On the Usefulness of Outer-loop Power Control with Successive Interference Cancellation

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Abstract—In this paper we investigate FER-based outer-loop power control for Successive Interference Cancellation. Specifically, we show that for unlimited mobile powers, FER-based outer-loop power control will drive the received powers to the power profile required to achieve equal performance. Further, when we consider power limits for specific mobiles, we find that individual mobile limits will not affect the performance of other signals and based on limited simulation results, the system appears to be stable in the presence of such limits.

I. Introduction

Since the advent of CDMA in commercial wireless systems, the area of multiuser detection has been an area of intense research [1], [2]. One form of sub-optimal multiuser detection, successive interference cancellation or SIC, has received significant attention [3], [4], [5], [6]. One difficulty in the implementation of SIC is that for equal received signal strengths, the BER performance will vary significantly. Power control in current CDMA systems is designed to guarantee equal received power for all signals (and thus equal performance) using a combination of inner-loop and outer-loop power control. To obtain equal performance for all signals with SIC, the received power profile must vary geometrically according to the cancellation order [3], [5], [6], [7]. Creating power control tables which have unequal thresholds to maintain such received power levels using inner-loop power control could be problematic. In this letter we show that FER-based outer-loop power control will provide sufficient control for SIC without using different power control tables and without causing a degradation in SIC performance. Further, using outer-loop control to guarantee BER performance with SIC simply requires a coarse knowledge of the power limits of the mobile. That is, we must use some knowledge of the relative shadow fading and path loss experienced by each mobile to determine cancellation order. This information is available using reported pilot strength measurements. We show that when the power limits are known incorrectly, it affects only the performance of the signal in question but does not cause catastrophic system failure. In the next section, we briefly discuss previous work considering power control with multiuser detection in CDMA systems as well as the proposed power control method. In section III we describe the system model assumed and describe successive interference cancellation. Simulation results are presented in section IV which show the behavior of the average received power and frame error rate when using FER-based outer-loop power control with SIC.

II. Power Control in CDMA

Power control is an extremely important part of current CDMA systems. If multiuser detection is to play a part in commercial CDMA, its interaction with power control must be well understood. Compared to the massive amount of work done on multiuser detection, relatively little work has been done on the interaction between power control and multiuser detection [8], [9], [10], [11], [12], [13]. The combination of power control with the linear MMSE receiver was considered in [8], [9], [10], [11], [12] while [13] considered power control with the linear decorrelator. Further, the impact of power control with SIC on system interference levels was analyzed in [6] although the method of power control was not discussed. All of the approaches considered SINR-based measurements at the base station which were used to determine an optimal power setting for each mobile. This information was then communicated back to the mobile for power adjustment. Essentially, these methods can be considered “outer-loop” techniques since they are aimed at adjusting long-term power to provide an optimal received power distribution between users. This is as opposed to “inner-loop” control which makes fine adjustments to counter Rayleigh fading. None of the studies mentioned were concerned with the effects of inner-loop control and we will likewise ignore this ef-

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fect although it is an important aspect to be considered in future work.

In contrast to these techniques we propose here an FER-based approach for reverse link power control to be used in conjunction with SIC as is currently done with matched filter receivers. Reverse link power control is accomplished by transmitting power control bits on the forward link to the mobile unit which it uses to increase or decrease its transmit power. Simply viewed, each power control group (PCG)[1] the base station receiver estimates E_b/I_o and compares this estimate with an internally saved threshold which is known as the E_b/I_o set-point. If the estimate of E_b/I_o is less than the E_b/I_o set-point, the power control bit is set to zero during the next PCG transmitted on the downlink. Otherwise, it is set to one. The mobile station interprets a zero as a request for more transmit energy, and a one as a request for less. This type of E_b/I_o-based power control is often called "fast power control" since it operates at a rate of up to 800 Hz (in cdma2000) and is intended to combat short-term multipath fading.

What we have described thus far is only the "inner-loop" portion of E_b/I_o-based power control. What happens with the E_b/I_o set-point is referred to as the "outer-loop." In FER-based outer-loop power control, after every frame the base station receiver determines whether it made an error in decoding or not via cyclic redundancy check (CRC) or some other method. If the frame is in error, the base station may raise its set-point by some value. If the frame is not in error, the base station may lower its set-point by some (usually smaller) value. In this manner, a target FER may be maintained. If, for example, a $y\%$ FER is desired, the base should raise its set-point by $+A$ dB when it records an error. The down step a is then given by $a = A \cdot \frac{y}{100-y}$ dB. Over time, this raising and lowering of the set-point is intended to result in the desired target FER. Maintenance of a desired FER is crucial to the capacity of virtually any CDMA system since one mobile station's signal is interference for the rest. This interference ultimately limits system capacity. We will show how this power control method can be used with SIC in the next section.

III. System Model and Analysis

We consider a CDMA system with K active transmitters communicating with a common base station. For ease of analysis we consider a single cell. The received signal at the base station can be expressed as

$$r(t) = \sum_{k=1}^{K} \sqrt{P_k(t)} b_k(t-\tau_k) a_k(t-\tau_k) e^{j\phi_k(t)} + n(t) \tag{1}$$

where P_k is the received power from transmitter k, $b_k(t)$ and $a_k(t)$ are the data and spreading waveforms of the kth signal respectively, τ_k and ϕ_k are the relative delays and phases of each signal with respect to an arbitrary reference, and $n(t)$ is a complex Gaussian random process with variance σ_n^2 and represents thermal noise. The combination of $\sqrt{P_k(t)}e^{j\phi_k(t)}$ is the complex distortion caused by the wireless channel. For the purpose of this investigation we assume that inner-loop power control is perfect, i.e., P_k and ϕ_k are constant over the observation interval. Thus, the effect of fading due to inner-loop power control error is not explicitly considered.

A successive cancellation receiver attempts to detect signals in succession by cancelling each signal from the aggregate received signal after detection [3]. We represent the signal used to detect data from signal k as

$$r^{(k)}(t) = r(t) - \sum_{i=1}^{k-1} \hat{s}_i(t-\tau_i) \tag{2}$$

where $s_i(t) = \sqrt{P_i} b_i(t) a_i(t) e^{j\phi_i}$ and $\hat{s}_i(t)$ are the received signal and the estimate of the received signal from mobile i. In this work we consider a linear receiver in which the estimated signal is a linear transform of the received signal. Specifically, we estimate the received signal as

$$\hat{s}_k(t) = \sum_{m=-\infty}^{\infty} z_{k,m} p_T(t-mT) a_k(t) \tag{3}$$

where $p_T(t)$ is a unit pulse defined on $[0,T)$, $z_{i,m}$ is the projection of the received signal onto the spreading code of signal i after cancellation of signal $i-1$ during the mth symbol interval, i.e.,

$$z_{k,m} = \frac{1}{T} \int_{(m-1)T+\tau_k}^{mT+\tau_k} r^{(k)}(t) a_k^*(t-\tau_k) dt \tag{4}$$

T is the symbol duration and * represents the complex conjugate. Now, if a Gaussian assumption is made on the decision statistic as is commonly done in CDMA system analysis[2] we are interested in the second order statistics of $z_{k,m}$. Namely, we define the SINR for signal k as

$$\Gamma_k = \frac{\mathrm{E}^2 \left\{ \Re\left[z_{k,m}\gamma_k^* \right] \middle| \, b_{k,m} \right\}}{\mathrm{var}\left\{ \Re\left[z_{k,m}\gamma_k^* \right] \middle| \, b_{k,m} \right\}} \tag{5}$$

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[1] A power control group or PCG is equivalent to 1.25ms in IS-95 and cdma2000.

[2] This assumption is commonly made in the case of successive cancellation where it may be less justified than in the case of simple matched filtering [4].

where $\gamma_k = \sqrt{P_k}e^{j\phi_k}$ is obtained from channel estimation process (i.e., the pilot channel). From [7] we can write the SINR of signal k (Γ_k) as

$$\begin{aligned}\Gamma_k \;=\; & \left\{\left[\frac{\sigma_n^2}{P_k} + \frac{\varrho}{N}\sum_{i=2}^{K}\frac{P_i}{P_k}\right]\left(1+\frac{\varrho}{N}\right)^{k-1}\right. \\ & \left. -\frac{\varrho}{N}\sum_{i=2}^{k}\left(1+\frac{\varrho}{N}\right)^{k-i}\frac{P_i}{P_k}\right\}^{-1} \qquad (6)\end{aligned}$$

where ϱ depends on waveform shape and the synchronism between users. Further, it is shown in [7] that the given receiver can provide equal SINR (i.e., $\Gamma = \Gamma_k \forall i$) and thus equal BER if the following power profile is used

$$\boxed{\mathbf{p}_{opt} = \left(\frac{1}{\Gamma}\mathbf{I} - \frac{\varrho}{N}\mathbf{X}\right)^{-1}\beta\sigma^2} \qquad (7)$$

where $\mathbf{p} = [P_1, P_2, \ldots P_k]^T$, $\mathbf{I}$ is a $K \times K$ identity matrix, β is a $K \times 1$ vector with $\left(1+\frac{\varrho}{N}\right)^{i-1}$ as the ith element, $\mathbf{X}$ is a $K \times K$ matrix with $\mathbf{x}_i^T$ as the ith row and $\mathbf{x}_k$ is a $K \times 1$ vector defined as

$$x_{k,m} = \begin{cases} 0 & m = 1 \\ \left(1+\frac{\varrho}{N}\right)^{k-1} - \left(1+\frac{\varrho}{N}\right)^{k-m} & m \le k \\ \left(1+\frac{\varrho}{N}\right)^{k-1} & m > k \end{cases} \qquad (8)$$

This power profile is shown in Figure 1 for $K = 10$, $N = 31$, $\varrho = \frac{1}{2}$, and $\Gamma = 6$dB. Note that this profile makes no assumptions about perfect cancellation. We can see that each signal requires a different received power to obtain equal BER based on cancellation order. User 10 requires the least power since it is cancelled last (i.e., it receives the most benefit from cancellation). User 1requires the most power since it is cancelled first and benefits the least from cancellation.

Thus, we could use the above values[3] to directly set the E_b/I_o set-point for the inner power control loop in order to provide equal BER. This would require power control tables for each cancellation slot and each number of total signals and SIR. However, as we will show, a better approach would be to use a generic set of values as a starting point and let the outer-loop control the set-points. Provided that all mobiles have sufficient power, the outer-loop will guarantee equal FER. Thus, the most obvious strategy is to assign those signals which have the larger fade margins[4] to the early cancellation slots and those with the smaller fade margins to the later cancellation slots. Such a scheme would have the added benefit of producing lower out-of-cell interference as discussed in [6]. The initial received energy estimate need not be perfect just simply close and can be obtained using pilot strength measurements. Specifically, for handoff purposes, the mobile reports measured pilot levels. This information could also be used for cancellation ordering. The FER-based outer loop would then drive the set-point to obtain the desired profile as we will show. The inner-loop can use standard energy or E_b/I_o measurements along with the current set-point to combat fading. Note that since the measurements are performed after cancellation of users earlier in the cancellation process, they will provide estimates consistent with the specific cancellation slot.

IV. Results

Simulations were run using the above SIC receiver design along with FER-based outer-loop power control as described above. It was assumed that inner-loop power control was perfect and that the system was synchronous with random phases and random spreading codes. The outer-loop used a step size of 0.3dB per frame error. Coding was not used and frame errors were defined as the event where any one of the bits in the frame was in error. The frame size considered was 50 bits. Since coding was not used the target FER considered was fairly high at 12% which corresponds to approximately a 0.2% BER. These simulations focused on a spreading gain of $N = 64$ and $K = 10$ signals. It can be shown that this BER requires an SINR of 6dB.

Figure 1 presents the average received power for each of the 10 signals in the system when no power limits are placed on the mobiles. The predicted normalized power from equation (7) with an SINR $\Gamma = 6$dB is also plotted. Note that signals are ordered according to decreasing received power which is also the cancellation order. All signals obtained the target 12% frame error rate. Thus, the outer-loop was stable and the prediction from (7) provided a good estimate of the required receive power. The outer-loop power control did indeed drive the mobile powers to the optimal power profile to achieve the target FER. The main assumption here is that all mobiles have sufficient power for the cancellation slot they are assigned. However, this requires intelligent assignment of cancellation order. If the first signal in the cancellation order corresponds to the signal furthest from the base station, not only will it result in more out-of-cell interference [6], but it is possible that the signal would have insufficient power to achieve its target. A coarse knowledge is available from pilot measurements as mentioned.

To determine the effect that power limits (i.e., incorrect cancellation order) would have on the receiver

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[3] The exact levels would have to be adjusted for the number of fingers and would be dependent on the measurements being used for power control at the base station.

[4] Fade margin is inversely related to the total path loss and shadow fading experienced by the mobile.

performance we ran simulations in which some mobiles are limited in their transmit power. In the first secenario (Limit 1), signal 4 is limited to a normalized received power (i.e., $\sigma_n^2 = 1$) of 4.4. As we can see from Figure 2 (plots denoted by 'o'), this prevents signal 4 from achieving its target FER since the power limit is below that necessary for the assigned cancellation slot. If that signal were assigned to the first cancellation slot, it would have achieved the target FER. Of further interest is the effect that the power-limited signal has on those signals which are cancelled before and after it. Signals cancelled before the power-limited signal (#1-3) benefit in that they see less interference power (due to the lower received power of signal 4) and thus can transmit less power and still achieve the target FER. Signals which are cancelled after the power-limited signal are unaffected by the increased error rate and the lower received power. The effect of higher error rate (which increases interference) is offset by the lower received power (which decreases interference).

In Limit 2 (Figure 2, plots denoted by □), signals 9 and 10 are limited to a normalized value of 3. These signals cannot reach the FER target but the others signals are not affected. Since these are the last two signals cancelled, the limits have the effect of reducing the necessary transmit power required for the signals cancelled before them. A more serious potential problem is a limit on the first two signals cancelled as shown in Figure 2 (Limit 3 - plots denoted by 'x'). Here it is anticipated that since the first two signals will not achieve their target FER, they will not be cancelled properly and will thus introduce more interference to those signals cancelled afterwards due to error propagation. However, since they are power limited, their effect is both increased (due to inaccurate cancellation) and decreased (due to reduced power). The net effect is that the signals cancelled afterward require essentially the same receive power as without the limits. The receiver with SIC and power control is thus fairly robust. The main problem then with inaccurate ordering is (1) the performance of the mobile in question may be degraded (i.e., it may not achieve target) and (2) the system creates larger out-of-cell interference than with proper ordering.

As a last example, Figure 2 (denoted by '*'), plots the average received power and the achieved frame error rate for the power limits of [7,6.5,6.3,6,5.6,5.4,5.2,4.7,4.6,4.4]. This essentially represents an ordering which is the opposite of the optimal ordering scheme since the more limited signals are cancelled first and the less limited signals are cancelled last. Again, we see that signals which are power-limited cannot reach their target FER, but they do not have an adverse effect on the other signals in the system. This suggests that the SIC receiver with outer-loop power control is fairly robust. The base station need not specify separate fine-tuned threshold tables for each cancellation situation in order for SIC to be effective. Instead, the base station simply needs to have a rough idea of the relative shadow fading and path loss (as a gauge to the relative power limits of the mobiles) in order to make an ordering assignment. This can be gauged by using pilot strength measurements. Further, if a particular signal is not meeting its FER target, it can be moved down in the cancellation order to improve its performance based on its power limit. This order control can be done at a much slower rate to combat long term fading changes. System software can detect high FER values and instruct the base station to move the signal down in the cancellation order.

V. Conclusions

In this paper we have shown that FER-based outer-loop power control can be used with successive interference cancellation to provide stable error rate performance without having sophisticated power threshold tables. Further it was shown that the effect of making errors in the assignment of cancellation order does not have an adverse effect on the whole system. Rather it effects only the signal which is limited. This effect can be detected at the base station by monitoring FER and making corrections in the cancellation order. Future work should investigate the impact of power control errors, conduct more sophisticated stability analysis and investigate algorithms for changing the cancellation order.

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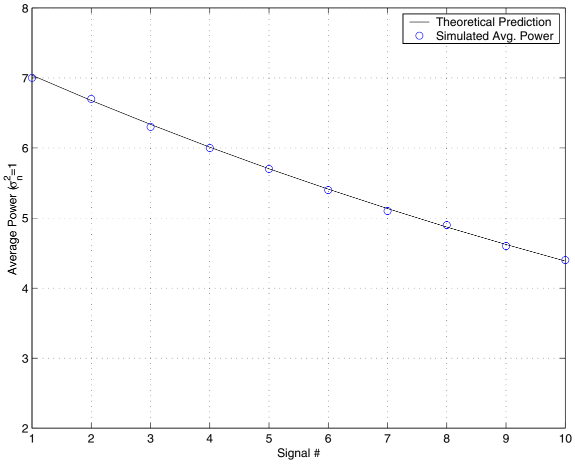

Fig. 1. Simulated and Theoretical Normalized ($\sigma_n^2 = 1$) Received Powers for 12% Target FER using FER-based Outer-Loop Power Control with SIC (perfect inner-loop power control is assumed)

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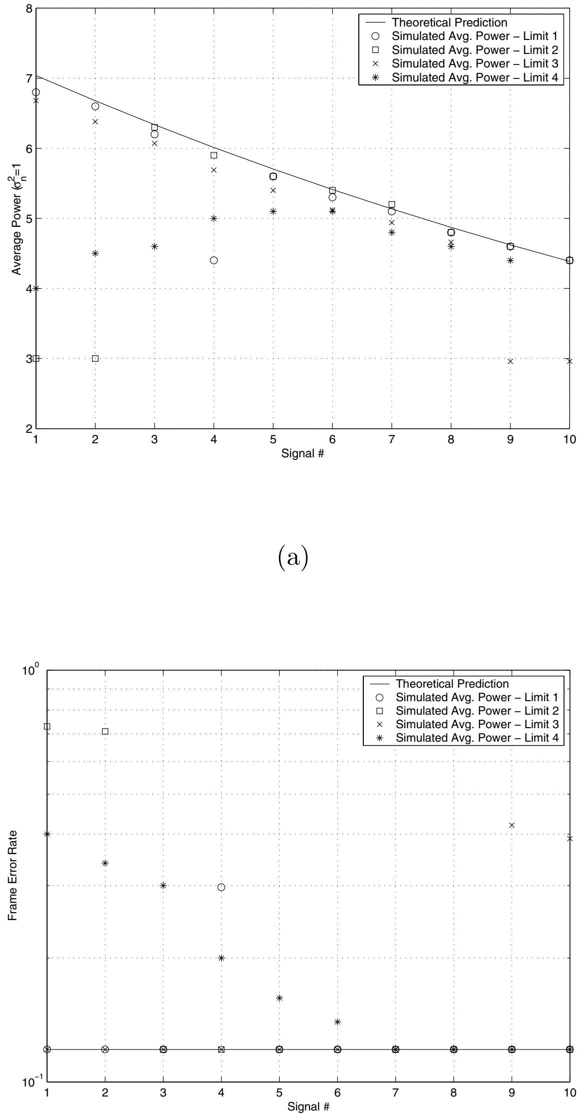

(a)

(b)

Fig. 2. Simulated and Theoretical Normalized ($\sigma_n^2 =$ 1) Received Powers (a) and Resulting FER (b) for 12% Target FER using FER-based Outer-Loop Power Control with SIC and Various Power Limits (perfect inner-loop power control)