is the number of cells in the system. The number of snapshots N was chosen to be sufficiently large that results provided a reasonable level of confidence.

IV. Results and Discussion

The estimated outage probabilities of the simulated systems are shown in Fig. 3. These results indicate that a two band system with the proposed power-control-based band allocation algorithm provides significantly better outage performance than both the wideband system and least load allocation at low loads. If the required outage probability is 10^{-3}, the power-control-based algorithm provides a capacity 20 Erlangs/sector, while least load allocation provides 14 Erlangs/sector and the wideband system provides 12 Erlangs/sector. This translates to a capacity gain of 43% over least load allocation and 67% over wideband CDMA. Thus, for a high quality of service (QoS) requirement, power-control-based band allocation offers significant capacity gains over other band allocation algorithms and wideband CDMA.

However, the simulated power-control-based algorithm performs slightly worse than the other two systems at high loads. If the required outage probability is $2{*}10^{-2}$, the capacity of systems using power control based allocation will be less than the capacity of both least load allocation and wideband CDMA systems. The power-control-based algorithm provides 5% lower capacity than wideband CDMA, while it gives a 12% capacity loss compared to least load allocation.

Note that the measured outage probabilities are almost two orders of magnitude lower than those of [3]. This is due primarily to the use of soft handover in this study and hard handover in [3]. Also, in contrast to the results of [5], least load consistently outperformed wideband. This is because we assumed the cost of switching bands to be negligible, and thus the “least load” condition was enforced more strictly.

The degradation in performance of the power-control-based band allocation algorithm at high loads translates to a lower capacity than the wideband system and the multiband system with least load band allocation. A possible explanation of the rapid increase in outage is the large fraction (25%) of users experiencing poor quality that are switched to alternate bands at each iteration. Also, the removal of all users that experience poor quality and have cycled through all bands might contribute to the increasing outage. With these mechanisms in place, more users than necessary may be switched to the protected band, and when their performance does not improve, more than necessary may be removed from the system. A remedy to this problem would be to switch bands and remove users more conservatively. For example, one user could switch to the protected band and at most one user could be removed from the system at each iteration of the algorithm, and the particular users could be chosen as those with the lowest CIR. The switching or removal of the ‘worst’ user may improve the performance of others such that they would not need to be removed from the system. Such a remedy would be more computationally complex than the proposed algorithm, but it could provide the improved outage performance needed at high loads and thus increase capacity.

There are other possible means of improving performance. Note that the “protected” band of a cell, say band 2, is the “preferred” band of its neighbours, and thus initially has high other-cell interference (OCI). As users in neighbouring cells swap out of band 2, the OCI decreases. The current algorithm drops users based on their current CIR, even if a subsequent reduction in OCI would make their CIR acceptable. Outage may potentially be reduced by performing a second pass, once the propsed algorithm has converged, in which some dropped users are tentatively added back to bands whose OCI levels have dropped significantly.

In addition, it may be possible to combine the proposed algorithm with least load allocation [5]. Outage is caused by “tail events” in which the interference at a cell is anomolously high. Dividing users equally between the bands (with the stronger users in the preferred band) helps to avoid tail events. Strong users not receiving their required CIR can move to the protected band. Alternatively, to increase the CIR of users already in the protected band, the strongest user in that band could be moved into the preferred band.

V. Conclusion

In this paper, we propose the use of power control for band allocation in multiband CDMA. We evaluate a power-control-based algorithm that uses quality-based power control to switch users to protected bands when they experience poor quality and removes users that experience poor quality on all bands. Simulation of this algorithm shows significant capacity gains over wideband CDMA and least load band allocation for high QoS requirements. Thus we conclude that power-control-based band allocation can provide additional capacity in multiband CDMA.

Finally, we note that the performance of the evaluated algorithm is dependant on parameters chosen for implementation. The chosen power control algorithm, the method of band assignment at call connection, and the method by which

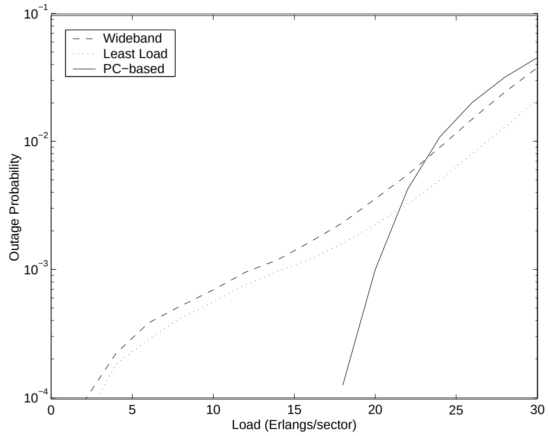

Fig. 3. Outage probability versus load for wideband CDMA, multiband CDMA with least load band allocation, and multiband CDMA with the power-control-based band allocation. The 95% confidence intervals support the trends shown here.

users are chosen for band switching or call removal all affect the performance of the evaluated algorithm. Future work in power-control-based band allocation should involve investigations into these chosen parameters in an effort to further improve performance.

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