Correlated Interference Analysis in CDMA Multi-Antenna Systems*

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ABSTRACT

CDMA sectorized distributed antenna system constitutes the logical extent of the soft handoff scheme where all the users communicate with all the antennas in the service region. It has been reported that, in the reverse link, such systems, in comparison to conventional single-antenna systems, have the potential to achieve a capacity increase which is equal to the number of antenna elements used. In order to achieve this gain, the interference picked up by different antenna elements must be uncorrelated. In this paper, we present a spatial correlated interference analysis for the simplest non-trivial system which has 2 antenna elements and 2 users. The effects of system parameters and user & antenna element locations on the correlated interference are investigated. This work lays down a foundational framework that may yield a comprehensive understanding of the performance of CDMA multi-antenna systems.

I. INTRODUCTION AND DEFINITIONS

The CDMA sectorized distributed antenna (SDA) system has recently been proposed as a promising alternative to the conventional wireless access system that employs a single central antenna (base station) [1-2]. An SDA is a multi-antenna system in which many simple antenna elements (AE's) are connected to a central station (CS) with separate feeders. All of the intelligence is centralized at the CS; thus, there is no signal-specific processing at the AE's. In the reverse link of an SDA system, a user's signal is received by all of these AE's and decoded jointly at the CS. It is worth noting that in an SDA system the AE's are distributed throughout the coverage area, unlike an antenna array where the AE's are located only a few wavelengths apart. The SDA scheme is the logical extent of the soft handoff scheme where all the users communicate with all the antennas in the service region, and where the decision making process is centralized.

It has been shown in [1-2] that the total interference experienced in the reverse link of an SDA system with L AE's can be as small as $(1/L)$th of that experienced in a conventional single antenna system. This yields an approximately L-fold increase in the reverse link SIR (signal-to-interference ratio), which can be transformed into an equivalent increase in the capacity and/or information rate. The reverse link capacity of a network of antennas is also investigated in [3]. Although the approach in that study is different than that used in [1-2], the results are in agreement.

In [1-3], a maximal ratio combiner (MRC) is used at the receiver. In order for an MRC to maximize the output SIR, the interference components at the branches of the combiner must be uncorrelated. If this is the case, then the output SIR turns out to be the algebraic sum of the branch SIR's. If, however, the interference components are correlated, then the output SIR will be less than the sum of the branch SIR's. In the limiting case of identical signal and interference components at the branches, there is no gain at all from multi-antenna reception (combining), since amplification does not increase the SIR. Therefore, in multi-antenna systems, it is critical to investigate the presence of correlated interference in the branches of the combiner.

In this paper, we will present a spatial correlated interference analysis for the simplest non-trivial system which has 2 AE's and 2 users. The effects of system parameters (such as the processing gain and size of the coverage region) and the user & AE locations on the correlated interference will be demonstrated. To the best of the authors' knowledge, there exists almost no literature in this topic. Therefore, we believe that our work will lay down a foundational framework that may yield a comprehensive understanding of the relationship between the number of AE's and the yielding system capacity in CDMA multi-antenna systems.

We consider an SDA system with 2 AE's, AE I and AE II, and 2 users. We assume that wireless user 1 (w_1) is the user of interest. Fig. 1 shows the propagation delays in the system. The the total propagation time from w_1 to the CS through AE I, $t_{1I,t}$, is equal to the sum of the propagation times in the air, t_{1I}, and in the cable, $t_{I,c}$:

$$t_{1I,t} = t_{1I} + t_{I,c}. \tag{1}$$

We note that $t_{I,c}$ does not depend on the location of w_1. Similarly, $t_{1II,t} = t_{1II} + t_{II,c}$. Propagation times

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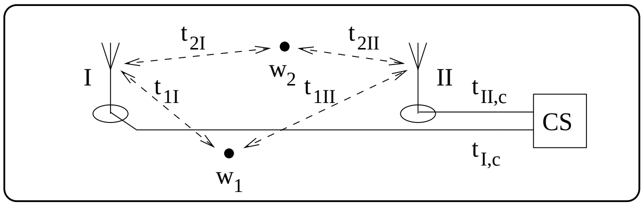

Figure 1: Propagation delays in an SDA system with $L = 2$ and $K = 2$.

regarding w_2 are defined in a similar way.

The baseband transmitters for the two users and baseband receiver for w_1 at the CS are illustrated in Fig. 2. Also, the spreading code and the related assumptions are

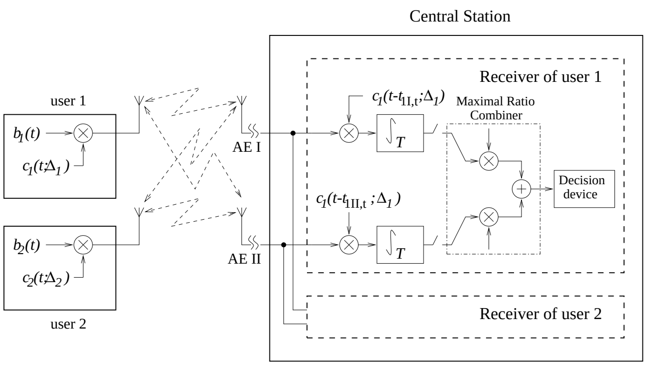

Figure 2: The baseband transmitters and receivers.

depicted in Fig. 3. At w_1's receiver, the despreading at

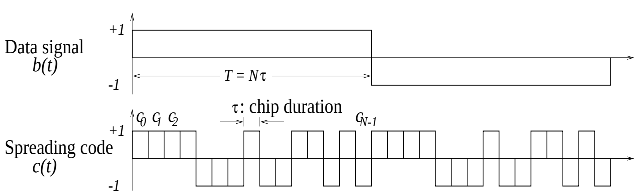

Figure 3: The data signal, $b(t)$, and spreading code, $c(t)$.

the Ist branch is performed by multiplying the received signal by $c_1(t - t_{1I,t}; \Delta_1)$, where $c_1(t)$ is the spreading code for w_1 and Δ_1 is the corresponding (normalized) code phase. Δ_1 is represented in terms of τ (chip duration); i.e., $c_1(t - t_{1I,t}; \Delta_1) = c_1(t - t_{1I,t} - \Delta_1 \tau)$. The situation at the IInd branch of w_1's receiver is similar; obviously, in this case the despreading is performed by $c_1(t - t_{1II,t}; \Delta_1)$. The background noise is omitted in our analysis.

II. CORRELATION COEFFICIENT ANALYSIS

Let n_{1I} and n_{1II} be the interference components (after despreading) at the branches of the MRC of w_1, corresponding to AE's I and II, respectively:

$$n_{1I} = \langle c_1(t - t_{1I,t}; \Delta_1) c_2(t - t_{2I,t}; \Delta_2) \rangle, \tag{2}$$

$$n_{1II} = \langle c_1(t - t_{1II,t}; \Delta_1) c_2(t - t_{2II,t}; \Delta_2) \rangle, \tag{3}$$

where $\langle . \rangle$ denotes the inner product (refer to Fig. 3).

We are interested in evaluating the correlation coefficient of the random variables n_{1I} and n_{1II}, ρ, which is defined as

$$\rho = \frac{\mathbf{E}(n_{1I}\, n_{1II}) - \mathbf{E}(n_{1I}) \mathbf{E}(n_{1II})}{\sqrt{\mathbf{E}(n_{1I}^2) - \mathbf{E}^2(n_{1I})}\, \sqrt{\mathbf{E}(n_{1II}^2) - \mathbf{E}^2(n_{1II})}}, \tag{4}$$

where $\mathbf{E}(.)$ denotes the expectation operator.

We also define (normalized) differential code phase, Δ_{12}, as the difference between the spreading code phases of w_1 and w_2; i.e., $\Delta_{12} = \Delta_1 - \Delta_2$. Without loss of generality, Δ_{12} is modeled as a uniform random variable in the interval $[0, 1)$.

We note that although $c_1(t)c_2(t) \neq c_1(t - t_0)c_2(t - t_0)$, where t_0 denotes some delay, the following equation holds: $\langle c_1(t)c_2(t) \rangle = \langle c_1(t - t_0)c_2(t - t_0) \rangle$. Therefore,

$$\langle c_1(t - t_1; \Delta_1) c_2(t - t_2; \Delta_2) \rangle =$$
$$\langle c_1(t - [t_1 - t_2]; \Delta_{12}) c_2(t) \rangle = \langle c_1(t) c_2(t - [t_2 - t_1]; \Delta_{21}) \rangle. \tag{5}$$

As a starting point, we make the assumption that users are synchronized, in other words, $\Delta_1 = \Delta_2$, that is, $\Delta_{12} = 0$. The general case, where Δ_{12} is a uniform random variable in the region $[0, 1)$, will be addressed at the end of this section.

A. Dependence of Correlation Coefficient on Propagation Delays

Equation (5) can be used to simplify n_{1I} and n_{1II}, defined by (2) and (3), as

$$n_{1I} = \langle c_1(t - t_{12I}) c_2(t) \rangle, \quad n_{1II} = \langle c_1(t - t_{12II}) c_2(t) \rangle, \tag{6}$$

where,

$$t_{12I} = t_{1I,t} - t_{2I,t} = (t_{1I} + t_{I,c}) - (t_{2I} + t_{I,c}) = t_{1I} - t_{2I}, \tag{7}$$

$$t_{12II} = t_{1II,t} - t_{2II,t} =$$
$$(t_{1II} + t_{II,c}) - (t_{2II} + t_{II,c}) = t_{1II} - t_{2II}. \tag{8}$$

It is observed from (7) and (8) that t_{12I} and t_{12II} depend only on the propagation delays in the air.

Without loss of generality we will first assume that $0 \leq t_{12I} \leq \tau$; we will consider the most general case later in this section. Now, n_{1I} can be computed as

$$n_{1I} = \sum_{k=0}^{N-1} \left[(\tau - t_{12I}) c_{1,k}\, c_{2,k} + t_{12I}\, c_{1,k}\, c_{2,k+1} \right]. \tag{9}$$

We assume that $\{c_{ik}\}$ are independent identically distributed equi-probable Bernoulli random variables with values equal to ± 1. With this assumption, it is easy to show that

$$\mathbf{E}(n_{1I}) = 0, \qquad \mathbf{E}(n_{1I}^2) = N\left((\tau - t_{12I})^2 + t_{12I}^2 \right). \tag{10}$$

It is observed from (9) that in order for n_{1I} and n_{1II} to be correlated, n_{1II} should have components in the form of $c_{1k}\, c_{2k}$ and/or $c_{1k}\, c_{2,k+1}$. It is not difficult to show that for $t_{12II} < -\tau$ or $t_{12II} > 2\tau$, n_{1II} does not have such components. We will investigate the remaining range for t_{12II} in three intervals, namely, $-\tau \le t_{12II} \le 0$, $0 \le t_{12II} \le \tau$, and $\tau \le t_{12II} \le 2\tau$.

If $-\tau \le t_{12II} \le 0$, then it can be shown that

$$n_{1II} = \sum_{k=0}^{N-1} \left[-t_{12II}\, c_{1,k}\, c_{2,k-1} + (t_{12II} + \tau) c_{1,k}\, c_{2,k}\right]. \quad (11)$$

The mean and variance of n_{1II} are found as

$$\mathbf{E}(n_{1II}) = 0, \quad \mathbf{E}(n_{1II}^2) = N\left((t_{12II} + \tau)^2 + t_{12II}^2\right). \quad (12)$$

Now, using (9) and (11), the correlation, $\mathbf{E}(n_{1I}\, n_{1II})$, can be computed as

$$\mathbf{E}(n_{1I}\, n_{1II}) = N(\tau - t_{12I})(t_{12II} + \tau). \quad (13)$$

Substituting (10), (12), and (13), in (4), ρ is obtained as

$$\rho = \frac{(\tau - t_{12I})(t_{12II} + \tau)}{\sqrt{(\tau - t_{12I})^2 + t_{12I}^2}\,\sqrt{t_{12II}^2 + (t_{12II} + \tau)^2}}. \quad (14)$$

The calculations are similar for the other intervals and omitted here.

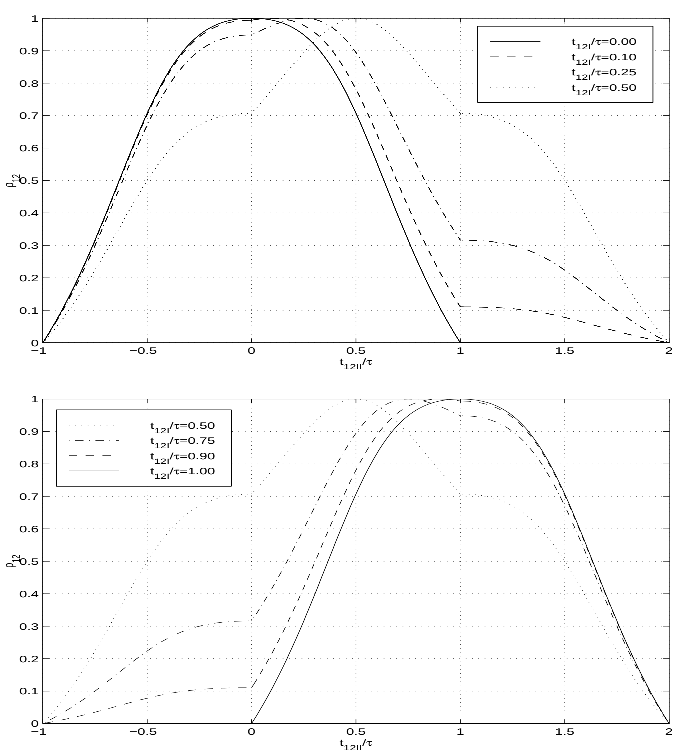

Figure 4: Correlation coefficient as a function of t_{12II}, for various values of t_{12I}/τ, for synchronous users ($\Delta_{12}=0$).

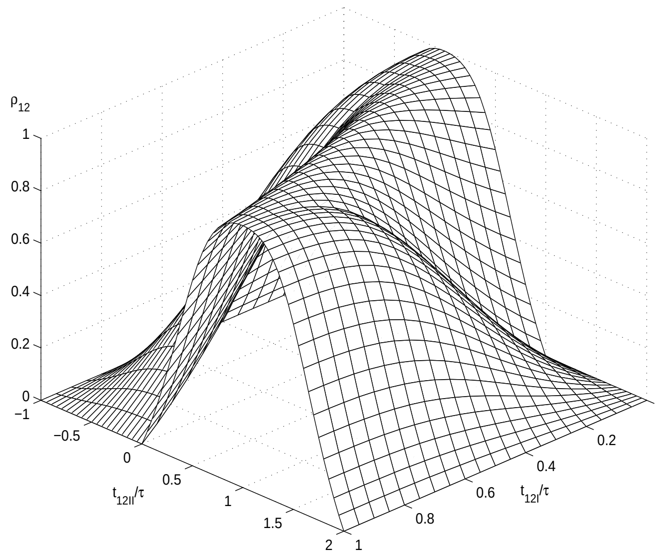

Figure 5: Correlation coefficient as a function of t_{12I} and t_{12II}, for $0 \le t_{12I} \le \tau$ and $-\tau \le t_{12II} \le 2\tau$, for the case of synchronous users ($\Delta_{12}=0$).

ρ is plotted for various values of t_{12I}, in the range of $[0, \tau]$, in Fig. 4. As it is already discussed, if $0 < t_{12I} < \tau$ then the range of t_{12II} for nonzero ρ is $(-\tau, 2\tau)$. Also, the 3-dimensional plot of ρ in the analyzed intervals of $0 \le t_{12I} \le \tau$, and $-\tau \le t_{12II} \le 2\tau$ is shown in Fig. 5. We note that in Fig. 5, the intersection of the vertical ρ–t_{12II} plane with the 3-dimensional plot at certain values of t_{12I} yield the curves shown in Fig. 4.

The results obtained so far for the case of $0 \le t_{12I} \le \tau$, can be generalized for t_{12I} values in any interval. In Fig. 6, the general expression for ρ is plotted with respect to t_{12I} and t_{12II} [4].

It is observed from Fig. 6 that

$$\begin{aligned} & t_{12I} = n\tau \quad \longrightarrow \\ & \begin{cases} \rho = 0, & \text{for } t_{12II} \le (n-1)\tau \text{ and } t_{12II} \ge (n+1)\tau \\ 0 < \rho \le 1, & \text{for } (n-1)\tau < t_{12II} < (n+1)\tau, \end{cases} \\ & n\tau < t_{12I} < (n+1)\tau \quad \longrightarrow \\ & \begin{cases} \rho = 0, & \text{for } t_{12II} \le (n-1)\tau \text{ and } t_{12II} \ge (n+2)\tau \\ 0 < \rho \le 1, & \text{for } (n-1)\tau < t_{12II} < (n+2)\tau, \end{cases} \end{aligned} \quad (15)$$

where n is an integer.

B. Dependence of Correlation Coefficient on User and AE Locations

Our goal in this section is to find the region for w_2 which will result in a non-zero ρ, for a given set of AE and w_1 locations. The time domain requirements for this region is already known from (15). Therefore, the task is to find the equivalent of (15) in terms of distance.

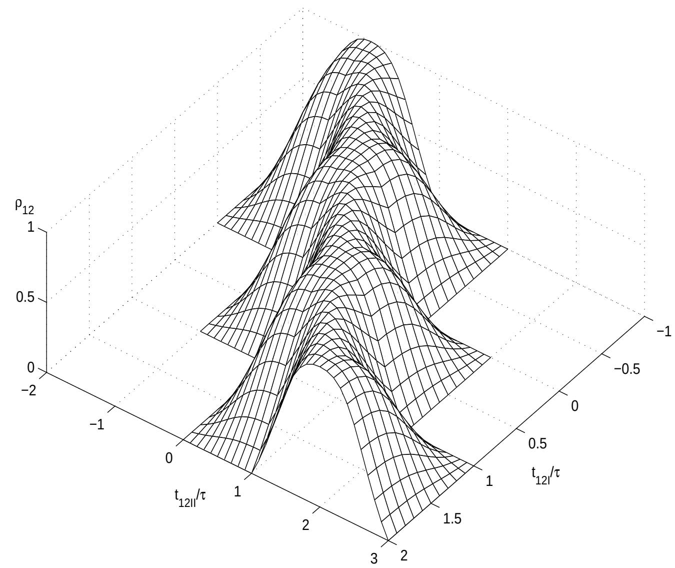

Figure 6: Correlation coefficient as a function of t_{12I} and t_{12II}, for the case of synchronous users ($\Delta_{12}=0$).

As it is well known, the propagation time, t, depends on the distance, d, as $t = d/c$, where c is the speed of light which will be taken as 3×10^8 m/sec. Therefore, from (7) and (8), t_{12I} and t_{12II} can be stated in terms of distances as

$$t_{12I} = (d_{1I} - d_{2I})/c, \qquad t_{12II} = (d_{1II} - d_{2II})/c, \quad (16)$$

where d_{ij} is the distance between w_i and AE j, $i \in \{1,2\}$, $j \in \{I, II\}$.

We will work on a unit square area with side 1 meter. Distances in this unit service area will be denoted by h. In other words, h is the normalized distance which is related to the actual distance, d, as

$$d = h\,s, \quad (17)$$

where s is the scaling factor. For instance, if $s=500$, this means that the service area has the shape of a square with side length 500 meters. Also, we define the chip rate, R_c, as $R_c = 1/\tau$.

We will first find the region corresponding to $n\tau < t_{12I} < (n+1)\tau$. This region is a function of the locations of w_1 and w_2, and AE I (but, not AE II). Then, we will find the region corresponding to $(n–1)\tau < t_{12II} < (n+2)\tau$, which is a function of the locations of w_1 and w_2, and AE II (but, not AE I).

We start by analyzing the $n=0$ case. Using (16) and (17), we can write

$$0 < t_{12I} = t_{1I} - t_{2I} < \tau \;\longrightarrow\; 0 < (h_{1I} - h_{2I}) < c\tau/s,$$

$$-\tau \;<\; t_{12II} = t_{1II} - t_{2II} \;<\; 2\tau \;\;\longrightarrow$$

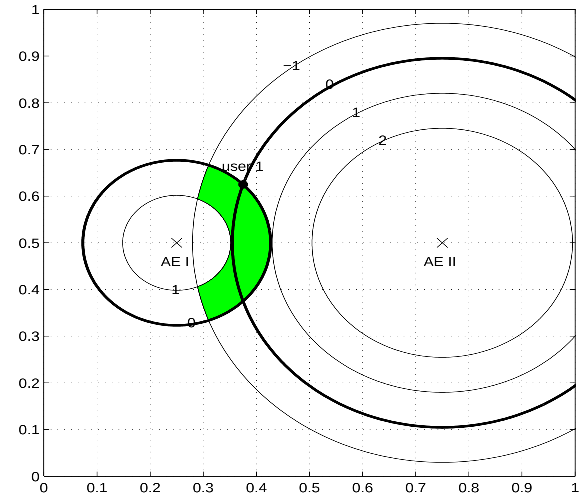

Figure 7: For the case of synchronous users ($\Delta_{12}=0$), the shaded area shows the following region: $0 < (h_{1I} - h_{2I}) < 0.075$ and $-0.075 < (h_{1II} - h_{2II}) < 0.15$ ($s = 400$ and $R_c = 10$ Mcps).

$$-c\tau/s \;<\; (h_{1II} - h_{2II}) \;<\; 2c\tau/s. \quad (18)$$

It is observed from (15) that the intersection of these two regions yields the non-zero ρ region for w_2, for $n = 0$. In a similar way, the corresponding regions for other n values can also be found. We call the union of all such regions the *caution zone* for w_1; because, the interference resulting from a user in this zone, at the Ist branch of w_1's combiner at the CS, will be correlated with the corresponding interference at the IInd branch.

As an example, we consider a system with $s=400$ and $R_c = 10$ Mcps (Mega chips/sec). Then, $c\tau/s = 0.075$. We assume that AE's I, II, and w_1 are placed at the coordinates (.25,.5), (.75,.5), and (.375,.625), respectively, on the unit service area. The intersection of the regions given in (18) is depicted in Fig. 7. The integers on the circles in Fig. 7 indicate the $(t_{1I}–t_{2I})/\tau$ and $(t_{1II}–t_{2II})/\tau$ values for any w_2 location on those circles.

Similarly, using (15), (16) and (17), the corresponding regions for other n values can also be found. We realize that for $n \geq 1$, the conditions given in (18) do not yield an overlapping region. In Fig. 8 the *caution zone* for w_1 is shown, which is the union of the regions corresponding to $n=-6, -5, \cdots, 0$.

It can be shown that, for the case of asynchronous users, (15) can be modified accordingly [4]. In Fig. 9, the *caution zone* for w_1 is shown for the case of $\Delta_{12} = 0.5$.

III. APPROXIMATION OF THE CAUTION ZONES

We start by defining the differential delay, $\Delta t_{12,I–II}$, as

$$\Delta t_{12,I–II} \;=\; t_{12I} - t_{12II} \;=\; (t_{1I}–t_{2I}) - (t_{1II}–t_{2II}), \;(19)$$

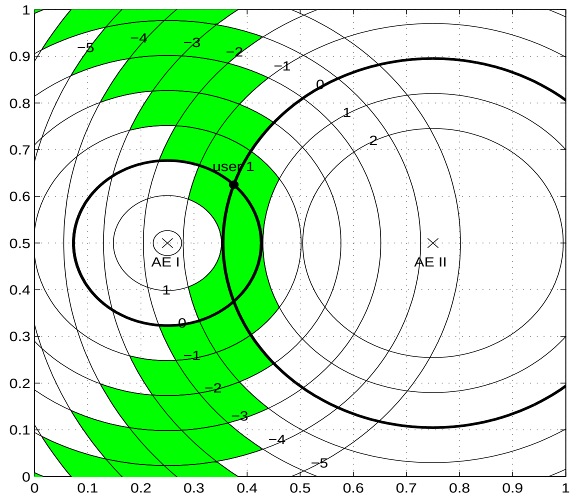

Figure 8: The *caution zone* for w_1 ($s = 400$ and $R_c = 10$ Mcps), for the case of synchronous users ($\Delta_{12} = 0$).

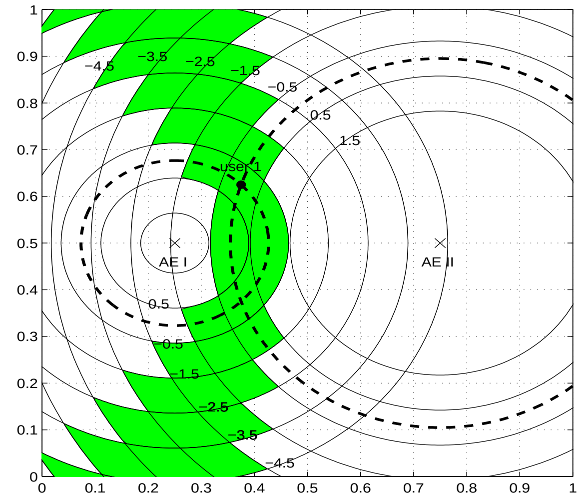

Figure 9: The *caution zone* for w_1 ($s = 400$ and $R_c = 10$ Mcps), for the case of asynchronous users ($\Delta_{12} = 0.5$).

which can be rewritten as $\Delta t_{12,I\text{–}II} = (t_{1I} - t_{1II}) - (t_{2I} - t_{2II})$. We note from (19) that $\Delta t_{12,I\text{–}II}$ is independent of the differential code phase, Δ_{12}, that is, $\Delta t_{12,I\text{–}II}$ is the same for both synchronous and asynchronous users.

We notice from (15) that ρ depends on the actual values of t_{12I} and t_{12II}, rather than their difference, $\Delta t_{12,I\text{–}II}$. In fact, it is observed from Fig. 6 that ρ exhibits periodicity with respect to $\Delta t_{12,I\text{–}II}$ when $-2\tau < \Delta t_{12,I\text{–}II} < 2\tau$. The correlation analysis would have been much simpler if ρ were constant (rather than being periodic) with respect to $\Delta t_{12,I\text{–}II}$. In that case, a (2-dimensional) plot of ρ, as a function of $\Delta t_{12,I\text{–}II}$ would have been sufficient.

Let us investigate the dependence of ρ on $\Delta t_{12,I\text{–}II}$ more closely. It is clear from Fig.s 4-6 that $t_{12I} = t_{12II}$ corresponds to the worst case and $|t_{12I} - t_{12II}| > 2\tau$ guarantees the uncorrelatedness. In other words, it can be stated using (19) that

$$|\Delta t_{12,I\text{–}II}|/\tau = 0 \quad\longrightarrow\quad \rho = 1, \tag{20}$$

$$|\Delta t_{12,I\text{–}II}|/\tau \geq 2 \quad\longrightarrow\quad \rho = 0. \tag{21}$$

One other important observation from Fig. 4 is that

$$1 \leq |\Delta t_{12,I\text{–}II}|/\tau < 2 \quad\longrightarrow\quad 0 \leq \rho \leq 0.5. \tag{22}$$

Obviously, it is desirable to have $\rho = 0$. However, it is important to note that even in the case of a ρ very close to unity, analytically there would still be some gain from diversity combining, although this gain would be minuscule. Even in the limiting case of $\rho = 1$, although there would be no gain from diversity combining, there would be no harm either. In a practical system, however, there are other factors to be taken into consideration besides SIR. If ρ is close to unity, the insignificant returns in SIR would not justify the increased processing, complexity, and thus, cost.

It would be efficient if a threshold value for ρ is determined, say ρ_o, such that it can be argued that if $0 \leq \rho \leq \rho_o$, then there would be benefit from diversity, however, if $\rho_o < \rho \leq 1$, then practically there would not be much gain from diversity. We note that in order for the output SIR in an MRC to be the sum of the branch SIR's, ρ should be equal to 0. Therefore, for $\rho = \rho_o$, as described above, the output SIR will be less than the sum of the branch SIR's.

We choose a conservative value for ρ_o: $\rho_o = 0.5$. Based on (20) and (22), setting ρ_o to 0.5 is equivalent to the following inequality:

$$|\Delta t_{12,I\text{–}II}|/\tau > 1. \tag{23}$$

It is obvious from the discussion so far that $|\Delta t_{12,I\text{–}II}|/\tau$ is a critical quantity in the correlation analysis.

Fig. 10 shows the $\Delta t_{12,I\text{–}II}/\tau = -2, -1, 0, 1,$ and 2 lines along with the caution zone for $\Delta_{12} = 0$, respectively, for the example case ($s = 400$, $R_c = 10$ Mcps). For any $\Delta_{12} \neq 0$ value, these lines will still be the same [4]. Fig. 10 is in conformity with (21), in other words, $\rho = 0$ for $\Delta t_{12,I\text{–}II}/\tau > 2$. Also from Fig. 10, (19) is confirmed, that is, $\Delta t_{12,I\text{–}II}/\tau$ does not depend on Δ_{12}.

The implication of (23) is that the caution zone (the shaded area) in Fig. 10 can be approximated by the area between the $\Delta t_{12,I\text{–}II}/\tau = -1$ and 1 lines. We know from (22) that ρ is less than 0.5 in the shaded regions outside the approximated caution zones, therefore, the performance degradation introduced by such an approximation is expected to be insignificant.

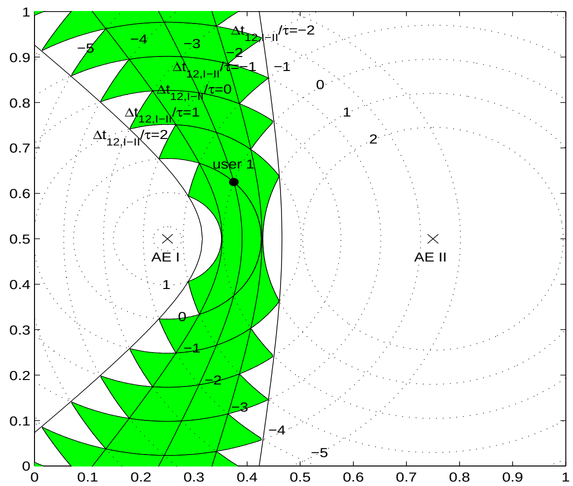

Figure 10: The $\Delta t_{12,I\text{–}II}/\tau = -2, -1, 0, 1,$ and 2 lines along with the caution zone for w_1, for the case of synchronous users ($\Delta_{12}=0$), with $s=400$ and $R_c=10$ Mcps.

Note that $\Delta t_{12,I\text{–}II}/\tau=-1$ and 1 lines are hyperbolas. If we draw all the hyperbolas for which $\Delta t_{12,I\text{–}II}/\tau$ is an integer, then we construct an *hyperbolic grid*. The "origin" of the hyperbolic grid is the hyperbola on which w_1 is located.

IV. THE EFFECTS OF SYSTEM PARAMETERS ON THE CAUTION ZONE

From (17) and (19), $|\Delta t_{12,I\text{–}II}|/\tau$ can be written as

$$\frac{|\Delta t_{12,I\text{–}II}|}{\tau} = \frac{sR_c}{c}|(h_{1I}-h_{1II}) - (h_{2I}-h_{2II})|. \qquad (24)$$

In the right hand side of (24), c is a constant, and h_{ij}, $i\in\{1,2\}$, $j\in\{I,II\}$, depends on the user and AE locations. Therefore, the product sR_c is the most important system parameter. It is also noticed that for a certain value of the product sR_c, the actual values of s and R_c do not matter. Hence, as long as the correlation analysis is concerned, a system with $s=400$ and $R_c=10$ Mcps is equivalent to the one with $s=1000$ and $R_c=4$ Mcps.

For a large sR_c value, the hyperbolic grid will be denser; in other words, the hyperbolas, for which $[(h_{1I}-h_{1II})-(h_{2I}-h_{2II})]sR_c/c$ is an integer, will be closer to each other. Since the approximate caution zone is the area between the hyperbolas -1 and 1, this area will be smaller. Therefore, it is desirable to have a large sR_c value [4].

The density and orientation of the hyperbolic grid also depend on the AE locations in the service area. For a given sR_c value, the density of the hyperbolic grid will increase with the increasing distance between the AE's. Therefore, to minimize the caution zone (and thus, the correlation effect), AE's must be placed as far apart as possible — an intuitively satisfying result.

V. SUMMARY AND CONCLUDING REMARKS

The objective of this paper was to present a spatial correlated interference analysis in CDMA multi-antenna systems. Towards that end, we analyzed the simplest non-trivial case of $L=2$ with $K=2$, in order to develop some insight into the problem of correlated interference. For this special case, we were able to obtain the correlation coefficient as a function of the distances involved in the service region. Hence, for a given user location, we were able to determine the portions of the service region in which other user(s) would cause correlated interference to the given user; we called this region the caution zone for the given user. We then found an approximate expression (and an approximate caution zone) in simpler terms.

We observed that the caution zone, for a given user, depends on the location of that particular user, as well as the AE locations, service region size, and the chip rate. Increasing the chip rate, and placing the AE's as far as possible from each other, results in a reduction in the correlation between the interference components at the combiner branches. This implies that for reasonably high chip rates (wideband-CDMA) and for service regions that are not very small, the level of correlation should be low in a system with 2 AE's and many users. Further investigation is required to make similar conclusions for systems with greater numbers of AE's.

This initial analysis may eventually enable us to develop a comprehensive understanding of the benefits of the CDMA multi-antenna systems. Currently, this work is being extended to analyze the most general case of many AE's with many users to answer various questions, such as the optimal number and location of AE's for a given irregular service region.

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