Modeling the Hand-off Mechanism Effect on the In-Cell and Other-Cell Interference of IS-95 Cellular CDMA Networks

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ABSTRACT

The reverse link in-cell and other-cell interference in power controlled cellular CDMA networks determine the reverse link capacity, and thus to a large extent the overall network capacity. A common modeling assumption is that a mobile is power controlled by a sector belonging to a set closest to it (minimum reverse link path-loss sense). However, in an actual IS-95-based system the mobile transmit power is controlled by that among the sectors **in the active set**, which requires the minimum transmit power to meet the reverse link FER requirement. Therefore, the power controlling sectors are not determined solely by reverse link path-loss, but also by system loading and forward link quantities. In this paper we model the reverse link in-cell and other-cell interference, jointly considering reverse link power control and the hand-off mechanism that defines the mobile's active set. This more accurate modeling can lead to improved performance predictions for CDMA networks.

I. INTRODUCTION

In interference limited systems, such as CDMA cellular systems, reverse link capacity is determined by interference levels caused to the serving base stations by all mobile stations located in the same local area and sharing the same frequency spectrum. Unless multi-user detection schemes are employed, tight power control schemes are necessary in order to combat the near-far effect and maximize system capacity. In order to calculate interference and estimate system capacity of power controlled CDMA systems, the concepts of in-cell interference caused by mobile stations power controlled by a sector and other-cell interference caused by mobiles power controlled by all other sectors were introduced in [1]. A common assumption in calculating these interferences is that mobile station transmit power is controlled by a serving sector belonging to a set containing the sectors nearest the mobile (in the minimum reverse link path-loss sense) [2], [3]. This assumption is justified by the argument that in this way, the interference level to all sectors is minimized. This is indeed true [4], [5] provided the effect of cell loading is included in the criterion for selecting the “nearest” cell. The hand-off mechanism of the IS-95 standard [6], combined with the reverse link power control algorithm, was designed to approximate the optimal solution of this interference minimization problem in a decentralized manner and with reasonable exchange of control information between mobiles and base stations. In an actual IS-95-based cellular network the mobile station is power controlled at a specific instant by that base station **belonging to its active set $\mathbf{B_A}$** that requires the minimum mobile transmit power. The active set for each mobile is determined by forward received pilot over interference (E_c/I_0) measurements and a set of thresholds.

In this paper we propose a practical approach to the calculation of in-cell and other-cell reverse link interference of IS-95-based cellular systems, combining forward link based hand-off, cell loading effects, and other system parameters such as maximum mobile transmit power. This model distinguishes between hand-off and the interference minimization power control mechanism, calculating interference in three stages. First, received E_c/I_0 levels and hand-off thresholds are used to calculate the probability distribution of events that different sectors belong in each mobile's active set $\mathbf{B_A}$. Second, conditioned on the above events defining the active set, received reverse link power levels and cell loading information are used to calculate the probability of each of the sectors in the active set power controlling the mobile. This is used in determining the conditional mean in-cell and other-cell interference contributed by the mobile. Third, desired mean in-cell and other-cell interference levels are obtained by averaging conditional means over the probability distribution of all possible active set events, and finally summing up the contributions of all network mobiles.

The paper is organized as follows: Section II describes the system modeling assumptions and the three stages of interference calculation analysis. Section III presents simulation results of the proposed model. Finally, Section IV presents the conclusions.

II. SYSTEM MODEL AND ANALYSIS

Consider an IS-95-based CDMA cellular system with N sectors. A number of mobile stations cause reverse link interference to each CDMA sector. This loading is reflected in the required received signal level (rsl_req$_j$, j=1,…, N) at each sector. This is the minimum necessary received user signal level at a specific sector to meet the reverse link FER requirement, the value of which depends on the noise floor elevation caused by all interfering users. We assume that if a mobile is power controlled by a sector, its received power at that sector is equal to the sector's required received signal level (rsl_req). The required received signal level is considered constant, although it may vary for different sectors. To illustrate, we are interested in calculating the average level of interference caused to each of the base station sectors by a user at location p, as depicted in Figure 1.

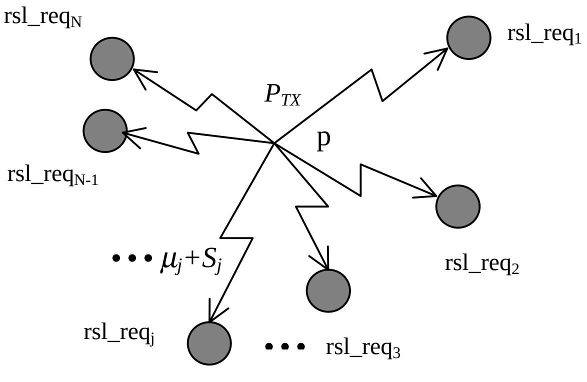

Figure 1: System topology

Transmitted signals are assumed to experience lognormal shadowing in both directions (forward and reverse link shadowing, although identically distributed, are considered independent). The reverse (forward) link path-loss pl_j between location p and each of the sectors j can be represented (in dB) as:

$$pl_j = \mu_j + S_j \tag{1}$$

where μ_j is a constant representing the average path-loss, and S_j is a Gaussian random variable (R.V.) with zero mean and standard deviation σ. The R.V.'s S_j (j=1,…,N) are identically distributed, with correlation depending on the angles formed between pair of lines connecting p and the sectors.

Due to the independence of shadowing in the two links, modeling of the reverse link interference proceeds in three stages, as previously described.

A. Statistical Characterization of the Active Set

The active set $\mathbf{B_A}$ corresponding to each mobile is determined dynamically by using continuous measurements of received pilot over total interference ratios (E_c/I_0) and a set of thresholds (T_ADD, T_DROP, T_COMP, T_TDROP) [6]. We characterize the complex hand-off mechanism statistically by considering a set of random realizations, neglecting the transient part (time dimension). The IS-95 hand-off mechanism is approximated by considering that in every random realization the active set $\mathbf{B_A}$ contains up to three serving sectors with the highest received E_c/I_0 ratios, above a given threshold parameter T_d (T_DROP). We denote $E_{i,j,k}$ ($i,j,k \in \{1,2,\ldots,N\}$, $i \neq j \neq k$), as the event having an active set containing sectors i,j,k. If the active set contains less than three sectors, the remaining indices are set to zero. Also, let $(E_c/I_0)_j$, j=1,…,N denote the R.V.'s expressing the received pilot over total interference power ratio (in dB) of sector j at location p. Lognormal shadowing and constant total forward received power are assumed, thus $(E_c/I_0)_j$ are Gaussian, with mean and standard deviation denoted e_j and σ respectively. The probability distribution of events $E_{i,j,k}$ is then described as follows:

$$P\{E_{i,j,k}\} = P\left\{\begin{array}{c} (E_c/I_0)_i, (E_c/I_0)_j, (E_c/I_0)_k \geq (E_c/I_0)_n, \\ \forall n \in \{1,\ldots,N\} \text{ and} \\ (E_c/I_0)_i, (E_c/I_0)_j, (E_c/I_0)_k \geq T_d \end{array}\right\} \tag{2}$$

The events described in (2) cover all possible combinations of sectors 1,…,N in groups of three (three-way hand-off), as well as cases when one, two, or all three indices are zero (corresponding to two-way, single hand-off, or outage respectively).

B. Conditional Mean Interference

Taking into consideration a mobile station's maximum transmit power (MAX_TX in dBm), we define R.V.'s Q_j (j=1,…,N) to represent the reverse link margin (in dB) observed at location p with respect to sector j as follows:

$$Q_j = \mathrm{MAX\_TX} - \mu_{\mathrm{j}} - S_j - \mathrm{rsl\_req}_{\mathrm{j}} \qquad (3)$$

From definition (3) it can be easily seen that R.V.'s Q_j are Gaussian with standard deviation σ and means

$$\varsigma_j = \mathrm{MAX\_TX} - \mu_{\mathrm{j}} - \mathrm{rsl\_req}_{\mathrm{j}} \qquad (4)$$

In a real system, user mobility prevents the mobile station transmit power from reaching a steady state, thus making the received signal level at the base stations always transient. We assume perfect reverse link power control, and model this dynamic system statistically by considering the ensemble of all random realizations, neglecting in each the transient part of the power control algorithm. We assume that, given the active set $\mathbf{B_A}$, in each random realization of the shadowing R.V.'s S_j "perfect power control" forces a mobile located at p to transmit power $P_{TX} |\mathbf{B_A}$ such that its signal is received at the rsl_req level of that sector belonging to the mobile's active set $\mathbf{B_A}$, which requires the minimum transmit power. If the minimum required transmit power is larger than MAX_TX, we assume that the mobile cannot be supported and its transmit power becomes zero (in mW). Based on the above, the R.V. $P_{TX} |\mathbf{B_A}$ is defined (in dBm) as follows:

$$P_{TX} \,|\, \mathbf{B_A} = \begin{cases} \min\limits_{j \in \mathbf{B_A}} \{\mathrm{MAX\_TX} - Q_j\}, & \text{if } \min\limits_{j \in \mathbf{B_A}} \{\mathrm{MAX\_TX} - Q_j\} \le \mathrm{MAX\_TX} \\ -\infty \quad , & \text{otherwise} \end{cases} \qquad (5)$$

The condition on the right hand side of (5) can be written equivalently as follows:

$$\max_{j \in \mathbf{B_A}} \{Q_j\} \ge 0 \qquad (6)$$

We denote $\mathrm{A_j}$ as the event sector j (j=1,…,N) is power controlling the mobile. Using the above description of the power control mechanism and (6), this event can be expressed as follows:

$$\mathrm{A_j} = \left\{ (j \in \mathbf{B_A}) \text{ and } \left(Q_j = \max_{i \in \mathbf{B_A}} \{Q_i\} \right) \text{and} (Q_j \ge 0) \right\} \qquad (7)$$

The interference caused by a mobile station clearly depends on which sector is power controlling it. If a user is power controlled by a particular sector, it is characterized as an **in-cell interfering user** for that sector, otherwise it is characterized as an **other-cell interfering user.** We determine the number of in-cell and other-cell interfering users, or equivalently the number of in-cell and total number (in-cell+other-cell) of interfering users. The number of other-cell interfering users for a specific sector is expressed with reference to in-cell interfering users. It is defined as the number of equivalent in-cell interfering users that would cause the same level of interference as that caused by all other-cell interfering users. For example, other-cell interfering users equal to one means that all other-cell interfering users cause the same interference level to the sector as one in-cell interfering user. The contributions of a user located at p to the in-cell and total number of interfering users of each sector j (j=1,…,N), given the mobile's active set $\mathbf{B_A}$, are R.V.'s, which we denote with $IC_{\mathrm{j}}^{\mathrm{(p)}}|\mathbf{B_A}$ and $TOT_{\mathrm{j}}^{\mathrm{(p)}}|\mathbf{B_A}$ respectively. Based on the above, these R.V.'s are defined as follows:

$$IC_j^{(p)} |\mathbf{B_A} = \begin{cases} 1, \text{with prob. } P(A_j) \\ 0, \text{with prob. } 1\text{-}P(A_j) \end{cases} \qquad (8)$$

$$TOT_j^{(p)} |\mathbf{B_A} = \begin{cases} 10^{\frac{P_{TX} |\mathbf{B_A} - \mu_j - S_j - rsl\_req_j}{10}} & ,\text{if } \max\limits_{i \in \mathbf{B_A}} \{Q_i\} \ge 0 \\ 0 & , \text{ otherwise} \end{cases} \qquad (9)$$

Considering the definition of the reverse margin (3) and the transmit power $P_{TX} |\mathbf{B_A}$ (5), we can rewrite (9) in a more useful and compact form:

$$TOT_j^{(p)} |\mathbf{B_A} = \begin{cases} 10^{\frac{Q_j - Q_i}{10}} & , \text{with prob.} \, P(A_i) \, , \forall i \in \mathbf{B_A} \\ 0 & , \text{ otherwise} \end{cases} \qquad (10)$$

We are interested in the first moment of R.V.'s $IC_{\mathrm{j}}^{\mathrm{(p)}}|\mathbf{B_A}$ and $TOT_{\mathrm{j}}^{\mathrm{(p)}}|\mathbf{B_A}$ given their definitions in (8) and (10). It is easy to see from (8) that

$$E\{IC_j^{(p)} \mid \mathbf{B_A}\} = P(A_j) \tag{11}$$

The probabilities $P(A_j)$ can be calculated analytically using the distribution of the maximum among a set of Gaussian R.V.'s Q_i , although this can become cumbersome. The analytical calculation of the first moment of $TOT_j^{(p)}|\mathbf{B_A}$ becomes more involved, because although, as it can be seen in (10), $TOT_j^{(p)}|\mathbf{B_A}$ is lognormal conditioned on each of the events A_i , the same R.V.'s Q_j are involved in the calculation of $P(A_i)$ (i=1,…,N) and a simple expression of averaging of the conditional means over the distribution $P(A_i)$ cannot be used. The estimation of both moments, however, can be easily achieved through computer simulation.

C. Average In-Cell and Other-Cell Interference

Having characterized the distribution (2) of events $E_{i,j,k}$ that statistically describes the active set $\mathbf{B_A}$, we can find the unconditional mean interference at sector m contributed by a mobile located at p by averaging over this distribution:

$$\begin{aligned} E\{IC_m^{(p)}\} &= \sum_{i,j,k\in\{0,1,\dots,N\}} E\{IC_m^{(p)} | E_{i,j,k}\}\cdot P\{E_{i,j,k}\} \\ E\{TOT_m^{(p)}\} &= \sum_{i,j,k\in\{0,1,\dots,N\}} E\{TOT_m^{(p)} | E_{i,j,k}\}\cdot P\{E_{i,j,k}\} \end{aligned} \tag{12}$$

To calculate the overall in-cell and other-cell reverse link interference at each sector in the CDMA footprint, we sum contributions of all users weighted by the spatial traffic load distribution.

III. SIMULATION RESULTS

In this section, simulation results of the proposed model are presented. In all cases we consider four (N=4) candidate sectors, and concentrate on the in-cell and other-cell interference caused to sector 1 by one mobile. The lognormal shadowing with respect to all four sectors is assumed uncorrelated, with common standard deviation σ = 7 dB. As shown in Section II, two main groups of quantities determine the level of reverse link interference: the mean received E_c/I_0 (denoted e_j, j=1,2,3,4) at the location of the mobile, and the mean reverse link margins (denoted ζ_j, j=1,2,3,4) observed by the mobile with respect to the four sectors. Several cases are presented with varying e_j, ζ_j levels. Mean received E_c/I_0 levels e_j together with the value of threshold T_d determine the distribution (2) of events $E_{i,j,k}$. Figure 2 demonstrates this, focusing on sector 1.

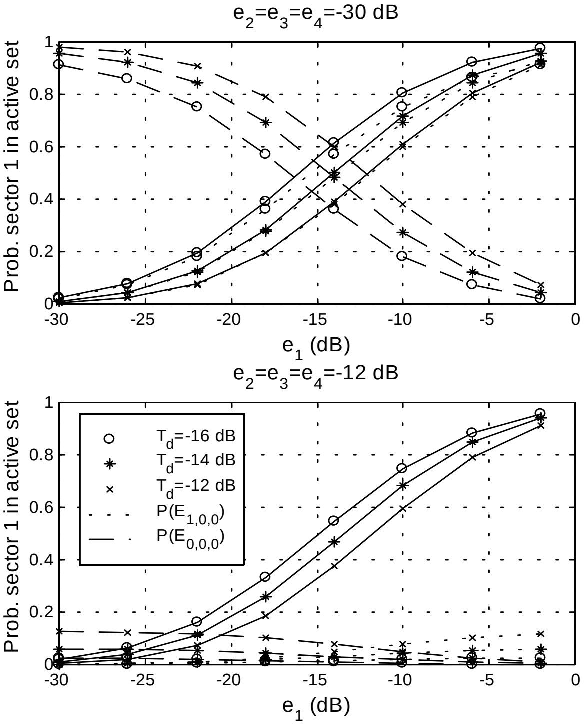

Figure 2: Probability of sector 1 in B_A

The solid lines depict the overall probability of sector 1 being in the active set as a function of e_1 for different thresholds. This probability is the sum of the probabilities of all events including sector 1, i.e. $E_{1,0,0}$, $E_{1,2,0}$, $E_{1,3,0}$, $E_{1,4,0}$, $E_{1,2,3}$, $E_{1,2,4}$, $E_{1,3,4}$. For comparison the probability of the active set containing only sector 1 is plotted with dotted lines and the probability of outage caused by an empty active set with dashed. We note that, as expected, when e_2, e_3, e_4 are much smaller than T_d (top) the event $E_{1,0,0}$ dominates as e_1 increases, while when they are comparable to T_d (bottom), the mobile has a much larger probability of being in soft hand-off, and the probability of event $E_{1,0,0}$ has a much smaller contribution to the overall probability of sector 1 being in $\mathbf{B_A}$. Another interesting remark is that, although in general the probability of sector 1 being in $\mathbf{B_A}$ increases with decreasing T_d, the probability of $E_{1,0,0}$ decreases with decreasing T_d, when e_2 =e_3 =e_4=-12 dB (bottom). This is because as T_d gets lower it becomes more probable that at least one of sectors 2,3,4 will also be in $\mathbf{B_A}$.

Figure 3 depicts the average in-cell (top) and total interference (bottom) caused by a mobile to sector 1 as a function of e_1 for two cases. In the first case all other e_j 's are kept at a low e_x=–30 dB level, which results (see Figure 2 top) in high probability of single hand-off. Thus, the total interference caused by the mobile is almost entirely in-cell. Total interference increases with increasing e_1 (and with decreasing T_d) because the probability of an outage (empty active set) decreases (see Figure 2 top).

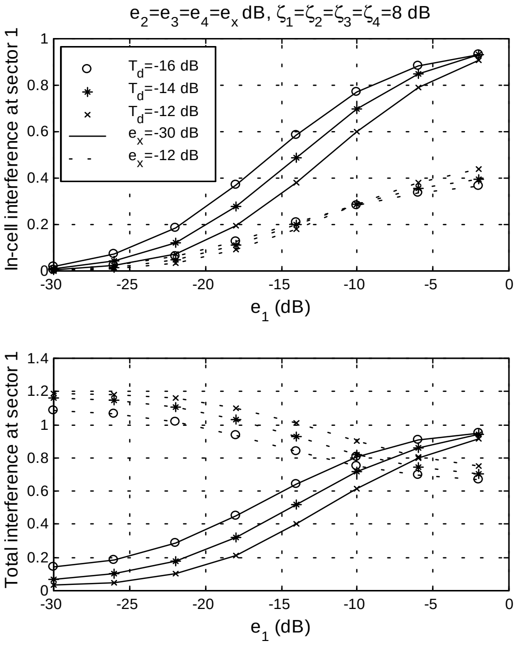

Figure 3: In-cell/total interference of sector 1

In the second case (e_x=–12 dB) the mobile is most likely to be in soft hand-off regardless of e_1. Increasing e_1 (or decreasing T_d) increases the number of sectors eligible of power controlling the mobile, causing the total interference to decrease. Note in Figure 3 (top, dotted lines) that for high e_1, since decreasing T_d makes more sectors besides 1 eligible for power controlling the mobile, the probability of sector 1 power controlling decreases and therefore (11), the in-cell interference of sector 1 as well.

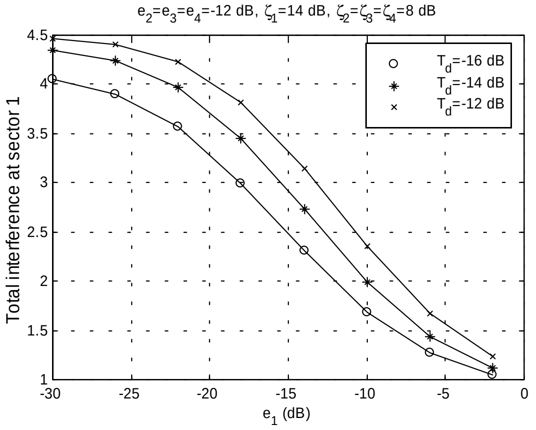

Figure 4: Total interference of sector 1

Importantly, this model can accommodate cases that divert from idealized assumptions. This is illustrated in Figure 3 (bottom, dotted lines) and Figure 4, where, depending on the pilot power settings, a mobile may cause larger than one total interference to sector 1. This is more obvious in Figure 4, where (assuming similar noise floor elevations) a mobile which is “closer” to sector 1 is forced by the pilot power levels to be power controlled by some of sectors 2,3, or 4.

IV. CONCLUSIONS

A new method of modeling reverse link in-cell and other-cell interference in power controlled cellular CDMA networks has been proposed. Reverse link interference is calculated by jointly considering reverse link power control and the hand-off mechanism that defines the mobile’s active set. Simulation results were presented for various combinations of E_c/I_0, threshold levels, and reverse link margins. By more accurately modeling the hand-off mechanism effect on in-cell and other-cell interference of IS-95 based CDMA networks, better performance predictions can be expected.

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