Power Control for Code Division Multiple Access Cellular Systems

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Cellular systems based on code division multiple access (CDMA) are being proposed as candidates for an international cellular system. CDMA systems capacity is known to be interference limited. Reducing the interference results in a direct increase in the system capacity. Power control is the most important requirement to reduce the interference. In this work, we show how power control is implemented in current cellular CDMA systems using an inner loop (which consists of an open loop and a closed loop) and an outer loop algorithms. The efficiency of the power control algorithm is then investigated for different mobile velocities. Finally, we look at the power control algorithms from a system point of view. Power balancing and SIR balancing are introduced for macrodiversity systems.

1. Introduction

Power control in the reverse link (from mobile to base station) is essential for overcoming the near-far problem. Independent simultaneous transmissions by users at different locations in a cell give rise to the near-far problem: here the received signal from the desired user is masked by the signals received from users much closer to the receiver. In the limit, the desired user's signal becomes undetectable. To maximise the number of users that a spread spectrum system can support, a form of power control is required to ensure equal levels of received signals from different multiple transmitters at different locations. The received signal level changes depending on the distance, the shadowing, and the multipath fading between the mobile and the base station. A power control algorithm that eliminates the effect of these three parameters on the signal level is said to be perfect. The power control algorithm is divided into two loops: inner loop and outer loop.

2. Inner Loop Power Control

The inner loop power control itself is divided into open loop power control and closed loop power control.

2.1 Reverse Link Open Loop Power Control (OLPC)

Variations in the signal level due to distance and shadowing are not frequency dependent, but rather location dependent. Hence, these variations are reciprocal on both the forward (from base station to mobile) and the reverse links. A mobile can eliminate the variations due to distance and shadowing by measuring the average received signal on the forward link and adjusting its power accordingly. Averaging eliminates variations due to multipath fading. This is called open loop power control. The reception of a strong signal by the mobile indicates that the mobile is either close to the base station or has good propagation conditions to the base station. This means that less mobile power is needed to produce a nominal received power at the base station. In the case of a sudden improvement (degradation) in the channel, the OLPC mechanism adjusts the mobile power downward (upward) and thus prevents the mobile power from being too high (low) at the base station. The OLPC is analog in nature and should provide a very rapid response over a period of a few milliseconds.

2.2 Reverse Link Closed Loop Power Control (CLPC)

In a cellular system, full duplex transmission is provided by using one frequency band from the mobile to the base station and another frequency band from the base station to the mobile. These two frequencies are separated by 45 MHz in the current AMPS system to prevent interference from the transmitter into the receiver. This 45 MHz separation is much larger than the coherence bandwidth of the channel, which makes the forward and the revere links fade independently. Hence, multipath fading on the reverse link can not be estimated by the mobile. To account for this independence, the mobile transmitter power is also controlled by the base station. The base station measures the signal received from the mobile, compares it with a desired threshold and then sends a command to the mobile asking it either to decrease or increase its power. Usually a one bit command is sent periodically to adjust the power level by a fixed amount. The power control step size is usually in dB units. In addition to reducing interference, PC on the reverse link saves mobile power and hence increases battery lifetime. Most of the time propagation conditions are benign and the mobile can lower its transmitted power. Reducing the transmitted power also reduces health hazards.

3. Reverse link feedback model

Figure 1 shows a model for closed loop power control that is used to the power control on the reverse link [3]. From this figure, we can identify the parameters that affect the performance of the power control algorithm. An important parameter is the channel variation which is determined by the channel Doppler rate (mobile velocity) and the number of resolvable fading paths between the mobile and the base station. When the mobile is moving fast, it will be hard for the PC algorithm to track the fast fading changes in the channel. Also, when the number of resolvable paths is large, it would be impractical to use a large number of correlators in each receiver to capture all the signal energy. If the average number of paths exceeds the number of correlators used, the signal power captured by a user's receiver will be less than the amount of interference that the user causes for other users.

Another parameter is the power control rate ($1/Tp$). The power control rate should be fast compared to the rate of change in the channel, but if it is too fast, then it will track multipath fading perfectly. The results in [3] show that controlling the transmitted power instantaneously actually results in a lower SIR. This is because the signal from the desired user might go into deep fades, and equalising the received power requires transmitting a high power which

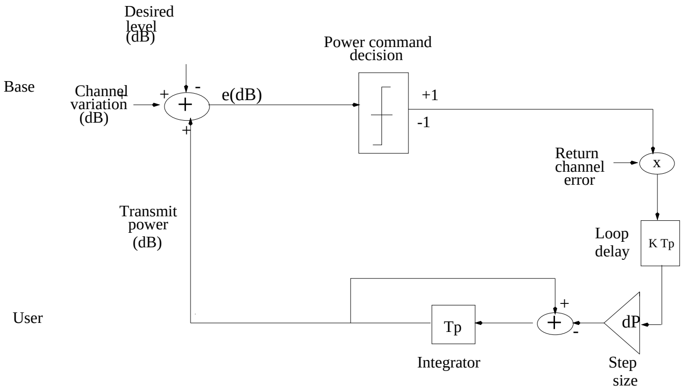

Figure 1: Feedback power control model

causes high interference at other base stations. The power control command rate in IS-95 standard is 800 corrections per second. This rate is also used in the North American proposal for 3G cellular system (cdma2000). In the European proposal, this rate is increased to 1600 power commands/sec. Because this is a fast control mechanism, PC becomes almost perfect for slow users.

However, the errors in the received powers from fast users are known to follow a lognormal distribution with a standard deviation that is a function of the mobile's velocity [3]. The lognormal distribution of errors is expected because the power adjustments are constant steps in dB units. In metropolitan areas, a large proportions of users are expected to be pedestrians.

Another parameter is the return channel error. The power control command is assumed to be uncoded, since the usual long delay associated with coding/interleaving is inconsistent with the need for fast power control. Usually this error is assumed to be 10% [3]. This error becomes higher during soft handoff and usually the power control commands will be sent with a higher power level compared to the data bits to give them extra protection.

Figure 1 also includes the possibility of extra loop delay ($K\,T_p$), where K is an integer which accounts for the two-way signal propagation delay and the time delay involved in generating, transmitting and executing a power control command. This delay undermines the fast tracking requirement and prediction techniques were proposed to eliminate it.

4. Outer Loop Power Control

In the above, we have assumed the target used for issuing the power control commands to be the signal strength. This is called signal strength based power control. In reality, it is the signal to interference ratio (SIR) that determines the quality of the communication channel. Thus, there is another category of power control algorithms that are based on SIR target. SIR target is the one used in 3G

Table 1: Standard deviation determined from lognormal fitting of signal power after power control for a user communicating with the desired base station and a user communicating with a different base station.

	$M = 2$		$M = 3$		$M = 4$	
V(Km/h)	σ_s dB	σ_o dB	σ_s dB	σ_o dB	σ_s dB	σ_o dB
5	0.35	4.90	0.33	3.90	0.31	3.10
10	0.67	4.75	0.43	3.81	0.37	3.07
15	1.0	4.65	0.62	3.74	0.44	3.04
20	1.40	4.40	0.94	3.67	0.6	2.93
25	1.64	3.82	1.21	3.61	0.78	2.84
30	1.88	3.63	1.40	3.38	0.83	2.70
35	2.0	3.52	1.67	3.34	0.98	2.54
40	2.20	3.41	1.75	3.25	1.25	2.48

systems. Data bits are transmitted in frames. Each frame has some additional bits to determine if the frame is error free or not (CRC bits). The base station adjusts its target SIR based on the frame quality. If the frame is in error, the target SIR is increased while the SIR target is decreased if the frame is error free.

5. Variations in the received signal level

The efficiency of the power control algorithm depends on it is ability to equalise the received signal power (or SIR) to the desired target. The smaller the variations in the received power (SIR), the better the power control algorithm. The assumed multipath fading is composed of M equal strength Rayleigh fading resolvable paths. CDMA systems employs a RAKE receiver that can combine resolvable multipath components. Hence, the power fading will have a chi-square pdf with $2M$ degrees of freedom [4]. We will model the effect of the multipath fading on the received signal after power control by a lognormal variable. A common misconception is not to distinguish between users communicating with the desired base station (d) – where the interference is calculated – and users communicating with other base stations when determining the standard deviation of this lognormal variable. If a user is communicating with the desired base station, it will cause intracell interference, and the variations in its received signal will be low because the power control algorithm tries to remove these variations. However, when the user is communicating with another base station (m), it will cause intercell interference to the desired base station, and the variations in its received signal will be much larger because the power control now tries to remove the variations in the received signal at base station m and not at base station d [5]. This of course assumes the fading processes between a user and different base stations to be independent. We will use simulation to find the distribution of the received power after power control and fit it with a lognormal variable $10^{\zeta_s/10}$ if the user is communicating with the desired cell and with a lognormal variable $10^{\zeta_o/10}$ if it is not where ζ_s and ζ_o are Gaussian with a standard deviation that is a function of the user velocity and is given by σ_s and σ_o, respectively.

A slow user will have a lower σ_s compared to a fast user because the power control algorithm will eliminate the variations in the received signal more efficiently when the user is slow. However, σ_o will be higher for the slower user because the power control algorithm will remove the variations at a different base station, which requires transmitting high power levels occasionally and thus increasing the intercell interference level. We will assume the power control rate to be 800 commands/sec and the power adjustment step size to be 0.5 dB. If the power control commands are sent at a faster rate, then the received signal will also be lognormal but with a different standard deviation. Table 1 shows the values of σ_s and σ_o for different velocities and different numbers of resolvable paths. Fig. 2 shows the distribution of the received signal from a user communicating with the desired base station and from a user communicating with a different base station where both users are moving at a speed of 25 Km/h and $M = 2$. In the following, we look at the power control from a system point of view. We also introduce power balancing and SIR balancing for macrodiversity systems.

6. System Model

We consider a CDMA system with L BS's and a total of K users. We denote the wireless user i by w_i, and the set of all users by S; in other words, $S = \{w_i\}_{i=1}^{K}$. So, $C(S) = K$, where $C(.)$ denotes the cardinality.

The powers of the received signals at the BS's are represented by a $K \times L$ matrix $\mathbf{P} = [P_{ij}]$ such that

$$P_{ij} = G_{ij}\tilde{P}_i, \tag{1}$$

where $\tilde{P}_i$ is w_i's transmit power, and G_{ij} is the link gain between w_i and BS j. When we refer to a user$i$ as an index (such as in Eqn.1), we use only i instead of w_i.

The PC problem involves finding the set of transmit power levels, $\{\tilde{P}_i\}_{w_i \in S}$, based on some criterion, so that all or most of the users' SIR levels be above a target threshold level, γ.

7. Power Control in Single-Antenna Systems

When there is no macrodiversity, each user is assigned to a single BS – we will refer to this case as the single-antenna (SA) type. In a SA system, S can be partitioned into L subsets, S_j, with $C(S_j) = k_j$. We note that $\sum_{j=1}^{L} k_j = K$ since $\bigcup_{j=1}^{L} S_j = S$.

Let us assume that user i is assigned to BS j; that is $w_i \in S_j$. Then, in a

SA CDMA system, SIR for w_i, $\Gamma_{i,\mathrm{SA}}$, can be given as

$$\Gamma_{i,\mathrm{SA}} = N \frac{G_{ij}\tilde{P}_i}{\sum\limits_{w_m \in S_j, m \neq i} G_{mj}\tilde{P}_m + \sum\limits_{w_n \notin S_j} G_{nj}\tilde{P}_n}, \quad \forall w_i \in S, \tag{2}$$

where N is the spread-spectrum processing gain. Note that the first and second terms in the denominator of Eqn. 2 represent the intracell and intercell interference components, respectively.

7.1 Power-Balanced Power Control Algorithm

Many different PC algorithms have been suggested and examined in the literature. From the implementation point of view, the simplest PC algorithms are the ones that work based on the power-balancing criterion.

In a power-balanced PC (PBPC) algorithm, the total received usable power for each user is kept at the same constant level. In a SA system, since each user's message is decoded based on the corresponding signal received at the assigned BS only, the total usable power for $w_i \in S_j$ is P_{ij}. Therefore, the PBPC problem in a SA system can be defined as follows:

$$\text{find } \tilde{P}_i, \text{ subject to } P_{ij} = G_{ij}\tilde{P}_i = 1, \quad \forall w_i. \tag{3}$$

This obviously yields

$$\tilde{P}_i = \frac{1}{G_{ij}}, \quad \forall w_i. \tag{4}$$

It is apparent from Eqn. 4 that if the link gains are known, PBPC is computationally very simple.

When power-balancing is incorporated in Eqn. 2, we get

$$\Gamma_{i,\mathrm{SA,PBPC}} = N \frac{1}{(k_j - 1) + \sum\limits_{w_n \notin S_j} G_{nj}\tilde{P}_n}. \tag{5}$$

The second term in the denominator of the above equation is the same

for all users assigned to this BS. There, it is observed from Eqn. 5 that when PBPC is employed in a perfect manner in a SA system, SIR will be the same for all the users assigned to a particular BS; however different users in different BS will, in general, experience different SIR values. That is, if $w_i \in S_j$ but $w_l \notin S_j$, then, in general, $\Gamma_i \neq \Gamma_l$.

7.2 SIR-Balanced Power Control Algorithm

SIR balancing is a more *fair* PC scheme since it yields the same SIR level for all users. In fact, PC algorithms which *balance* the SIR value have been studied in the literature, for conventional SA cellular systems, under the name

SIR-balancing. In an SIR-balanced PC (SBPC) algorithm, the transmit power levels are adjusted so that

$$\Gamma_{i,\mathrm{SBPC}} = \gamma, \ \ \forall w_i \in S. \tag{6}$$

An optimal global PC algorithm that minimises outage probability using SIR-balancing with cell removal was demonstrated in [10]; this PC algorithm is applicable mainly for TDMA and FDMA systems. The main drawback of this algorithm is that it requires continuous access to *all* radio paths in the system; therefore, its use in practical cellular systems is very difficult. Nevertheless, the results provide estimates for the optimal performance. An almost-distributed algorithm that converges to the optimal one is discussed in [11]. In that study, each BS (and user) would control its own transmit power based on only limited knowledge about the link gain matrix. In [9]–[11], the problem of SBPC is first presented in matrix notation, then transformed into an eigenvalue problem, and finally, solved analytically using matrix algebra.

8. Power Control in Macrodiversity Systems

Next, we consider a macrodiversity system (MA) where each user communicates with all the BS's in the service region. In such a system, a user's signal is individually demodulated at each BS and then jointly decoded in a centralised manner through maximal ratio combining to enhance the performance [12], [13]. In this case, the set membership idea introduced in Sec. 6 is not valid any more since all the users collectively belong to S. It is worth noting that the macrodiversity system that we consider here constitutes the logical extent of the soft handoff scheme.

Now, the output SIR for any w_i will be

$$\Gamma_{i,\mathrm{MA}} = \sum_{j=1}^{L} \Gamma_{ij}, \quad \forall w_i \in S, \tag{7}$$

where Γ_{ij} is the SIR at the jth finger of the combiner, that is, the SIR contribution from BS j. Then, Γ_i can be expressed as

$$\Gamma_{i,\mathrm{MA}} = N \sum_{j=1}^{L} \frac{G_{ij}\tilde{P}_i}{\left(\sum_{k=1}^{K} G_{kj}\tilde{P}_k\right) - G_{ij}\tilde{P}_i}, \ \ \forall w_i \in S. \tag{8}$$

8.1 Power-Balancing in Macrodiversity Systems

Since PBPC works well in SA systems, it would be logical to investigate the performance of this PC scheme in macrodiversity systems. However, it is shown in [14] that in a macrodiversity system employing PBPC, SIR for different users may vary significantly. Therefore, SIR-balancing criterion should be considered.

8.2 SIR-Balancing in Macrodiversity Systems

For the case of SIR-balancing criterion, the PC problem can be stated using Eqn.s 6 and 8 as follows:

find $\{\tilde{P}_i\}_{i=1}^{K}$ subject to

$$\Gamma_{i,\mathrm{MA,SBPC}} = N \sum_{j=1}^{L} \frac{G_{ij}\tilde{P}_i}{\left(\sum_{k=1}^{K} G_{kj}\tilde{P}_k\right) - G_{ij}\tilde{P}_i} = \gamma, \quad \forall w_i \in S. \tag{9}$$

It has already been stated in Sec. 7.2 that in SA systems the problem of SBPC can be solved analytically using matrix algebra. However, because of the outmost summation ($\sum_j$) in Eqn. 9, which appears as a result of diversity combining, the set of equations given in Eqn. 9 become nonlinear. Therefore, the eigenvalue method described in Sec. 7.2 does not apply, and thus, no closed-form solution can be found.

Nevertheless, the transmit power levels can be found by solving Eqn. 9 iteratively. The performance of such an iterative algorithm is investigated in [14], and it is shown that the algorithm always converges to the target $\tilde{P_{ij}}$ values within reasonable number of steps.

9. Conclusion

In this paper we looked at the power control (PC) problem in cellular systems. We looked at how the PC is implemented in 3G systems. We have investigated the efficiency of the power control algorithm from a link level point of view. We also analysed the PC algorithms from a system level point of view. Finally, we discussed PC for macrodiversity systems.

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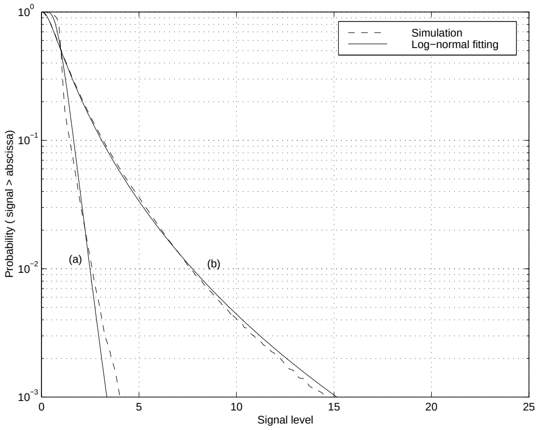

Figure 2: Power control error distribution for 2 Rayleigh fading resolvable paths and a speed of 25 Km/h. (a):user is communicating with the desired base station. (b):user is communicating with a different base station.

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