CDMA Sectorized Distributed Antenna System *

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ABSTRACT — The objective of this study is to utilize antennas in novel ways so as to achieve performance benefits at the system level in future wireless networks. Despite possessing many appealing features, CDMA distributed antenna (DA) systems suffer from low capacity per antenna element (AE) as a result of the multiple access interference (MAI) accumulated in the common feeder. To overcome this capacity limitation, we propose an antenna architecture called CDMA sectorized distributed antenna (SDA). In an SDA system, a cell has many sectors in which separate feeders run, so MAI in the reverse link is reduced. In this study, the limiting case of one AE per sector is investigated. In such a case, a wireless user's signal can be picked up by all the AE's in an SDA cell, and then, can be optimally combined at a central station. It is demonstrated analytically and through simulations that in the reverse link of such a system, the SIR increases approximately linearly with an increasing number of AE's, which can be transformed into an equivalent increase in capacity and/or information rate.

1. Introduction and System Model

The CDMA distributed antenna (DA) system has been proposed as a promising alternative to the conventional wireless access systems which employ central antennas (CA's) [1]-[4].

In a DA cell, many simple omni-directional antenna elements (AE's) are coupled to a common feeder, as shown in Fig. 1, and the same signal is transmitted from (and received by) all of these AE's. All of the intelligence is centralized at a central station (CS); thus, there is no signal-specific processing at the AE's. It is worth noting that in a DA system the AE's are distributed *throughout* the cell, unlike an antenna array where the AE's are located only a few wavelengths apart.

At the CS[1] the Rake receiver employed is capable of distinguishing the signals received by different AE's, through the use of CDMA modulation and the inserted delay elements in the feeder (which guarantee the resolution of the signals coming from various AE's). Consequently, it is obvious that the DA system discussed here (and also those in [1]-[4]) is not of a simulcast type.

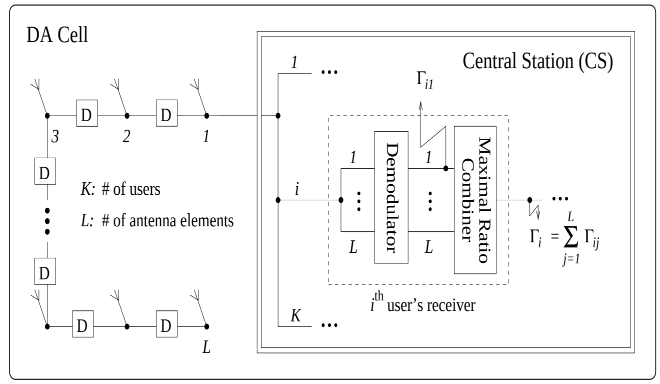

Figure 1: CDMA distributed antenna (DA) system.

The resolved signals are individually demodulated and then combined in a maximal ratio combining scheme to attain diversity as illustrated in Fig. 1. In such a case, the output SIR (signal-to-interference ratio)[2] at the CS for any user i, Γ_i, would be $\Gamma_i = \sum_{j=1}^{L} \Gamma_{ij}$, $i \in \{1, \ldots, K\}$, 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.

In addition to the well known features of CDMA DA, there is yet another appealing feature which is demonstrated in [5]. It is shown in that study that the DA is an ideal antenna type for systems employing CDMA modulation, in the sense that by employing DA, power control (PC) may be maintained perfectly in such systems, without causing significant interference to other cells or systems.[3].

Throughout this paper, a flat fading channel is considered. In other words, there is assumed to be only one path between a user and an AE. In such a case, a total of L distinguishable signals would be received at the CS from each user. We use a matrix notation similar to the one in [5]. The powers of the received signals at the CS are represented by an $K \times L$ matrix $\boldsymbol{P} = [P_{ij}]$ such that $P_{ij} = G_{ij} \tilde{P}_i$, where $\tilde{P}_i$ is the ith user's transmit power, and G_{ij} is the link gain between user i and AE j.

In a DA system, the intercell interference is expected to be much less significant compared to a system with a

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[1] The discussion presented here is for the reverse link of a DA system, however similar arguments are true also for the forward link.

[2] Since multiple access interference is the dominant "noise" source, all other types of noise are omitted in this paper.

[3] A PC scheme is called *perfect* if the required PC dynamic range is *always* within the allowable limits, in other words, if it is possible to maintain PC *continuously*.

CA. Therefore, along with the background noise, the intercell interference is also omitted in our analysis.[4] Based on these assumptions, a user's SIR at a finger of the corresponding Rake receiver would be the ratio of the signal power at that finger to that of the intracell interference. The total interference power is modeled as the sum of the powers of the individual active (intracell) interferers. Then, SIR for a user i_o can be calculated as

$$\Gamma_{i_o,\mathrm{DA}} = \sum_{j=1}^{L} \Gamma_{i_oj,\mathrm{DA}} = N \sum_{j=1}^{L} \frac{P_{i_oj}}{\left(\sum_{j=1}^{L}\sum_{i=1}^{K} P_{ij}\right) - P_{i_oj}}. \quad (1)$$

In the above, N denotes the CDMA processing gain.

2. Limitations of DA System

Although the simple structure of the DA system is quite attractive, it possesses an inherent limitation: since all the AE's are coupled to a common feeder and there is no signal-specific processing at the AE's, the multiple access interference, MAI, is accumulated in the feeder. This imposes a direct limit on the capacity since CDMA systems are interference limited.

As it is shown in [5], in a single cell system (where intercell interference is not an issue), the maximal performance a DA can achieve, as far as SIR is concerned, is that of an optimal CA, which would most likely be a hypothetical one however, where signal fluctuations can be compensated for, in all fading conditions by a perfect PC scheme. In fact, if such a system were possible, then, from solely an SIR point of view, there would be no need to introduce a DA system.[5] So, in a single-cell DA system, once the dynamic range of PC is reduced to its practical limits, adding more AE's would be unnecessary as far as the SIR is considered.

In a multi-cell system, on the other hand, a greater number of AE's would yield a lower level of intercell interference, which would correspond to a higher SIR value; however, even in this case, the returns would diminish gradually. Moreover, the increasing complexity and processing in the system further imposes a limit on the number of AE's.

In summary, in a DA system, the "SIR", or equivalently, the "capacity", versus "number of AE's (L)" curve would plateau with increasing values of L due to MAI. It is worth noting that although the capacity of a DA system may be considerably higher than that which employs a CA (due to diversity, maintenance of perfect PC, minimization of intercell interference, and so on), the resultant increments in the capacity are nevertheless due to indirect effects. Therefore, the capacity is still low per AE, especially for high L values. Indeed, this is the main limitation of a DA system.

3. Sectorized Distributed Antenna System

The accumulation of MAI is a consequence of the simple architecture of the DA system. It would be most desirable

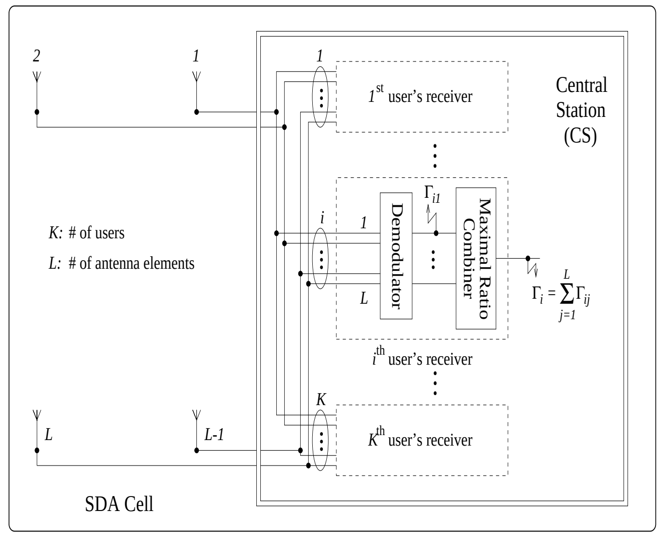

Figure 2: CDMA sectorized distributed antenna system.

if an architectural change yielding substantial reductions in the MAI were possible without significantly complicating the structure of the system.

In fact, such a change can be realized simply by connecting the AE's with separate feeders to the CS as illustrated in Fig. 2. In this study, the limiting case of one AE per sector is investigated. In such a case, a wireless user's signal can be picked up by all the AE's in a cell, and then, can be optimally combined at the central station to enhance the performance. We call this novel antenna architecture *sectorized distributed antenna, SDA*. In the reverse link of an SDA system, MAI can be reduced by approximately a factor of L, and therefore, the SIR can be increased approximately L times. The rest of the discussion regarding SDA will be on the reverse link, and in Section 5 we will address the possibilities in the forward link.

The SDA system is, in essence, still of a DA type, since all the salient characteristics of the DA are preserved, such as the reception of the same signal by all the AE's, and the performance of all the signal-specific processing at the CS. The AE's are also omnidirectional — the term *sectorized* is used for this system because of the conceptual parallelism with sectorization in the conventional cellular systems.

Along with possession of all the appealing features of

[4] If, however, the intercell interference is required to be included in the analysis, then the effective number of users in a DA cell can be assumed to be $K_o = \beta K$, where $\beta \leq 1$. Note that if a single cell DA system is considered, then $\beta = 1$.

[5] However, it is worth noting that even in such a case DA has still other benefits. For instance, both the average and peak transmit power levels are considerably less in a DA system compared to that which employs a CA. This translates into compactness and/or extended battery life for wireless terminals, which might be quite an important factor.

the DA system, such as diversity and reduction of intercell interference, the SDA system has one additional feature: the capacity limitation in the DA system is eliminated. The increase in capacity will be demonstrated quantitatively in Sections 3.2 and 4; nevertheless, for the sake of illustration, we give the following example to compare the SIR's corresponding to DA and SDA systems.

Consider a hypothetical situation where each user's signal is received at approximately the same power level at each AE. If this system is a DA type, then there would be a total of LK signals accumulated in the feeder, from which only one would be utilized at a Rake finger. Thus, the SIR for a user i can be calculated by using Eqn. 1 as

$$\Gamma_{i,\mathrm{DA}} = NL/(LK-1). \tag{2}$$

In the case of the SDA system, however, there would only be K signals accumulated in each of the separate feeders. Therefore,

$$\Gamma_{i,\mathrm{SDA}} = NL/(K-1). \tag{3}$$

Now, the ratio of $\Gamma_{i,\mathrm{SDA}}$ to $\Gamma_{i,\mathrm{DA}}$ can easily be found as

$$\Gamma_{i,\mathrm{SDA}}/\Gamma_{i,\mathrm{DA}} = (LK-1)/(K-1) \approx L, \tag{4}$$

which maps to an approximately L-fold increase in capacity.

In an SDA system, certain system parameters, such as the cell geometry, location of AE's and propagation conditions, can be such that a user's signal may efficiently be received by only $L_o \leq L$ AE's. Let us consider a system in which each user's signal is received by only L_o AE's at the same power level, and the remaining $L-L_o$ AE's do not receive any signal from that particular user. If we assume that the users and AE's are distributed uniformly throughout the SDA cell, then, there would be a total of L_oK/L signals in each feeder. Therefore,

$$\Gamma_{i,\mathrm{SDA}|_{L_o}} \approx \frac{NL_o}{(L_oK/L)-1} = \frac{NL}{K-(L/L_o)} \approx \frac{NL}{K-1}. \tag{5}$$

From Eqn.s 3 and 5 we conclude that even for the case of $L_o \leq L$ significant signals, the almost-linear increase in SIR is preserved. In the rest of this paper, however, we assume that $L_o = L$, unless otherwise stated.

3.1 SIR-Balanced Macro Power Control

In [5], a power-balanced PC (PBPC) algorithm similar to that of IS-95 is used: for every user, the sum of the powers received by all the AE's is kept at a constant level. Although PBPC works very well in DA systems, it yields great variations among the SIR values of different users in the SDA system [6].

In order to fix this problem, we propose a PC algorithm which keeps the SIR for all users at the same constant level, say γ, as follows: find $\tilde{P}_{i_o}$ subject to

$$\Gamma_{i_o} = N\sum_{j=1}^{L} \frac{G_{i_oj}\tilde{P}_{i_o}}{\sum_{i=1}^{K} G_{ij}\tilde{P}_i - G_{i_oj}\tilde{P}_{i_o}} = \gamma,\ \forall i_o. \tag{6}$$

We refer the above PC scheme as SIR-balanced macro power control (SBMPC).

SIR-balanced PC algorithms have been studied in the literature for conventional cellular systems with CA's, and closed form solutions are found. When there is diversity, however, the set of SIR equations become nonlinear (due to the outermost summation, $\sum_j$, in Eqn. 6), and a closed form eigenvalue solution does not exist. Therefore, Eqn. 6 should be solved iteratively for $\tilde{P}_i$'s. The details of the nonlinear SBMPC algorithm, its iterative solution, and the convergence characteristics of these iterations are analyzed in [6].

3.2 Lower and Upper Limits of SIR in an SDA System with SBMPC

The lower and upper limits of SIR in a DA system with PBPC, namely, $\Gamma_{\mathrm{DA,PBPC,LL}}$ and $\Gamma_{\mathrm{DA,PBPC,UL}}$, have been found in [5] to be

$$\Gamma_{\mathrm{DA,PBPC,LL}} = \frac{NL}{LK-1},\quad \Gamma_{\mathrm{DA,PBPC,UL}} = \frac{N}{K-1}. \tag{7}$$

Similarly, we will compute the lower and upper limits of SIR in an SDA system with SBMPC, namely, $\Gamma_{\mathrm{SDA,SBMCP,LL}}$ and $\Gamma_{\mathrm{SDA,SBMPC,UL}}$. It should be borne in mind that, in general, $\Gamma_{i_k,\mathrm{DA,PBPC}} \neq \Gamma_{i_l,\mathrm{DA,PBPC}}$ for $i_k \neq i_l$; however, $\Gamma_{i_k,\mathrm{SDA,SBMPC}} = \Gamma_{i_k,\mathrm{SDA,SBMPC}}$ for $\forall i_k, i_l$.

In an SDA system, the users will experience the lowest possible SIR value if, at each AE, the received signals from all the users are at the same power level; that is, $P_{ij} = m_j$, $\forall i,j$. In the above, m_j is a constant. In general, $m_{j_k} \neq m_{j_l}$ for $j_k \neq j_l$, where $j_k, j_l \in \{1,\ldots,L\}$. In this case, at each Rake finger, there would be K signals of equal power (one of them is the signal of interest and the remaining $K-1$ are the interfering signals), and the contribution to SIR from each Rake finger would be the same. Based on these facts, $\Gamma_{\mathrm{SDA,SBMPC,LL}}$ can be computed as

$$\Gamma_{\mathrm{SDA,SBMPC,LL}} = NL/(K-1). \tag{8}$$

On the contrary, the users will experience the highest possible SIR, if only one of the entries in each row of $\boldsymbol{P}$ is nonzero, and in each column there are K/L (assuming K/L is an integer) nonzero entries with the same value; i.e., $(P_{ij} = (n_j \vee 0)) \wedge (\sum_{j=1}^{L} P_{ij} = n_j) \wedge (\sum_{i=1}^{K} P_{ij} = n_jK/L)$, where n_j is a constant, and $\wedge$ and $\vee$ denote the logical "and" and "or" operation, respectively. In general, $n_{j_k} \neq n_{j_l}$ for $j_k \neq j_l$, where $j_k, j_l \in \{1,\ldots,L\}$. In this case, there is no need for diversity combining, and

$$\Gamma_{\mathrm{SDA,SBMPC,UL}} = \frac{N}{K/L-1} = \frac{NL}{K-L}. \tag{9}$$

The above expression is valid for the cases where $L < K$. If, however, $L \geq K$, then $\Gamma_{\mathrm{SDA,SBMPC,UL}}$ may approach infinity according to our modelling. We note that in practical cases, almost always $L < K$. Even in the exceptional

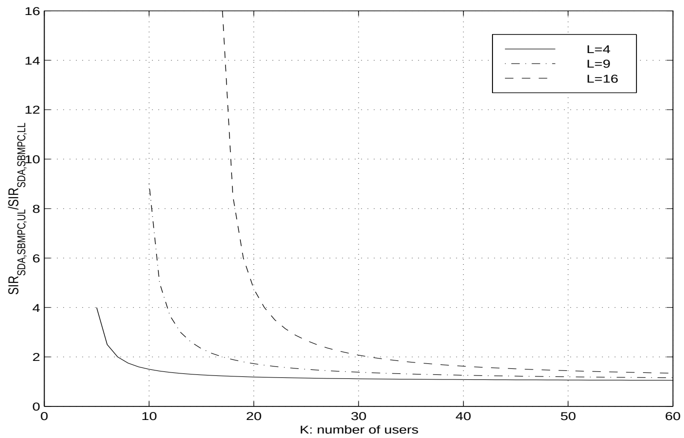

Figure 3: Comparison of the ratio of the upper and lower limits of SIR, for various values of L, in an SDA system with SBMPC.

cases where $L \geq K$, SIR will never approach ∞, because of the background noise that we are omitting.

Now, using Eqn.s 7, 8, and 9, we obtain

$$\Gamma_{\text{SDA,SBMPC,LL}}/\Gamma_{\text{DA,PBPC,LL}} = (LK-1)/(K-1) \approx L, \quad (10)$$

$$\Gamma_{\text{SDA,SBMPC,UL}}/\Gamma_{\text{DA,PBPC,UL}} = L(K-1)/(K-L) \approx L. \quad (11)$$

The results shown in Eqn.s 10 and 11 translate into an approximately L-fold increase in capacity.

Finally, we calculate the ratio of $\Gamma_{\text{SDA,SBMPC,UL}}$ to $\Gamma_{\text{SDA,SBMPC,LL}}$, using Eqn.s 8 and 9, as

$$\Gamma_{\text{SDA,SBMPC,UL}}/\Gamma_{\text{SDA,SBMPC,LL}} = (K-1)/(K-L). \quad (12)$$

The above expression is plotted in Fig. 3 as a function of K for various values of L, with $K > L$. It is observed that for loaded systems (where $K/L \gg 1$), the ratio given in Eqn. 12 is close to unity; however, it may assume much greater values for unloaded systems (where K is in the order of L). The reason for this is that when K is in the order of L, the relative positions of the users and the AE's have a greater impact on the SIR expression. Because, in an unloaded system, it is possible to have a user distribution such that each user (or group of few users) is close to a different AE. For the cases where $K/L \gg 1$, on the other hand, there would always be many users around each AE.

4. Simulation Results

For simulations, a single SDA cell with L AE's and K users is considered. The AE's are assumed to be uniformly placed in the cell which has a square shape with side length a meters. It is assumed that $\sqrt{L}$ is an integer, and that the AE's are elevated h meters above the user level. Then, AE locations can be represented by the vector $\boldsymbol{Z} = [Z_1, Z_2, \ldots, Z_l, \ldots, Z_L]^T$, where Z_l's are triplet entries, in meters, denoting the coordinates of AE's:

$$Z_l = \left(\frac{2[(l-1) \bmod \sqrt{L}]+1}{2\sqrt{L}} a, (1 - \frac{2\lceil l/\sqrt{L}\rceil - 1}{2\sqrt{L}}) a, h \right). \quad (13)$$

In the above, $\lceil . \rceil$ denotes the ceiling function. In the simulations, $L = 4$ and $L = 16$ cases are considered with $h = 0.02\,a$.

The users are placed randomly throughout the SDA cell. 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. The simulations are run for various number of users with a processing gain of $N = 128$.

As stated in Section 2, the intercell interference is omitted in our analysis (refer to footnote 3). It is further assumed that the multipath fading is averaged out; in this case, the performance of the system will only depend on the local average received power. Based on these assumptions, the link gains are modeled as $G_{ij} = A_{ij}/d_{ij}^{\alpha}$, where d_{ij} is the distance between user i and AE j, α is the distance power law coefficient, and A_{ij} is a random quantity that models the power variation due to shadowing. A_{ij}'s are assumed to be independent, identically distributed log-normal random variables with 0 dB expectation and 8 dB standard deviation. Also, $\alpha = 4$ is used in the simulations.

In the simulations, for a certain set of random user locations, first, the $\boldsymbol{G}$ matrix is formed, and then the balanced SIR value is calculated through the iterative solution of the SBMPC algorithm. This process is repeated for 10,000 different user location sets in order to collect enough data to plot the cumulative distribution functions (CDF's) accurately.

The SIR CDF's for various SDA systems with varying K and L values are shown in Fig. 4(a), (b), and (c). In these figures, the number of users is kept fixed ($K = 20$, 80, and 400, respectively), but the number of EA's is increased from 1 to 4 to 16. It is observed that when L increases from 1 to 4, there is a gain of 6.5, 6.1 and 6.0 dB in the median values of the SIR's corresponding to $K = 20$, 80, and 400 cases, respectively; when L increases from 4 to 16, the corresponding gains are 7.4, 6.4, and 6.1 dB, respectively. This variation in gain is a result of the difference between the loaded and unloaded systems discussed in the last paragraph of the previous section. In Fig. 5, the median SIR values corresponding to the curves given in Fig. 4 are plotted against L, for various values of K — the approximately linear increase in SIR is obvious.

In Fig. 6, the number of AE's is kept fixed ($L = 4$), and the number of users is varied from 5 to 400. As expected, SIR improves as K decreases. When K is decreased from 20 to 5, the increase in the median value of SIR is 8.22 dB, while when it is decreased from 400 to 100 (still, $\times 4$), this increase is only 6.12 dB. Once again, this variation is due to the difference between the loaded and unloaded systems.

5. Discussions

The idea of sectorization in the context of DA is first introduced in [3] in a qualitative manner. In that conceptual

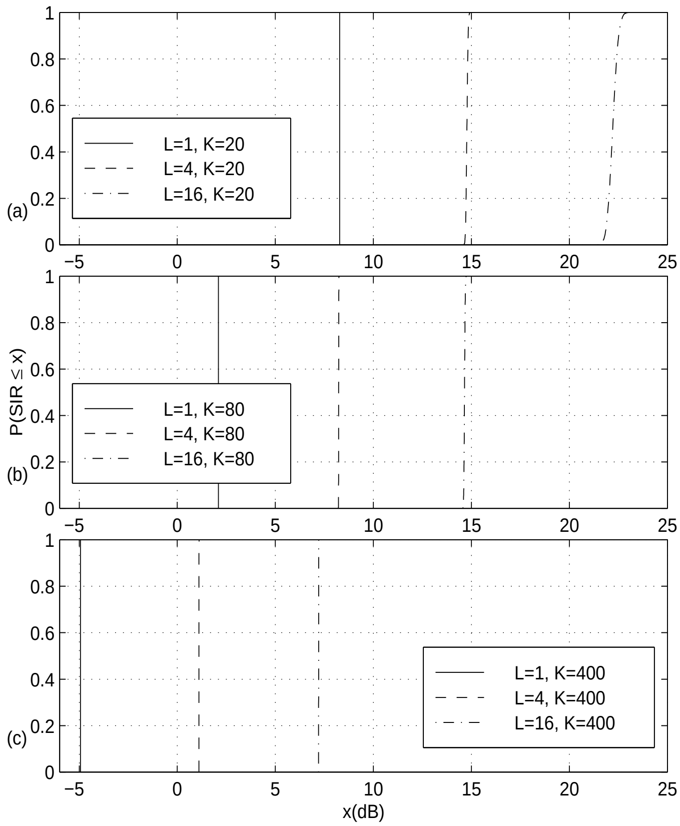

Figure 4: Comparison of SIR CDF's for SDA systems (employing SBMPC) for (a) $K=20$, $L=4$, and 16, (b) $K=80$, $L=4$, and 16, (c) $K=400$, $L=4$, and 16.

study, a few AE's are placed in each DA sector; therefore, the SDA architecture presented here can be considered as the limiting case of one AE per sector. In [7], the ultimate reverse link capacity of a CDMA network is investigated. Although the terminology and modeling in [7] is different than those used here (our work was done independently from that in [7]), the two systems are conceptually very similar. Yet, the entirely different motivation, approach, and emphasis in our paper make it a different study than that of [7].

One very important characteristic of the SDA system is its macro diversity capability. This feature will become even more important with the increasing interest in wireless systems operating at higher frequency bands where the line of sight (LOS) communications may be essential. Since a user will almost always be in the close vicinity of an AE in an SDA system, maintaining LOS would not be difficult. Therefore, SDA may be a very suitable antenna architecture for systems operating at, for example, 10 GHz and higher frequencies.

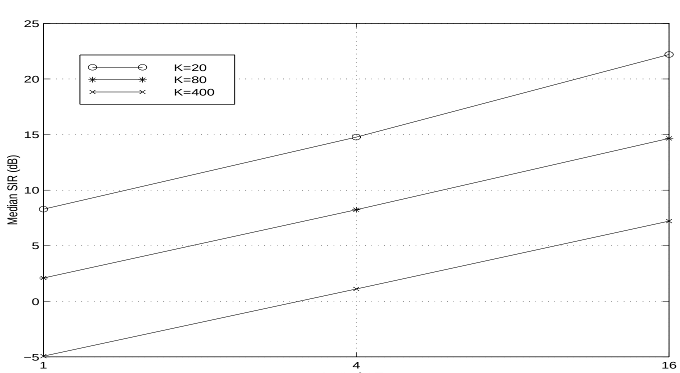

Figure 5: Median SIR value (dB) with respect to L.

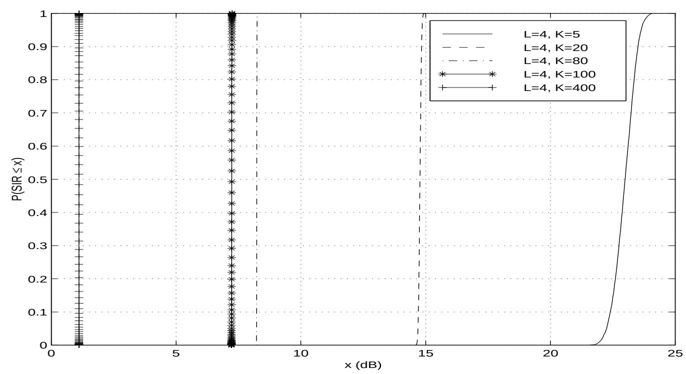

Figure 6: Comparison of SIR CDF's for SDA systems (employing SBMPC) which have $L=4$ AE's, with $K=5$, 20, 80, 100, and 400.

It is reported in the literature that by using antenna arrays, a reverse link capacity increase in the order of the number of AE's in the array is achievable [8]. However, it should be borne in mind that the antenna arrays do not have macro diversity capability. Hence, when a blockage occurs in the radio link, an antenna array cannot provide a solution! Thus, an antenna array cannot offer the immunity against shadowing effects that an SDA architecture can.

In microcellular systems, intercell interference is a nuisance that must be managed; therefore, in cellular design, the propagation characteristics should be taken into account in order to find appropriate base station locations that would minimize the overlapping of the antenna radiation patterns, and thus the intercell interference. However, intercell interference cannot be entirely eliminated, and this inevitably introduces degradation in system performance. In an SDA system, on the other hand, overlapping of the AE radiation patterns is not a problem; in fact, this may yield an even better result due to diversity reception.

One other important point to note is that in the capacity calculations of microcellular systems, the assumption of homogeneous user distribution throughout the service area is generally made. In practise, however, this is usually not the case. As an example, let us consider a microcellular system with 4 cells. If the capacity per cell is K users, then the system capacity is said to be $4K$. However, if these $4K$ users are in fact distributed as, say, $2K/3$, $2K/3$, $2K/3$, and $2K$ users, among the 4 cells in the system, then the system would be able to support only $3K$ users, not $4K$! The inhomogeneous user distribution is, in general, not a significant problem in an SDA system.

The discussions presented so far have been on the reverse link of SDA systems. As mentioned in Section 3, in the reverse link of an SDA system, although a user's signal is picked up by all the AE's, having separate feeders for each AE prevents the accumulation of MAI. This is not the case, however, for the forward link. If, in the forward link, a user's signal is transmitted by all the AE's, then the system will operate as a conventional DA type. Clearly, this would result in quite a large difference in the forward and reverse link capacities. As a remedy for this situation we propose the following solution: in the forward link, the signal for a particular user could be transmitted through the AE which has the highest SIR in the reverse link for that particular user. Therefore, there would be selection diversity in the forward link, and thus, the benefits of the macro diversity would still be valid. In this SDA system, the reverse link would still outperform the forward one. Yet, it should be noted that higher capacity in the reverse link is never a "problem"; in order to equalize the capacities in both links, more resources (such as bandwidth), from the given pool, can be allocated for the forward link.

The CDMA SDA system described in this paper may have quite diverse applications with a wide range of cell sizes and number of AE's. For example, an SDA cell may be as small as a microcell (or even a picocell) with only a few AE's (even 2), or it may cover many square kilometers with many AE's. The SDA structure may be utilized both indoors and outdoors, including linear service areas, such as highways.

One other issue is related to the cost of the SDA system: since the SDA architecture has logical star topology (that is, each AE requires a separate link to the CS), in an SDA system with a large number of AE's, the deployment cost of the wired-network infrastructure may be of concern. Robust, flexible, and cost efficient AE interconnection strategies are discussed in [9] and [10].

6. Concluding Remarks

We have demonstrated analytically and through simulations that in a CDMA SDA system the SIR increases approximately linearly with increasing numbers of AE's (sectors). This increase in SIR can be mapped into an equivalent increase in the capacity. If there is not enough demand for all of the potential capacity offered by an SDA system, the increase in SIR can always be partly transformed into higher transmission rates for the existing users.

Although an SDA cell with one AE per sector is similar in essence to a microcellular cluster with many microcells, the SDA system has two main advantages as a result of the macro diversity capability, combined with the SBMPC algorithm: the increase in capacity in an SDA system is still valid (unlike in a microcellular type), even if (a) the antenna patterns of the AE's overlap, and (b) the users are not distributed homogeneously throughout the service area. Therefore, sectorization in the context of DA is more efficient than cell-splitting in the conventional cellular systems.

There still remains a fundamental question: in a given service area that is to be covered by an SDA cell, can we put as many AE's as we wish without an upper limit? In an SDA system, putting more AE's would always yield better performance (this is analogous to a dish antenna: the greater the diameter, the better the performance). However, the returns in SIR may diminish gradually as L increases, since signals received by different AE's would start being correlated. This is an immediate consequence of the fact that when L increases, the AE's become closer together. Taking the increasing complexity and processing in the system into account, adding more AE's would not be worthwhile after a point, which puts an upper limit on the number of AE's (sectors). Our research on the correlation effect is under progress. The initial results indicate that for reasonably high chip rates and for cells that are not very small, the effect of correlation is mild if the number of AE's is not very high.

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