Power Control and Number of Antenna Elements in CDMA Distributed Antenna Systems*

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ABSTRACT — In this study the relationship between the number of antenna elements in a CDMA distributed antenna (DA) system and the yielding reverse link SIR is investigated by taking power control dynamic range into account. In environments hostile to propagation, perfect power control may not be realized with a central antenna (CA), because this would require an impractically high dynamic range. This situation may yield a significant decrease in capacity. In such environments, the DA system is an ideal solution, since as the number of antenna elements increases, the dynamic range of the power control decreases. It is demonstrated that by using a DA system with as small as 4 AE's, a capacity increase of almost 30% is achievable, compared to the CA type. However, in a single-cell system once there are a sufficient number of antenna elements to implement perfect power control within a reasonable dynamic range, there is no need for additional antenna elements. Also, in a multi-cell system with CA's, the occasional transmissions at very high power levels in order to maintain perfect power control cause significant intercell interference. Since with DA such situations are almost eliminated, the intercell interference is kept at a minimal level. Therefore, the DA is an ideal antenna type for both single- and multi-cell systems employing CDMA modulation.

1. Introduction

The CDMA distributed antenna (DA) system has been proposed as a promising antenna architecture for the future wireless systems [1]-[6].

In a DA system, the same signal is transmitted from (and received by) many simple omni-directional antenna elements (AE's) in a cell, which are coupled to a common feeder. These AE's are *distributed* throughout the cell area as shown in Fig. 1; this is in contrast with the situation in conventional cells where the antenna (base station) is *centralized*, we refer to this latter case as the central antenna (CA) type. Note that the conventional CA system can be though of as a special case of the DA type with one AE.

In a DA system, there is no intelligence at the AE's, all the signal-specific processing is performed at a central station (CS). Furthermore, there is no need for handoff as long as

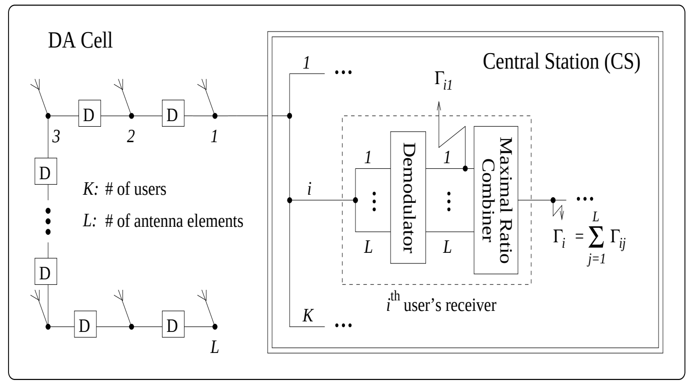

Figure 1: CDMA DA system.

a user is in the same DA cell. In fact, presence of radio links between a user and more than one AE is an advantage. Theoretically, the user would receive signals from all of the AE's (although, in practice, only a few of these signals may be strong enough to make use of), and would utilize them by diversity combining (the same is true in the reverse link also). Obviously, this is macro diversity which is effective against not only multipath fading but also shadow type.[1]

In order to differentiate the many replicas of the same signal at the receiver, CDMA modulation is employed, and delay elements are inserted into the feeder in order to make sure that the time difference between the signals received from any two AE's is at least one PN (pseudo-noise) code chip duration.

The maximal ratio combining scheme is employed at the Rake receiver; thus, the output SIR (signal-to-interference ratio)[2] for any user i, Γ_i, is the algebraic sum of the SIR's at the individual fingers of the Rake receiver:

$$\Gamma_i = \sum_{j=1}^{L} \Gamma_{ij}, \quad i \in \{1, \ldots, K\}, \tag{1}$$

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[1] Note that although the classical antenna diversity, implemented by collocated antennas, has proven to be very effective against multipath fading, it cannot offer a remedy against shadow fading.

[2] The background noise is omitted in this paper since the multiple access interference is the dominant factor affecting the performance.

where K is the number of users, L is the number of AE's, and Γ_{ij} is the SIR at the jth finger of the receiver corresponding to user i.

CDMA DA system has many other appealing features besides macro diversity, such as transmission with relatively low transmit power levels, less interference to other systems, uniform coverage of a service area, and formation of cells with desirable shapes, even non-contiguous ones [1]. In this study, yet another feature of this system is investigated: the maintenance of perfect power control in a DA system compared to that in a CA type. Also, the relationship between the number of AE's in a DA cell and the yielding reverse link SIR is analyzed by taking power control (PC) dynamic range (DR) into account, in order to develop an understanding of the optimal number of AE's in such a system.

2. DA and Perfect Power Control

In the absence of PC, every user in a cell would transmit at the same power level.[3] Then, in a CA system, the signals of the users which are close to the CA would be received much more strongly than those of distant users; this would be detrimental in the reverse link of a CDMA system — a phenomenon known as the near-far problem. In addition, shadow and multipath fading occurs. Therefore, it is essential to employ PC to eliminate the potential excessive differences in the powers of the received signals corresponding to different users.

We consider a PC algorithm similar to that of IS-95; i.e., the total received power for every user is kept at a constant level.[4] If this can *always* be maintained despite distance, and shadow & multipath fading, then we refer such a case as the perfect PC (PPC) type.

2.1 Single-Cell System

Let us consider a single-cell system with a CA and K users. For small cell sizes with IS-95 type chips rates (around 1 Mcps), the flat fading assumption would be a realistic one; that is, there would only be one resolvable path between any user and the CA. If PPC is possible, then, if factors such as the voice activity and frequency re-use efficiency are omitted, the SIR is simply given by

$$\Gamma_i = \frac{N}{K-1}, \quad \forall i, \tag{2}$$

where N is the processing gain. This is the best value achievable for such a scenario, therefore there is no need for DA in this case.

However, in environments with shadow and multipath fading, as the one depicted in Fig 2(a), to maintain PPC continuously is often impossible. When a user's signal is in a deep fade, especially because of blockage, a very high level of power would needed to be sent for relatively long periods, and this would require an impractically large DR. It is worth noting that if PPC were possible, then the SIR would still be the expression given in Eqn. 2.

[3]Throughout this paper, only the reverse link PC is considered.

[4]The actual value of this constant does not affect the SIR value, because the SIR will be the ratio of the signal and interference powers (when the background noise is omitted). In the rest of this paper, we will assume that this constant is 1.

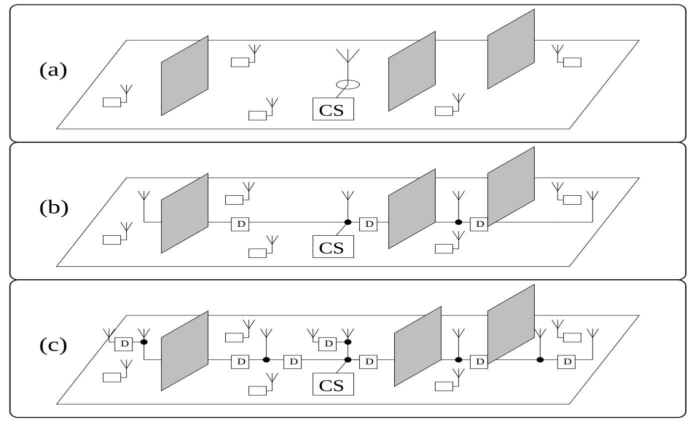

Figure 2: Coverage in a hostile environment: (a) with a CA, (b) with a DA with few AE's, and (c) with many AE's.

The unrealistic requirements on the DR of PC, due to the blockage and shadow fading problems, can be alleviated by using a DA (Fig 2(b)). In a DA cell, no user is almost ever significantly affected from shadow fading; therefore, the SIR is close to that of an ideal CA case as given in Eqn. 2, where PPC is possible.

If the DR of PC is still very high due to multipath fading, additional AE's can be used — even the collocated ones which are only many wavelengths apart as illustrated in Fig. 2(c) [3].

2.2 Multi-Cell System

The situation is quite different in a multi-cell system because of the intercell interference. As stated earlier, if a user's signal is in a deep fade or if blockage occurs between the user and the corresponding CA, then this user must transmit at a very high power level in order to maintain PPC. Since the multipath fading (and also to some extent the shadow fading) between a user and the neighboring CA's is independent of that between the user and the corresponding CA, high levels of interference occur for those neighboring CA's during the maintenance of PPC.[5] Therefore, continuous maintenance of PPC, which yields optimal results in a single-cell system, may yield a considerable decrease in SIR (and thus in capacity) in a multi-cell system employing CA's [7]. In fact, it is shown in [7] that limiting the maximum transmitted power level in situations requiring the transmission of very high levels of power, is a good compromise that increases the SIR (and thus the capacity) by reducing the excessive intercell interference.

In a DA system, on the other hand, such situations requiring the transmission of very high levels of power are almost eliminated, even in systems with moderate L values. Therefore, in a multi-cell environment even if maintaining PPC is

[5]The same reasoning is valid even if the required power level for maintaining PPC is beyond practical limits and thus the wireless user transmits at the maximum power level available instead.

possible with a CA, a DA system should be preferred; because, by this way interference to adjacent cells is kept at a minimal level and thus the system capacity is increased.

In the rest of this paper, the benefits of using the DA in a single-cell system is demonstrated; it is worth noting that the returns are even more when the DA is employed in a multi-cell system.

3. Power Control Algorithm

Since the signals picked up by all the AE's accumulate in the feeder, there are a total of LK signals delivered to the CS. In a particular user's receiver, each finger of the Rake locks unto that user's signal received by one of the AE's, and all the remaining $LK-1$ signals are treated as interference, including the user-of-interest's signals received by the other AE's.

The powers of the received signals at the CS can be represented by an L×K matrix $\mathbf{P}=\{P_{ij}\}$ in the form of

$$P_{ij} = G_{ij}\tilde{P}_i, \tag{3}$$

where G_{ij} is the link gain between user i and AE j, and $\tilde{P}_i$ is the ith user's transmit power. Then, the PC problem can be defined as follows:

$$\text{find } \tilde{P}_i, \text{ subject to } \sum_{j=1}^{L} P_{ij} = \sum_{j=1}^{L} G_{ij}\tilde{P}_i = 1, \ \forall i. \tag{4}$$

If there is no upper or lower limit imposed on the DR, or the required $\tilde{P}_i$ always turns out to be between these limits anyway, this case is referred to as the PPC type.[6] On the other hand, the case where these limits do exist due to the practical limitations and thus $\tilde{P}_i$ is at least occasionally hard-limited, is referred to as the *limited dynamic range* type.

Based on these definitions and by taking Eqn. 1 into account, the SIR for any user i can be calculated as

$$\Gamma_i = N\sum_{j=1}^{L} \frac{P_{ij}}{(\sum_{i=1}^{K}\sum_{j=1}^{L} P_{ij}) - P_{ij}}, \quad \forall i. \tag{5}$$

Note that for the PPC case (see Eqn. 4), $\sum_i \sum_j P_{ij} = K$.

4. Analysis and Simulation Results

Simulations with and without multipath fading have been run. For these cases, G_{ij}'s are simply taken to be

$$G_{ij,\text{no-fading}} = \frac{1}{d_{ij}^4}, \quad G_{ij,\text{multipath-fading}} = \frac{\alpha_{ij}}{d_{ij}^4}. \tag{6}$$

In the above, d_{ij} is the distance between user i and AE j, and α_{ij}'s are independent exponential random variables with $E(\alpha_{ij}) = 1, \ \forall i,j$ ($E(.)$ denotes the expected value). As it is well known, the square of a Rayleigh distributed random variable is exponentially distributed.

[6]In the PPC case, the power adjustments are assumed to be performed instantaneously with the required step size.

Simulations have been run for various values of L which are chosen such that $\sqrt{L}$'s are integers; namely, $L = 1$, 4, 16, and 100. $L = 1$ corresponds to the CA, and $L = 100$ is considered to give an example of a case where L is very large. The AE's are assumed to be uniformly placed on a square cell with side length a meters. It is further assumed that the AE's are h meters above the users, so the minimum value of d_{ij} is h.

Based on these assumptions, the AE locations can be represented by the vector $\mathbf{Z} = \{Z_1, Z_2, \ldots, Z_l, \ldots, Z_L\}^T$, where Z_l's are triplet entries denoting the coordinates of AE's:

$$Z_l = \left(\frac{2[(l-1) \bmod \sqrt{L}] + 1}{2\sqrt{L}}\, a,\ (1 - \frac{2\lceil l/\sqrt{L}\rceil - 1}{2\sqrt{L}})\, a,\ h \right). \tag{7}$$

In the above, $\lceil . \rceil$ denotes the ceiling function. In the simulations h is taken to be $0.02\,a$.

The first two coordinates of the user locations are determined by two independent uniform random variables in the range $[0,\ a]$, and the third coordinate is always kept at zero. Finally, the following values are chosen for N and K: $N=128$, $K=50$.

For a certain set of user locations, the SIR's for all the users are calculated, and this process is repeated 200 times yielding a collection of 10,000 points to plot the CDF's (cumulative distribution functions) accurately.

4.1 Range of SIR for the Case of PPC

For the case of PPC, the lower and upper limits of the SIR can be calculated. It is worth noting that, in general, $\Gamma_{i_m} \neq \Gamma_{i_n}$, for $\{i_m, i_n\} \in \{1, ..., K\}$ and $i_m \neq i_n$ (see Eqn. 5).

A user i_m will have the lowest possible SIR if the signals from this user have equal strengths at each AE; i.e., $P_{i_m j} = 1/L, \forall j$ (see Eqn. 4). If there is no fading, this will occur when the user is at a point which is equidistant from all the AE's in the cell; i.e., if $G_{i_m j}$ is the same for $\forall j$. From Eqn. 5, the SIR at a finger of the Rake receiver of this user is calculated as

$$\Gamma_{i_m j} = N\frac{1/L}{K - 1/L} = \frac{N}{LK-1}, \ \forall j. \tag{8}$$

After combining, the lower limit of SIR, Γ_{LL}, is found as

$$\Gamma_{\text{LL}} = L \times \Gamma_{i_m j} = \frac{LN}{LK-1}. \tag{9}$$

On the contrary, a user i_n will have the highest possible SIR, if only one of the entries in the i_nth row of $\mathbf{P}$ is 1, and all the rest are 0; i.e., if

$$P_{i_n j} = \begin{cases} 1 & \text{if } j = j_n, \\ 0 & \text{otherwise.} \end{cases} \tag{10}$$

For the case of no fading, this will occur when the user i_n is very close to an AE j_n, thus its signal is received by practically only this AE. In this case, there is no need for diversity combining, since $\Gamma_{i_n j} = 0$, for $j \neq j_n$. The upper limit of

SIR, Γ_{UL}, is then the SIR at the j_nth finger since there is no contribution from the other fingers of the Rake:

$$\Gamma_{UL} = \frac{N}{K-1}. \quad (11)$$

Note that the SIR expressions given in Eqn.s 2 and 11 are identical. Therefore, if the above described scenario for the upper limit of SIR is true for all the users, i.e., $\Gamma_i = \Gamma_{UL}$, $\forall i$, this means that the DA is behaving like a CA with PPC, which is the ideal case.

For an arbitrary set of user locations, the SIR's will be between the above limits depending on the locations of the AE's and the users in the cell:

$$\left(\frac{N}{K} <\right) \frac{LN}{LK-1} \leq \Gamma_i \leq \frac{N}{K-1}, \quad \forall i. \quad (12)$$

Note that in the above, the upper limit corresponds to the case of $L=1$ when there is power control, while the lower one corresponds to the general case of L AE's with the limiting case of $L \to \infty$ given in parenthesis in Eqn. 12. Therefore, in a single-cell system, once PPC is achieved with a certain number of AE's, adding more of them would not improve the performance. In fact, the SIR would deteriorate, but only slightly, since the upper and lower limits are very close to each other.

One may find this result counter-intuitive, because a greater L corresponds to a Rake receiver with a greater number of fingers, which, in turn, corresponds to more diversity branches. However, it should be remembered that in the reverse link of a DA system, since all the received signals accumulate in the feeder, with an increasing number of AE's the multiple access interference also increases. This is a case where the Rake receiver has more fingers with poorer SIR values, which, in the end, yields no further gain (once again, this is true as long as PPC is maintained).

In a multi-cell system, on the other hand, a greater L would yield a lower level of intercell interference, which would correspond to a greater SIR value; however, the returns would diminish gradually. Taking the increasing complexity and processing in the system into account, adding more AE's would not worth after a point.

The CDF's of the SIR's for various number of AE's, with and without multipath fading, is plotted in Fig. 3. It is observed from this figure that the range of SIR is

$$\frac{N}{K} = 4.08 \text{ dB} \leq \frac{NL}{LK-1} < \Gamma \leq \frac{N}{K-1} = 4.17 \text{ dB}, \quad (13)$$

in agreement with Eqn. 12.

4.2 Number of AE's and PPC Dynamic Range

As stated before, PC is essential to mitigate against the near-far problem. When the number of AE's increases, the near-far problem becomes less significant. Therefore, higher L values translate into smaller PC DR's.

For the case where there is no fading, the maximum and minimum values of the transmit power $\tilde{P}$, namely, $\tilde{P}_{\max}$ and $\tilde{P}_{\min}$, can be calculated, and then by taking their ratio, the PC DR can be found. The calculations for $L=1$ and $L=4$ cases are given below; those for $L=16$ and $L=100$ cases are more tedious but can be carried out in a similar way.

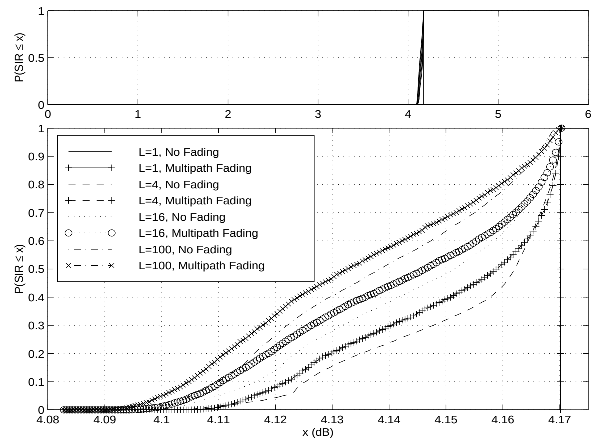

Figure 3: SIR statistics for varying numbers of AE's in a single-cell system, for the case of PPC, with and without multipath fading, drawn in regular and enlarged scales.

<u>$L=1$:</u> First, the following observation is made from Eqn.s 4 and 6: for the special case of $L=1$, $\tilde{P}_i$ reduces to $\tilde{P}_i = d_{i1}^4$, $\forall i$.

A user i_m will have to transmit at the maximum power level if it is at the farthest location from the single AE, which corresponds to the corners of the cell: $\{(0,a,0), (a,a,0), (0,0,0), (a,0,0)\}$. Since $\mathbf{Z} = \{(0.5a, 0.5a, 0.02a)\}$,

$$\tilde{P}_{\max} = d_{i_m 1}^4 = (0.5^2 + 0.5^2 + 0.02^2)^2 a^4 = 0.25a^4. \quad (14)$$

On the other hand, a user i_n will have to transmit at the minimum power level if it is at the point (0.5a, 0.5a, 0), which is the closest location to the AE. So,

$$\tilde{P}_{\min} = d_{i_n 1}^4 = (0.02a)^4 = 1.6 \times 10^{-7} a^4. \quad (15)$$

Now, the DR can be obtained from Eqn.s 14 and 15 as

$$\text{Dynamic Range} = \tilde{P}_{\max}/\tilde{P}_{\min} = 62 \text{ dB}. \quad (16)$$

<u>$L=4$:</u> Similar to the $L=1$ case, a user i_m will have to transmit at the maximum power level if it is at one of the corners of the cell; say, at the point $(0,a,0)$. The corresponding link gains are calculated from Eqn. 6 as $G_{i_m} = \{63.59, 2.56, 2.56, 0.79\} \times a^{-4}$, where G_{i_m} is the i_mth row of the link gain matrix, $\mathbf{G}$. Then, $\tilde{P}_{\max}$ is obtained as

$$\tilde{P}_{\max} = 1.44 \times 10^{-2} a^4. \quad (17)$$

A user i_n will have to transmit at the minimum power level when it is at the closest location to an AE, which corresponds to one of the following points: $\{(0.25a, 0.75a, 0), (0.75a, 0.75a, 0), (0.25a, 0.25a, 0), (0.75a, 0.25a, 0)\}$; for instance, the point $(0.25a, 0.75a, 0)$. Then, $G_{i_n} = \{6.25 \times 10^6, 15.95, 15.95, 3.99\} \times a^{-4}$, and

$$\tilde{P}_{\min} = 1.60 \times 10^{-7}. \quad (18)$$

Finally, from Eqn.s 17 and 18, the DR is calculated as

$$\text{Dynamic Range} = \tilde{P}_{\max}/\tilde{P}_{\min} = 49.5 \text{ dB}. \quad (19)$$

For comparison, the DR's obtained from the simulations are also given in the following table:

Dynamic Range (dB)				
L	1	4	16	100
No Fading	58.6	49.4	36.1	20.8
Rayleigh Fading	122.9	79.7	58.6	42.5

The CDF's of the DR's are plotted in Fig. 4, for the cases where there is no fading and where there is multipath fading. It is obvious from this figure and from the above table that

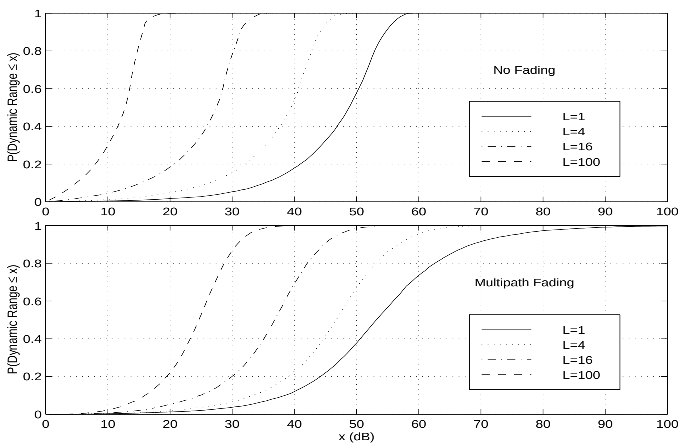

Figure 4: PPC dynamic range statistics in a single-cell system for varying numbers of AE's.

as L increases, the DR decreases. Also, note that for the case where there is multipath fading, the reduction in the DR is most significant (more than 43 dB) when L is increased from 1 to 4.

It is further observed from Fig.4 and the above table that the DR is considerably higher for the cases where there is multipath fading; this is even more significant for smaller L values.

In the limiting case, a 2-dimensional leaky feeder can be imagined; this would correspond to the case where $L \to \infty$. In such a case, there would not be any near-far problem, and thus, there would not be any need for PC:

$$\begin{aligned} L = 1 \quad &\Rightarrow \quad \text{Dynamic Range: Very high (may} \to \infty) \\ L \to \infty \quad &\Rightarrow \quad \text{Dynamic Range} = 0 \text{ dB}. \end{aligned} \quad (20)$$

However, it is worth noting that as L increases, so does the complexity and processing in the system; the case where $L \to \infty$ would require a Rake receiver with an infinite number of fingers!

A final note is that the SIR's corresponding to the cases addressed in this section will be similar to those plotted in Fig. 3, where, due to PPC, the maximum and minimum values are between the limits given in Eqn. 12.

4.3 SIR Statistics for the Case of no PC

Since the need for PC becomes less significant as L increases, it is worth investigating the statistics of SIR for the case where there is no PC at all. Fig. 5 shows the corre-

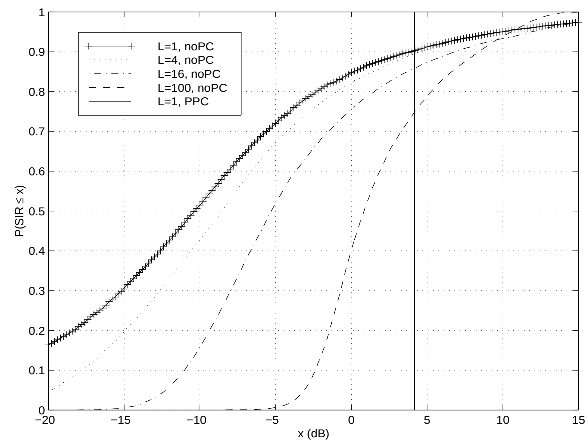

Figure 5: SIR statistics in a single-cell system, for varying numbers of AE's, when there is no PC, also for the CA when there is PPC (all for the case when there is no fading).

sponding CDF's for varying numbers of AE's, when there is no fading. For comparison purposes, the CDF of SIR for the case of $L = 1$ with PPC, i.e., the ideal case, is also shown in the same figure.

It is observed from Fig. 5 that as L increases, the SIR statistics approach that of the CA with PPC; however, even for very large L values (such as 100), PC is still essential, but the corresponding DR would be much smaller as discussed in the previous section.

Note that when there is multipath fading, the discrepancy between the cases where there is no PC, and the CA case with PPC, would be even greater.

4.4 SIR Statistics for the Case of PC with Limited DR

So far, a DR without any limits is considered for the PC, which is referred to as the PPC. In this section, the SIR statistics for the case of the limited PC DR, in the presence of multipath fading, is investigated.

In order to set a realistic range for the DR, it is assumed that if there were no multipath fading, PPC should have been maintained by one AE (i.e., the CA), therefore, the DR is set to 62 dB, the value given in Eqn. 16. If the required power level for any user i, $\tilde{P}_{i,\text{required}}$, is greater than the value given in Eqn. 14, or less than the one given in Eqn. 15, $\tilde{P}_i$ is hard limited to these values, respectively; that is,

$$\tilde{P}_i = \begin{cases} 1.6 \times 10^{-7} & \text{if } \tilde{P}_{i,\text{required}} < 1.6 \times 10^{-7} \\ \tilde{P}_{i,\text{required}} & \text{if } 1.6 \times 10^{-7} \leq \tilde{P}_{i,\text{required}} \leq 0.25 \\ 0.25 & \text{if } 0.25 < \tilde{P}_{i,\text{required}} \end{cases}, \forall i. \quad (21)$$

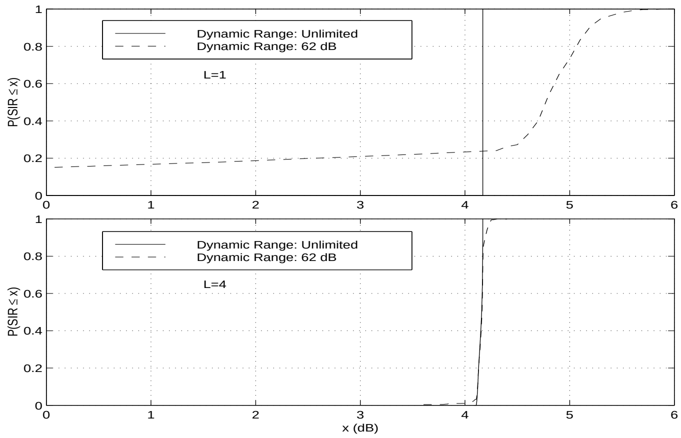

Figure 6: SIR statistics in a single-cell system for the case where there is multipath fading with limited and unlimited DR.

The effect of this hard-limiting is shown in Fig. 6, for the cases of $L=1$ and $L=4$. It is observed from these figures

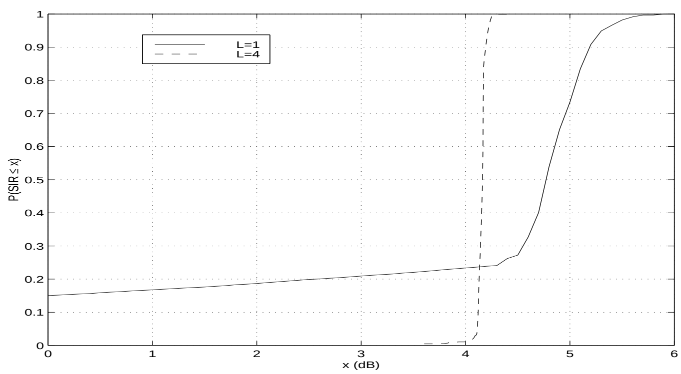

Figure 7: SIR statistics in a single-cell system for the case where there is multipath fading and the DR is limited to 62 dB, $L=1,4$.

that limiting the DR has a detrimental effect for the $L=1$ case; around 24% of the users have SIR values less than 4.08 dB given in Eqn. 13, which is assumed to be the minimum acceptable level. However, the effect is almost insignificant for the $L=4$ case, since only about 2% of the users are below this level. In other words, using a DA with $L=4$, instead of a CA type, yields $(.98-.76)/.76 = 29\%$ increase in capacity. For the limited DR case, the statistics of SIR is plotted in Fig. 7, for $L=1$ and $L=4$.

The conclusion is that if the DR is limited, then, for the parameters chosen in this study, a CA system does not perform satisfactorily; however, the performance can be improved almost to that of an ideal CA by using a DA with $L=4$.

5. Summary and Conclusions

In environments hostile to propagation, achieving PPC may not be possible by using a CA, because this would require an impractically large DR. This situation may yield a significant decrease in the capacity of the system. In such situations, the DA system is an ideal solution, since as the number of AE's in a DA system increases, the DR of the PC decreases. It is demonstrated that by using a DA system with as small as 4 AE's, a capacity increase of almost 30% is achievable, compared to the CA type. It should be noted, however, that PC is essential even for DA systems with very large numbers of AE's.

However, in a single-cell system, once the DR of PC is between practical limits, adding more AE's to a DA system does not improve the SIR. Yet, as L increases, so does the complexity and processing in the system. Therefore, the optimal strategy for a single-cell system can be stated as to put as many AE's as necessary to achieve PPC, but not to exceed this number. It is worth noting that in a single-cell system, even if all the energy in the air were to be collected by a DA with infinitely many AE's, the performance would not surpass that of an optimal CA; so, the only extra benefit would be the reduction in PC DR, at the expense of increased complexity. In other words, in a single-cell system the DA is, at best, equivalent to an optimal CA, that is, a CA which is not affected by coverage and fading problems because of the PPC employed.

In a multi-cell system, on the other hand, the DA system has the additional advantage of reducing the intercell interference (compared to the CA type) with increasing number of AE's, which would yield even higher SIR values. Therefore, the higher the L is the better the system performs; however, the returns would diminish gradually. Taking the increasing complexity and processing in the system into account, adding more AE's would not be worth after a point.

In conclusion, the DA is an ideal antenna type for both single- and multi-cell systems employing CDMA modulation.

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