

# Reverse-Link Power Control in CDMA Distributed Antenna Systems

Arif Obaid  
Chief Executive  
Global Engineering  
B-2 Panorama Center  
Fatima Jinnah Road  
Karachi, Pakistan.  
Email: [geng@super.net.pk](mailto:geng@super.net.pk)

Halim Yanikomeroglu  
Assistant Professor  
Department of Systems  
& Computer Engineering  
Carleton University  
Ottawa, Canada.  
Email: [halim@sce.carleton.ca](mailto:halim@sce.carleton.ca)

**ABSTRACT**--It is well known that transmit power control is an essential component of any CDMA system. In conventional cellular systems, the interface between the wired network and wireless medium is the base station antenna (or closely located antennas if there is microdiversity) placed at the geographic center of the cell area. With such a "centralized" antenna, however, it is often impossible to maintain perfect power control (even if the power levels are adjusted in a precise and instantaneous manner) due to the fact that the required transmit power levels would occasionally (or often) be beyond practical limits; this is especially true for environments that yield high path losses. In this paper, we investigate the peak and median transmit power requirements in a CDMA system that employs power control with a distributed antenna architecture. Computer simulations show that by using such an antenna architecture with only 4 antenna elements, the median and peak transmit power levels can be reduced by 13 dB and 20 dB, respectively. This may yield a substantial increase in system capacity, as well as a prolonged subscriber battery usage that may be critical in high data rate applications.

## I. INTRODUCTION

Reverse-link power control (PC) is an essential component of any CDMA system. In order to attain perfect power control in the reverse-link of a conventional Central Antenna (CA) system (we call the conventional base station antenna architecture that is composed of a single antenna, or multiple collocated antennas if there is microdiversity, at the geographic center of the cell as the CA type), some of the subscribers may be required to transmit at relatively high power levels -- this would especially be true in indoor environments with significant shadowing losses. But, transmitting at high power levels may not be possible due to hardware and battery limitations. This is also undesirable due to health reasons, and besides, it will cause high interference to the neighboring systems. Unfortunately, this limitation in the peak (upper limit) transmit power may result in a significant decrease in system capacity.

It should be noted that the average transmit power level is also very important in addition to the peak transmit power level. This is especially true in high data rate applications where the battery draining time is critically important.

In order to alleviate the capacity loss due to the limitation in the peak power level, as well as to reduce the average

transmit power level, we propose using a Distributed Antenna (DA) architecture. A DA system is a class of multi antenna system in which the Antenna Elements (AEs) are spatially distributed throughout the cell area. It has been shown that the CDMA DA system not only attains uniform coverage but it also mitigates against multipath and shadow fading by achieving path diversity [1-4]. In this paper, we investigate the performance of a CDMA DA system with respect to PC and compare it with the performance of a conventional CA system.

A typical CDMA DA system is illustrated in Fig. 1. As it can be seen from this figure, the signal transmitted by a user will be picked up by all AEs and fed to a central station (CS) by a common feeder. Delay elements,  $D$ , are inserted into the feeder, between each AE, so that the time difference between the signals received from any two AEs is at least one pseudo-noise code chip duration. These delay elements may have to be of different duration for the system to work effectively [5].

The signals thus received at the CS will be demodulated and combined in maximal ratio combining manner in order to attain diversity. Hence, the output signal-to-interference-ratio (SIR),  $\Gamma_i$ , at the CS, for user  $i$  would be

$$\Gamma_i = \sum_{j=1}^L \Gamma_{ij} \quad (1)$$

where  $L$  is the number of AEs, and  $\Gamma_{ij}$  is the SIR at the  $j$ th finger of the receiver corresponding to user  $i$ .

## II. SYSTEM MODEL AND POWER CONTROL ALGORITHM

We consider a square service region with a side length of  $a$  meters. The AEs are placed uniformly on a rectangular grid in the service region at a height of  $h$  meters above the users. In the simulations  $h=0.02a$ . With these definitions, the location of an AE  $l$ ,  $Z_l$ , can be represented by the following triplet, which shows the x-,y-,z-coordinates respectively:

$$Z_l = \left( \frac{2[(l-1) \bmod \sqrt{L}] + 1}{2\sqrt{L}} a, \left(1 - \frac{2\lceil l/\sqrt{L} \rceil}{2\sqrt{L}}\right) a, h \right) \quad (2)$$

In the simulations  $L=1, 4$ , and  $16$  cases are considered so that  $\sqrt{L}$  always remains an integer. We note that  $L=1$  corresponds to the CA case, whereas  $L=16$  is considered as an exemplary case where the number of AEs is large.

The  $x$ - and  $y$ -coordinates of the user locations are determined by two independent uniform random variables in the range  $[0,a]$ , and the  $z$ -coordinate is always kept at zero to maintain a vertical distance of  $h$  meters all the time.

It is clear from Fig. 1 that in a system with  $K$  users and  $L$  AEs, there are a total of  $LK$  signals received at the CS. At any branch of the combiner corresponding to a particular user,  $LK-1$  of these signals are treated as interference. The received signal powers at the CS form a  $K \times L$  matrix,  $\mathbf{P}=[P_{ij}]$ , such that

$$P_{ij} = G_{ij} P_i \quad (3)$$

where  $G_{ij}$  is the link gain between user  $i$  and AE  $j$ , and  $P_i$  is the  $i$ th user's transmit power. The link gain  $G_{ij}$ , is modeled as:

$$G_{ij} = \frac{\alpha_{ij} \beta_{ij}}{d_{ij}^n} \quad (4)$$

where  $d_{ij}$  is the distance between user  $i$  and AE  $j$ , and  $n$  is the propagation exponent which is taken to be 4.  $\alpha_{ij}$  and  $\beta_{ij}$  are independent Rayleigh and lognormal (with zero mean and a standard deviation of 9 dB) random variables representing multipath and shadow fading, respectively.

If we ignore intercell interference (which is much less significant in a DA system [4]), background noise, and factors like voice activity, SIR for a user  $i$  will be

$$\Gamma_i = \sum_{j=1}^L \Gamma_{ij} = N \sum_{j=1}^L \frac{P_{ij}}{\left( \sum_{k=1}^K \sum_{l=1}^L P_{kl} \right) - P_{ij}} \quad (5)$$

where  $N$  denotes the CDMA processing gain, which is taken to be equal to 128 in the simulations.

Since we omit the background noise, the SIR expression does not depend on the actual power levels; instead, it depends on the ratio of the transmit powers with respect to one another (see Eqn. 5). In other words, all the transmit power levels can be scaled by the same value. Because of this reason, we use *relative power levels* instead of the absolute values. For the sake of convenience, a certain power level is arbitrarily taken as the reference point and labeled as 0 dB.

In this paper, we consider a power-balanced power control algorithm; i.e., the total power (from all AEs) received from every user at the CS is kept constant (power measurement error and delay are not included in this work). Since we work with relative power levels, without loss of

generality, we assume the balanced power level to be equal to 1.

Finally, once again due to the omission of the background noise, the actual size of the square service region does not affect the simulation results; without loss of generality, we set  $a=1$ .

We note that power-balancing is in general not equivalent to SIR-balancing (except for  $L=1$ ). In other words, in a power-balanced system, the SIR value of each user will in general be different. It is shown in [4] that in a power-balanced CDMA DA system, the lower and upper bounds of the SIR turn out to be

$$NL/(LK-1) \quad \text{and} \quad N/(K-1) \quad (6)$$

respectively. Therefore, in a system with high number of users, the upper and lower bounds will be very close to each other, and thus the cumulative distribution function (CDF) of SIRs will resemble a unit step function. Note that while the upper bound is independent of the number of AEs, the lower bound is not and it approaches to  $N/K$  as the number of AEs is increased.

In the simulations, we set  $K_{max}=51$ , unless stated otherwise. This guarantees an SIR value of 4 dB for all users, with any number of AEs, as long as the power-balancing is maintained. In this case, the CDF of the user SIRs will be similar to a unit step function with the corner value of 4 dB.

### III. SIMULATION RESULTS

As described in Sec. I, the maximum allowable transmit power level is referred to as the *peak* value in this paper. We assume that this level is the same for all users. The required transmit power level, on the other hand, refers to the level that is necessary to maintain power-balancing (perfect power control). This level is in general different for each user, and depends on each user's location as well as the corresponding fading conditions.

#### III.A CDFs of Relative Transmit Power Levels

The CDFs of the required relative transmit power levels (to maintain power-balancing) are shown in Fig. 2 for  $L=1, 4$ , and  $16$ . It is observed from Fig. 2 that by increasing the number of AEs from 1 to 4, the median and peak transmit power levels are reduced by 13 dB and 20 dB, respectively. A further increase in the AEs from 4 to 16 yields an additional decrease of 14 dB and 20 dB in the median and peak transmit power levels, respectively. We also observe from Fig. 2 that increasing the number of AEs reduces the power control dynamic range as well (that is, the corresponding CDF curves look more like unit step functions).

The upper tails of the CDFs of the relative transmit power levels (Fig. 2) indicate the maximum required transmit power levels; for instance, this level is around 20 dB for  $L=1$ .

### III.B CDFs of User SIR Values

The CDFs of the user SIR values are shown in Figs. 3-5 for  $L=1, 4,$  and  $16,$  respectively, for various relative peak transmit power levels. As stated in Section II,  $K=51$  users in these figures. We observe from all these three figures that if the (relative) peak transmit power level is around the same value as (or higher than) the maximum required transmit power level (refer to Fig. 2), then perfect power control is achieved and all users have SIR values above the threshold, which yields 0% outage. On the other hand, if power-balancing cannot be achieved, then the CDF curves develop tails in both sides. This is due to the fact that the users that need to transmit at power levels above the peak level experience SIR values lower than the lower bound of the power-balanced DA system (see Eqn. 6); some other users, on the other hand, experience less interference, and thus, enjoy SIR values higher than the upper bound of the power-balanced DA system (which is slightly above 4 dB).

It is important to note from Figs. 3-5 that, when the tails do exist in CDFs, the lower tails extend to very low SIR values. This is true even if the difference between the maximum required power level and the peak level is relatively small (for instance, compare peak=20 dB and peak=10 dB in Fig. 3). The impact of this lower tail on system capacity and outage is detrimental. Let us consider  $L=1$  case with a peak value of 0 dB. We observe from Fig. 3 that, at any given time, around 10% of the users have SIR values less than 4 dB. The straightforward approach to decrease the outage is to reduce the number of users. This will yield a CDF curve which has a shape similar to that of  $K=51$  case, but shifted to right ( $K=40$  yields a threshold value of 5 dB). However, since the lower tail of the CDF is almost flat, the outage percentage will still be close to 10%. In summary, reducing the outage by decreasing the number of users is not an economic solution since the capacity has to be reduced to impractical levels in order to attain reasonable outage percentages. A better solution is to use a DA architecture; we observe from Fig. 4 that even with 4 AEs the outage can be reduced to almost 0% percent at the 0 dB peak value.

In some other systems where the peak power value is even lower, higher number of AEs may be required; for instance, a peak power value of -20 dB will require 16 AEs in order to have almost 0% outage (see Fig. 8).

### III.C Percent Outage with respect to Number of Users

The system outages are plotted with respect to the number of users for various peak power levels in Figs 6-8, for  $L=1, 4,$  and  $16,$  respectively. It is clearly observed from these figures that if the peak power value is less than the maximum required transmit power level, the outage increases to very high values. For instance, for  $L=1$  (Fig. 6), a peak power value of -10 dB yields an outage of 30% for  $K=51$  users. In order to reduce the outage even for 10%,  $K$  has to be reduced

to 8! As stated in the previous subsection, in such a case (where the peak value is low due to various reasons), a better approach is to use a distributed antenna architecture. We observe from Fig. 7 that with only 4 AEs, the outage is reduced to less than 1% for a peak value of -10 dB.

It is noticed from Figs. 6-8 that when the peak power level is in the same order or greater than the maximum required power level to maintain power-balancing, the percent outage curves exhibit break points at  $K=51$  (such as, peak=-20 dB and -30 dB cases in Fig. 8). Otherwise, no breakpoint is observed. The reason is as follows. For those sufficiently high peak power values, all the users have approximately the same SIR value which is slightly higher than the system threshold of 4 dB. Therefore, outage is 0% and the capacity is 51 users. When the 52<sup>nd</sup> user is introduced into the system, the SIR values of all the users become slightly less than the threshold, which results in 100% outage. On the other hand, in the cases where the peak power values are less than the maximum required levels, the discrepancy between the SIR values of the users is high as explained earlier. Introducing a 52<sup>nd</sup> user into such a system only slightly worsens the already problematic situation. Therefore, no breakpoint is observed in the corresponding CDFs.

It should finally be noted that Figs. 6-8 may not be very accurate for low  $K$  values since the background noise is omitted in our simulations.

### III.D Capacity with respect to Relative Peak Power Level

In Figs. 9 and 10, the system capacity is plotted with respect to the relative peak transmit power level, at 1% and 5% outage values, respectively, for  $L=1, 4,$  and  $16.$  It is observed from these figures that the capacity decreases very sharply by decreasing values of the relative peak transmit power level. Once again, this is due to the almost-flat lower tails of the CDF curves for user SIR values. For instance, for  $L=1,$  a peak power level of 14 dB yields a capacity of 51 users at 1%, while a peak power level of 4 dB supports only 8 users.

The capacity gain achieved by DA architecture is obvious from Figs. 9 and 10. At 1% outage level, the peak power level can be reduced by 24 dB without any capacity loss by using a DA structure with 4 AEs instead of the conventional CA (Fig. 9) This gain in the peak power level is around 20 dB at 5% outage (Fig. 10).

## IV. CONCLUDING REMARKS

The DA architecture results in significant power savings, both in average and peak transmit power levels. For instance, with only 4 AEs, the median and peak power levels can be reduced by 13 dB and 20 dB, respectively. Such power savings can be very important for wireless subscribers since it yields cheaper and lighter wireless terminals with prolonged usage times. Besides, communicating with less transmit power levels is considered to be a biological plus,

and this may be an issue of even more concern in the future. Finally, lower transmit power levels cause less interference to other systems.

Power savings may especially be critical in high data rate applications with stringent quality-of-service requirements. A more wired access network architecture, such as the DA type, may be inevitable for such applications. It is likely that all these benefits would compensate the increased wiring cost associated with the DA architecture.

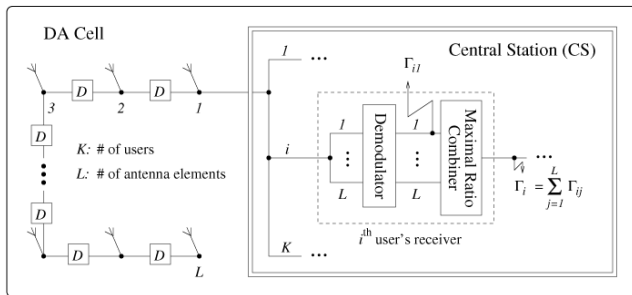


Fig. 1: CDMA Distributed Antenna System

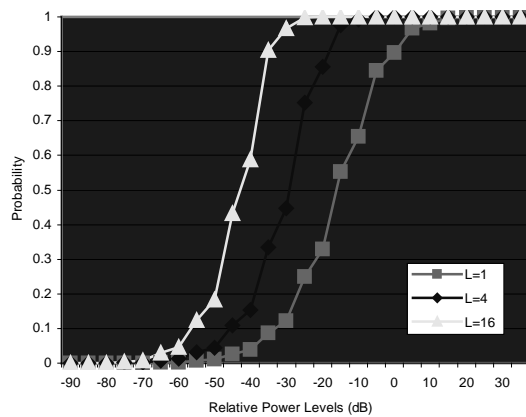


Fig. 2: CDF of the Relative Power Levels

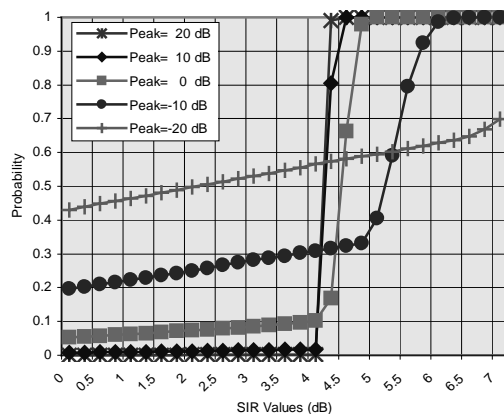


Fig. 3: CDF of the SIR Values for L=1

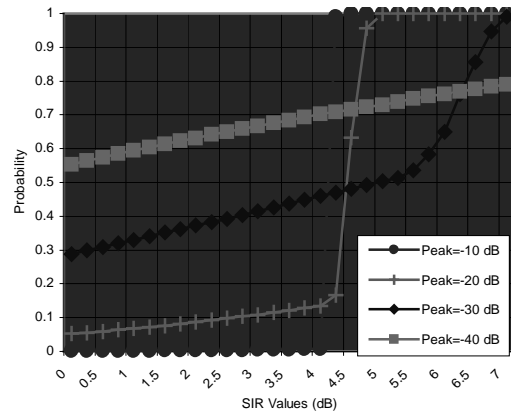


Fig. 4: CDF of SIR Values for L=4

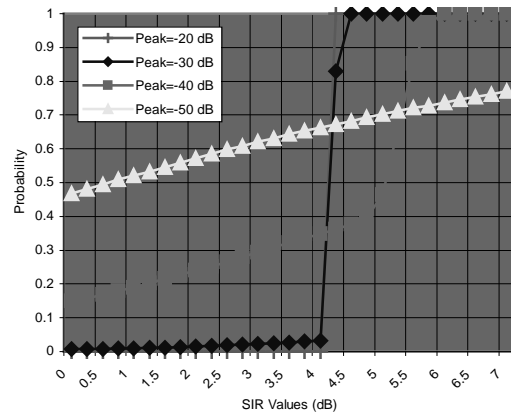


Fig. 5: CDF of SIR Values for L=16

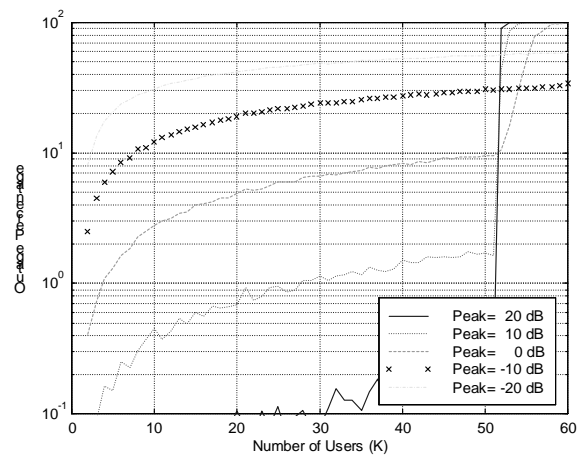


Fig. 6: Outage vs K for L=1

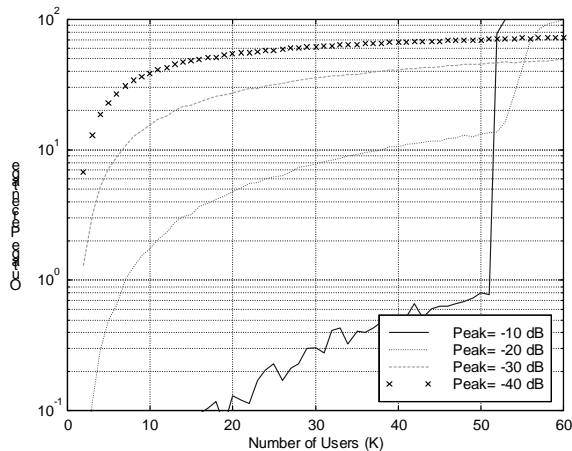


Fig. 7: Outage vs K for L=4

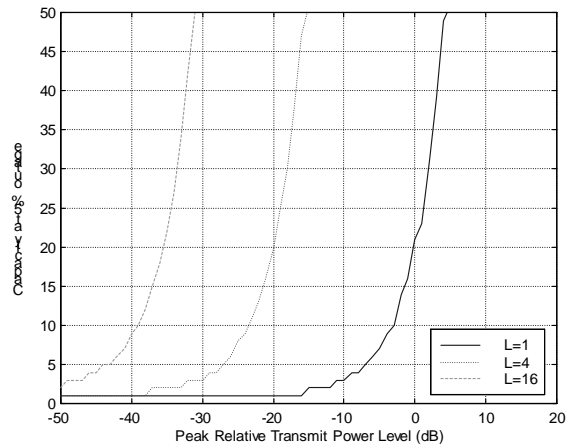


Fig. 10: Capacity at 5% outage vs peak power level.

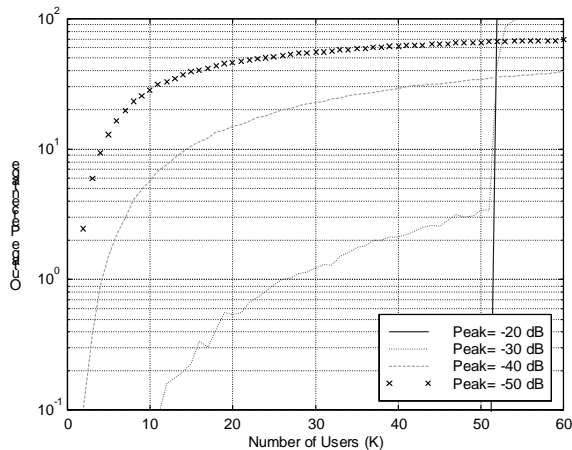


Fig. 8: Outage vs K for L=16

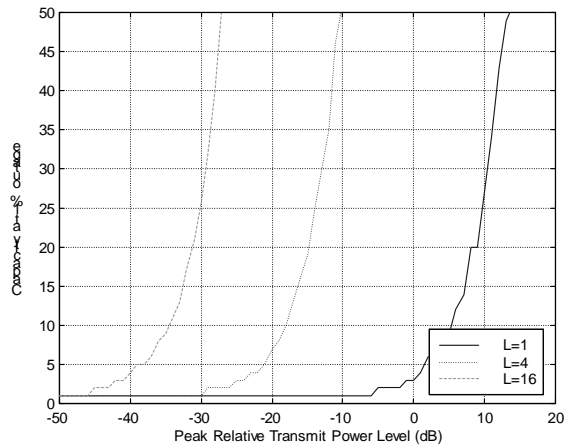


Fig. 9: Capacity at 1% outage vs peak power level

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