S-38.220
Licentiate Course on Signal Processing in Communications,
FALL - 97

Power Control in CDMA Cellular Systems

Hassan M. El-Sallabi

Helsinki University of Technology
IRC/Radio Laboratory
P. O. Box 3000
FIN-02015 HUT
Finland

Email: HEL@radio.hut.fi

Date: 06.11.1997

CONTENTS

ABSTRACT

The purpose of this report is to give an overview on power control in CDMA cellular systems. It gives general definition of power control, objectives, its employment in forward and reverse links, algorithms for both links. Effect of power control on forward link capacity is presented as well. Power control is essential for a cellular CDMA system to combat near far problem. The performance of power control algorithm is affected by the power control error.

1. INTRODUCTION

The use of Code Division Multiple Access (CDMA) techniques for wireless communication is mainly for capacity reasons. The analog cellular system started to experience its capacity limitation in 1987 [4]. The limitation in CDMA capacity is mainly due to interference, unlike Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) capacity which is bandwidth limited, this highlights that any reduction in interference converts directly to increase in capacity.

In fading environments, multipath fading, shadowing, path loss, and multiple access interference limit the system capacity. several techniques can improve the system capacity and reliable transmission over a time varying channel by using diversity combining, Forward Error Correction codes (FEC) introduces redundancy to combat transmission errors and, and power control. (i.e. adjusting the transmit power levels) is used to control received signal to noise ratio (SNR).

Regardless of the mode of multiple access, to mitigate the intercell interference in cellular systems that arises from frequency reuse, power control is necessary. In CDMA systems power control is further employed to reduce the intracell interference which is especially crucial on the DS/CDMA uplink for combating the near far effect. Power control can substantially impact the capacity and perceived quality of service of CDMA system

1.1 Effect of no power control

In the case of no power control, if a mobile’s signal is received at the base station with a too low level of received power (i.e. the mobile is far from the cell site or in a unusual high attenuation channel), a high level of interference is experienced by this mobile and its performance (bit error rate) will be degraded (high BER). On the other hand, if the received power level is too high (i.e. the mobile station is close to the base station or unusual low attenuation channel), the performance of this mobile is acceptable, but increases interference to all other mobiles that are using the same channel, and may result in unacceptable performance to other mobiles. This is called “near far problem”. Therefore a technique is needed to compensate not only for signal strength variation due to the varying distance between cell site and mobile but also attempt to compensate for signal strength fluctuations of atypical wireless channel.

1.2 Objectives of power control

The main purposes of power control is 1) "to maintain all users' signal energy received at the base station nearly equal in the spread spectrum which is shared in common " [7] (i.e. to combat the near far and CO-channel problems), 2)"to make the received power level less dependent on the fading and shadowing effects of the transmission channel " [8]

2. POWER CONTROL MECHANISMS

Two kinds of power control can be distinguished, the Open Loop Power Control (OLPC) and the Closed Loop Power Control (CLPC). Fig.1 shows a simplified diagram about closed loop and open loop.

2.1 Open loop power control

The open-loop power control (OLPC) adjusts the transmitted power according to its estimating the channel, it does not attempt to obtain feedback information on its effectiveness.

The major benefit of open loop power control, which is analog in nature and has about 80 dB dynamic range [6], is to provide for a very rapid response over a period of just a few microseconds (i.e. it does not wait for the feedback information) for cases of sudden change in the channel condition such as a mobile behind a building. It adjusts the mobile transmit level and thus prevents the mobile transmitter power from exceeding some threshold with respect to the forward link received power level.

The open-loop power control is not very accurate since it does not have feedback information for its effectiveness.

2.2 Closed loop power control

In cellular Frequency Division Duplex (FDD) CDMA systems, the frequency separation between links is greatly more than the coherence bandwidth of the channel This frequency separation has very important implications for the power control process: It causes multipath fading on the forward and reverse links to be independent. This means that the mobile can not measure the path loss of the reverse link by measuring the path loss on the forward link. This measurement technique, which is used for the open loop, usually provides the correct average transmit power, but additional provisions must be made for the effects of asymmetric Rayleigh fading. Therefore, the mobile transmitter power is also controlled by its cell. Each cell site demodulator measures the received signal power P_m (or $SINR_m$ in case of SINR based CLPC) from each mobile. The measured P_m is compared to the desired power level P_d

for that mobile and a power control adjustment command is sent accordingly. If the measured value is above the set point, then a one bit command is sent; to lower power by Δp dB, if below, the one bit command is sent to raise power by Δp dB. The transmitter adjusts its power up or down, relative to the open loop estimate.
The closed loop power control (CLPC) is a sort of "fine tuning" on the open loop power estimate. It should be fast enough to keep up with the fast fading. So, it is the crucial component of any effective scheme to combat Rayleigh fading.

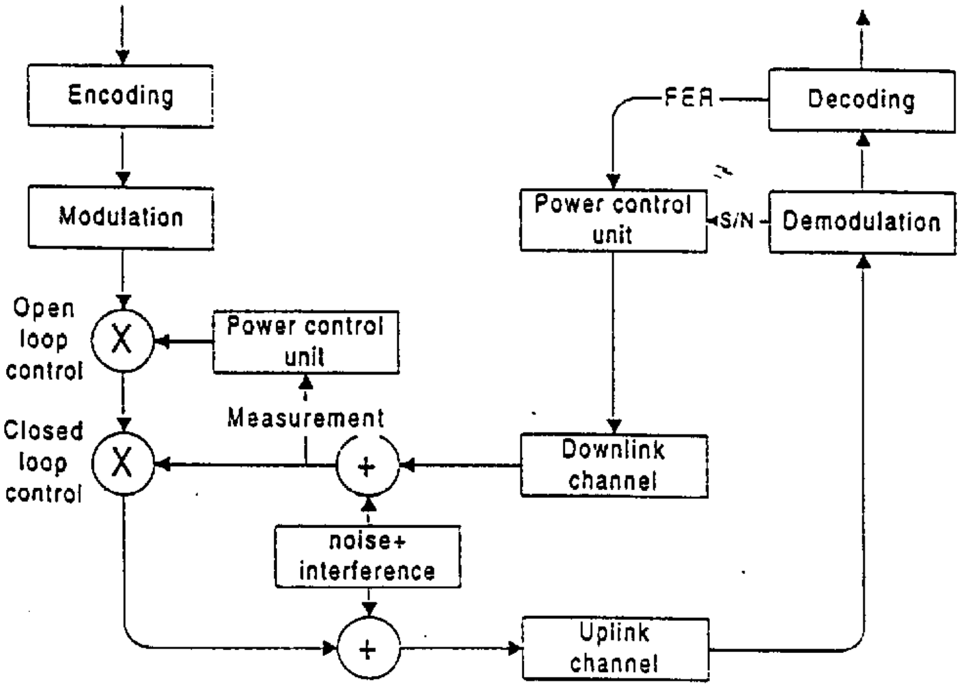


Fig. 1 shows a simplified diagram about closed loop and open loop[20]

3. FORWARD AND REVERSE LINK POWER CONTROL

Power control is employed in both in the reverse link (mobile to base station) and in the forward link (base station to the mobile).

3.1 Reverse link power control

The Reverse Link Power Control (RLPC) is for reducing near-end to far-end interference. "It is a unique type of interference occurring in the mobile environment" [4]. The RLPC serves the following two functions :

1. It makes equal received power level from all mobiles at the base station. The function is necessary for system operation. The better the power control performs, the more it reduces the Co-channel interference and, thus, increases the capacity.
2. It minimizes the necessary transmission power level to achieve good quality of service. This yields a reduction in the co-channel interference, which is converted to increasing the system capacity and alleviates health concerns. In addition, it saves the

battery power. Viterbi, 1994, has shown upto 20-30 dB average power reduction compared to AMPS mobile user as measured in field trials [4].

The reverse link power control system is composed of two subsystems: the closed loop system and the open loop.

3.1.1 Reverse link open loop power control

The principle operation of open loop control is shown in fig.2. The open loop power control bases its action on the estimation of the channel state. In the reverse link, it estimates the channel by measuring the received power level of the pilot from the base station in the forward link and adjusts the mobile's transmitted power level inversely proportional to it. The stronger the received signal, the lower mobile's transmitted power. Reception of a strong signal from cell site indicates that the mobile is either close to the cell or has an unusually good path to the cell site. This means that relatively less mobile transmitter power is required to produce a nominal received power at the base station. Ideally this insures that the average power level from the mobile at the base station remains constant irrespective of the channel variations. This approach, however, assumes that the forward and the reverse link signal strengths are closely correlated. Although forward and reverse link may not share the same frequency as in FDD CDMA systems and, therefore, the fading is significantly different, the long-term channel fluctuations due to shadowing and propagation loss are basically the same.

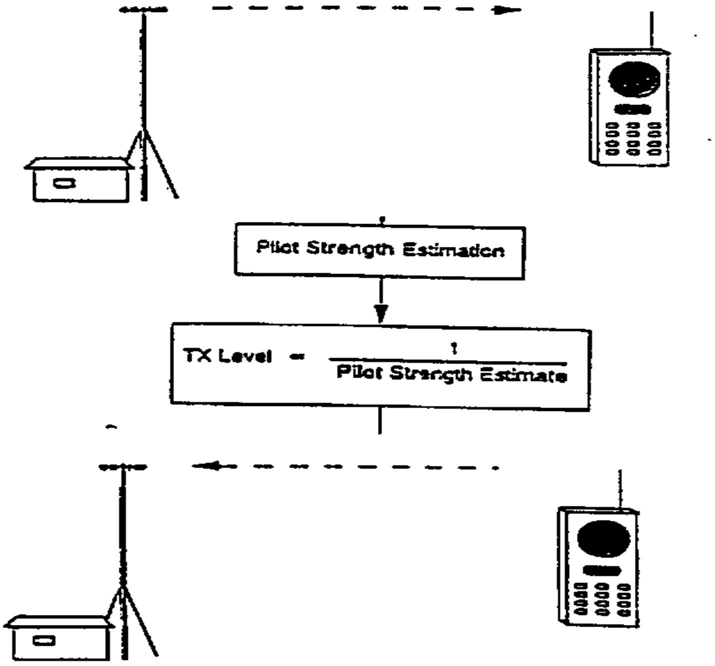


Fig.2 Reverse link open-loop power control. [2]

3.1.2 Reverse link closed loop power control

The closed loop power control system principle is shown in Fig.3. It bases its decision on an actual communication link performance metric, e.g., received signal power level, received signal to noise ratio, received bit error rate, or received frame error rate. In the case of the reverse link power control, this metric may be forwarded to the mobile as a base for an self-governing power control decision, or the metric may be evaluated at the base station and only the power control adjustment command is transmitted to the mobile. If the reverse link power control decision is made at the base station, it may be based on the additional knowledge of the particular's performance and/or a group of mobile's performance (such as mobiles in a sector, cell, or even in cluster of cells).

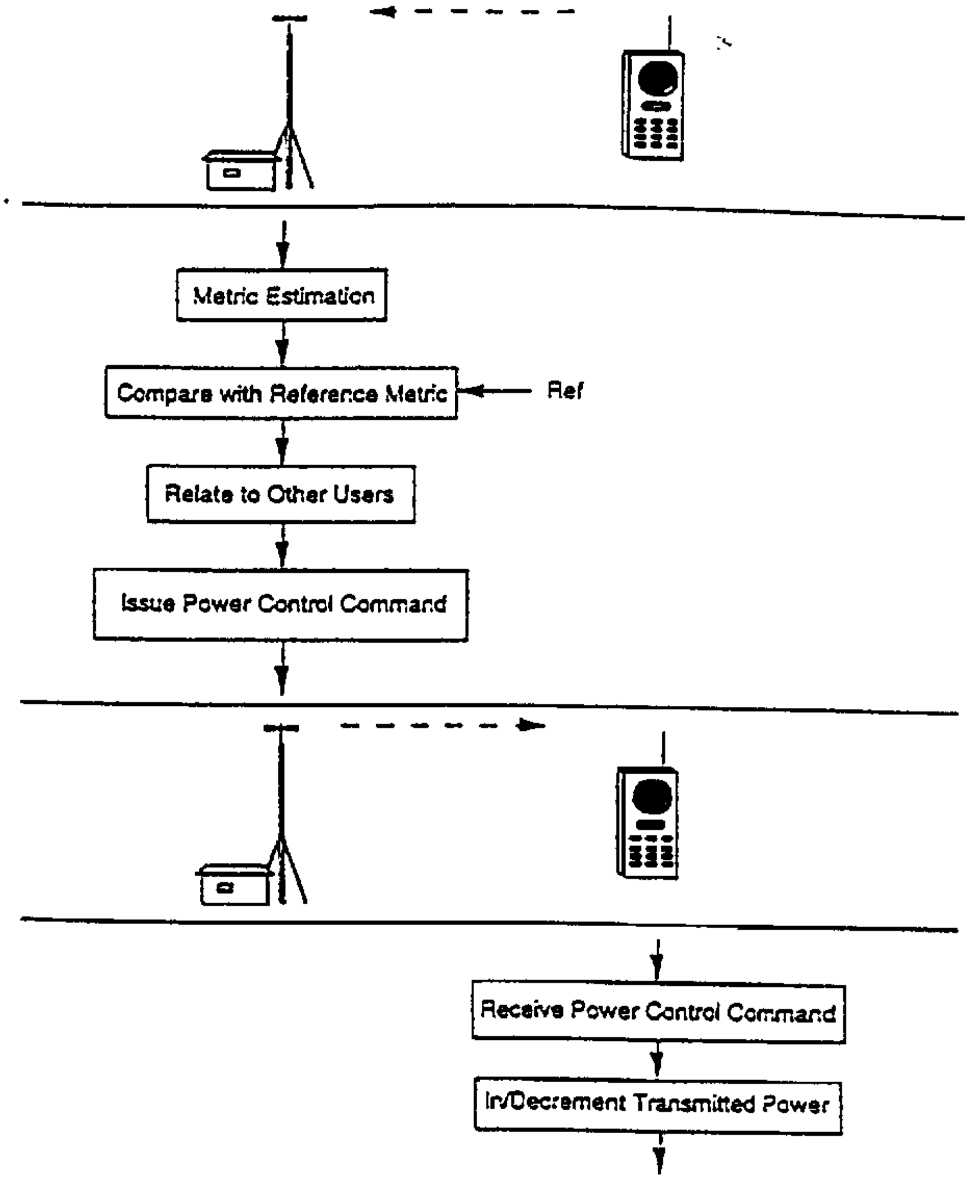


Fig.3 Reverse link closed-loop power control. [2]

3.1.3 Operation of reverse link power control

The system operates as follows. Prior to the application access, closed loop power control is inactive. The mobile station receives a signal suffering both the log-normal and Rayleigh fading from the forward link, as shown in fig.4.a. The average path loss is obtained as shown in the figure. If the transmitting and receiving ends are sharing the same frequency channel, then reversing the received signal strength as shown fig.4.b., indicated as the transmit power without smoothing filter, would eliminate the power variation at the cell site. Since CDMA uses duplexing channels, the Rayleigh fading on the forward channel and the reverse channel are not the same. Therefore, the desired average transmit power is sent back on the reverse channel.

At the cell site, determining whether to command a particular mobile to increase or decrease its transmit power is done by examining the available information on the instantaneous value versus the expected value of the Frame Error Rate (FER) of the received signal.. This is the CDMA closed loop power control mechanism. The mobile power received at a cell site after closed loop control is shown in fig.4.c.

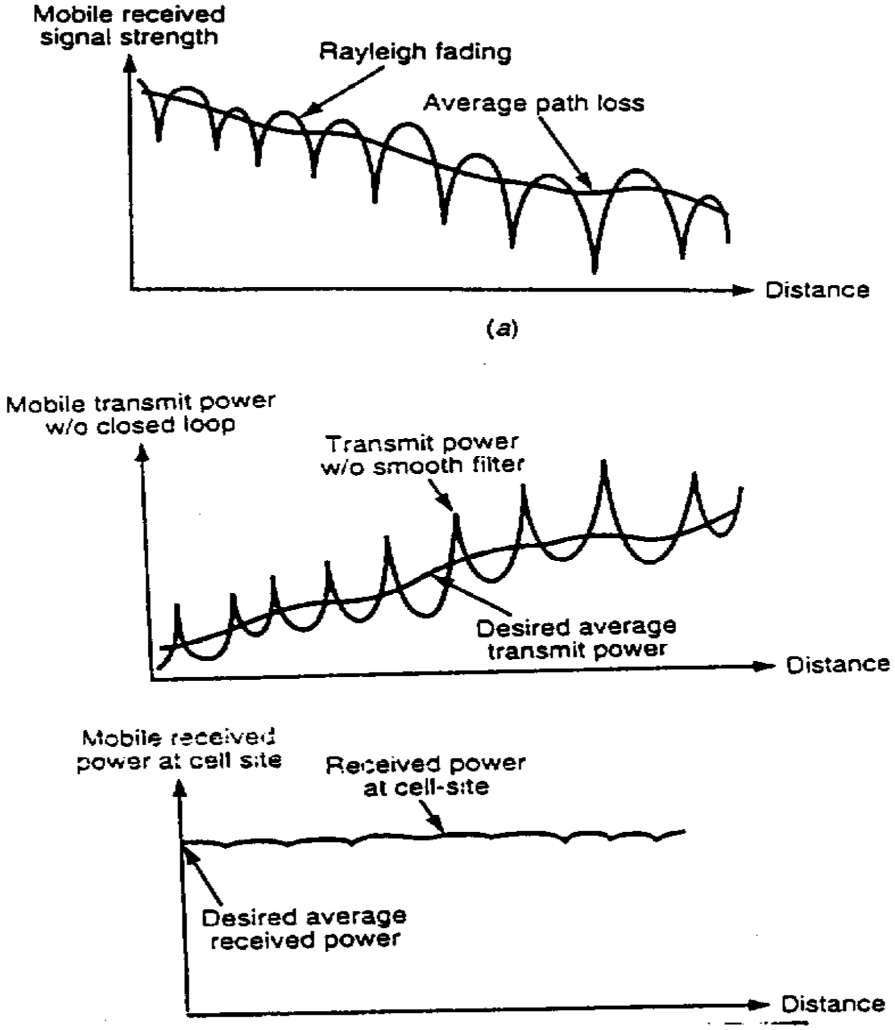


Fig.4. Power control mechanism. (a) Mobile received signal strength in log-normal shadowing and Rayleigh fading; (b) transmit power without closed loop control and without nonlinear filtering ; (c) mobile power received at cell site.[3]

In transmission mode, the mobile has two independent means for transmitted power adjustment:

1. Open loop output power

- The mobile station (MS) shall transmit the probe on the access channel:

$\overline{P_A}$ = mean output power (dBm) = - mean input power (dBm) - 73
+ NOMPWR, dB + INITPWR, dB (1)

where NOMPWR = the correction of the received power at the base station and INITPWR = adjustment of the received power less than the required signal power. When INITPWR = 0, $\overline{P_A}$ = ± 6dB.

- For initial transmission on the reverse channel,

$\overline{P_I}$ = mean output power (dBm) = $\overline{P_A}$
+ the sum of all access probe correction, (dBm) (2)

- For normal reverse traffic channel,

$\overline{P_R}$ = mean output power, dBm = $\overline{P_I}$
+ the sum of all closed loop control correction, dB (3)

The range of parameters NOM_PWR and INIT_PWR are shown table(1) shown below:

Table 1: NOM_PWR and INIT_PWR parameters[2]

	Nominal value (dB)	Range (dB)
NOM_PWR	0	-8-7
INIT_PWR	0	-16-15

2. Closed-loop output power (involving both the mobile station and the base station). The mobile station adjusts its mean output power level in response to each valid power control bit received on the forward traffic channel. The change in mean output power per single power control bit is 1 dB nominal, within ±0.5 dB of the nominal change.

The power control bits shown in fig.5 are sent uncoded and punctured into the forward traffic channel transmission replacing two symbols. The two symbols are coherently combined to make the power control decision, but otherwise unprocessed. The power control bits are sent uncoded for, like the open loop control, the interest of fast loop response. Any coding of these bits would result in a processing delay and hence a more sluggish loop The closed loop power control command arrives at the mobile every 1.25 ms (i.e.800 b/s). Therefore, the base station estimates the received power level for approximately for 1.25 ms. The mobile must respond to the power control level within 500 µs A closed loop power command can have only two values: 0 to increase the power level and 1 to decrease the power level.. The total range of the closed loop power control system is ±24 dB [2]. The total supported range of power control (closed loop and open loop) must be at least ±32 dB [2].

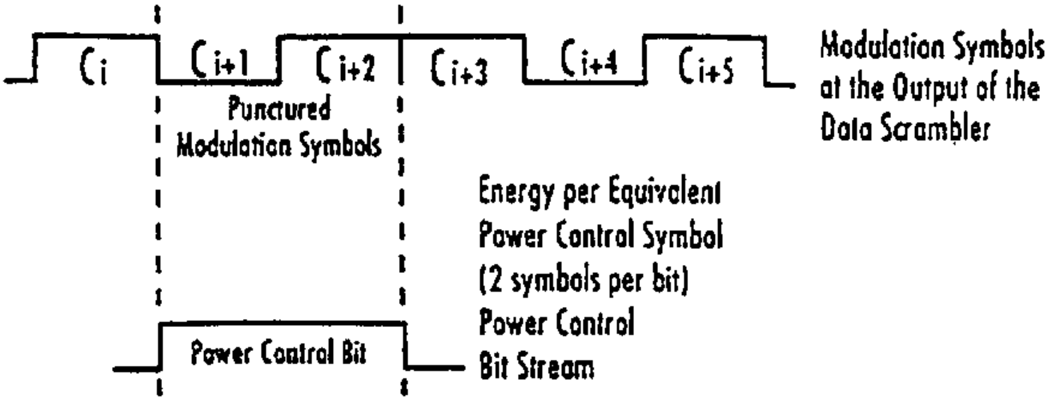


Fig.5 Power control bit puncturing. [21]

3.2 Forward link power control

The forward link power control is used to minimize the necessary interference outside its own cell boundary. Down link power control in CDMA cellular systems is identified by Lee [4] as an important issue of system capacity. For forward link, power control takes the form of power allocation at the cell site transmitter according to the needs of individual subscribers in the given cell. It serves the following three functions

1. It works to make equal system performance over the service area (good quality coverage of the worst case areas).
2. It provides the load shedding between unequally loaded cells in the service area by controlling the intercell to the heavy loaded cells.
3. It minimizes the necessary transmission power level to achieve good quality of service. This reduces the co-channel interference in other cells, which increases the system capacity and alleviates health concerns in the area around the base station.

The forward link power control fig.6 works as follows . The mobile monitors the errors in the frames arriving from the base station. It reports the frame-error rate (FER) to the base station periodically. (an other mode of operation may report the error rate only if the error rate exceeds a present threshold) [2]. The base station adjusts its transmitting power after evaluating the received frame-error. In this way, the performance of the forward links is equalized in the cell or sector. Since pilots from mobiles are usually unavailable, only closed loop power control is applied [2].

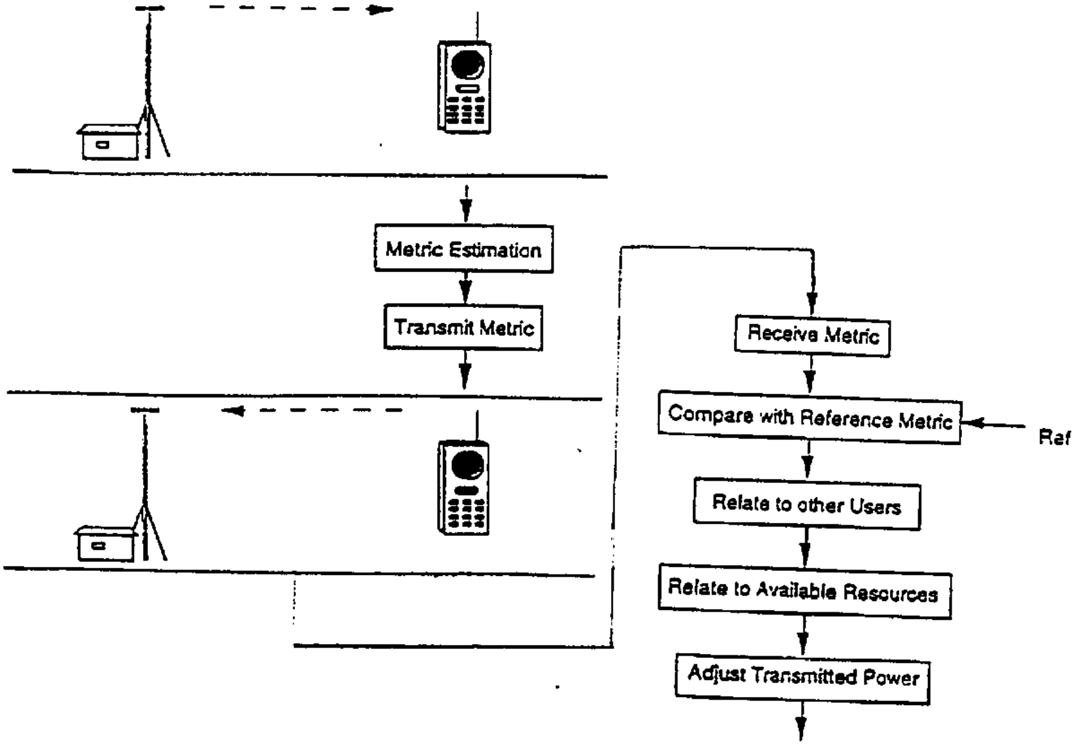


Fig.6 Forward link closed loop power control. [2]

4. POWER CONTROL ALGORITHMS

The aim of the power control is to assign each user a transmitter power level such that all users in the system satisfy their quality of service requirements. Many power control algorithms have been developed to date. Those algorithms may be classified as centralized or distributed, synchronous or asynchronous, iterative or noniterative, constrained or unconstrained. Work in [9-11] identified the power control problem as eigenvalue problem for non-negative matrix. The optimal power vector was found composed of channel gains of all users. Those algorithms are non-iterative, synchronous and centralized in the sense that all the power vector components are found by a matrix inversion. Due to the computational complexity of these centralized power control algorithms, distributed versions have been developed which need only path gains that can be obtained by local measurements [12]. In [13], a frame work for the uplink power control is developed.

The shortcomings of those algorithms are that they require knowledge or estimates of one or more of the following parameters: (i) channel gains, (ii) signal to interference ratio (SIR), (iii) received interference power, or (iv) bit error rate (BER). Non of those is easy to estimate. This highlights the need for power control algorithms which make use of available easy to estimate parameters. In [14], stochastic power control algorithm in which each user is needs only to know its own channel gain to its assigned base station and its own matched filter output at its assigned base station.

4.1 Ideal power control algorithm

In the ideal case, power control compensates for the propagation loss, shadowing, and fast fading. There many effects which prevent the power control from becoming ideal. Fast fading rate, finite delay of power control system, non-ideal channel estimation, non-ideal channel estimation error in the power control system, limited dynamic range, etc., all contribute to degrading the performance of power control system. It is very important to examine the performance of power control under non-ideal conditions since the research done has shown that the power control system is sensitive to some of these conditions,[7] .

4.2 Forward link power control schemes

4.2.1 *n*th-power-of-distance power control scheme

A distance driven power control scheme is proposed in [4] and it is further investigated by Gejji [18]. It assumes that continuos power control can be implemented. With knowledge on the location of the mobile, it is possible to minimize the total transmitted power by transmitting high power levels for far-end users and low power for near-in users, and hence reduce the interference level. The transmitted power for a mobile can be adjusted accordingly

$$Pt_j = \begin{cases} (r_o/R)^n P_R & \text{for } 0 \le r \le r_o \\ (r/R)^n P_R & \text{for } r_o < r \le R \end{cases} \tag{4}$$

where r_o is the close-in distance and n is the power control factor. P_R is the power required to reach the users at the cell corner (R,π/6).

4.2.2 Optimum power control

This model is presented in [17] which is a development of the algorithm proposed in [18]. To achieve a uniform service, the transmitted power for mobile located at (r, θ) can be adjusted to have the same shape as the total interference factor $x_I(r, \theta)$ [17]. Then P_j changes as interference changes with high P_j for large interference and small p_j for small interference.

$$P_{jopt}(r,\theta) = P_R \cdot p(r,\theta) = P_R \cdot \frac{x_I(r,\theta)}{x_I(R,30^o)} \tag{5}$$

where p(r,θ) is the optimum transmitted power function given by $p(r,\theta) = x_I(r,\theta)/x_I(R,30^0)$. P_R is the power transmitted to users located at the corner (R, 30°).

4.2.3 Quality based power allocation

This algorithm is proposed in [15], it shows how it allocates and adjusts power levels to a desired transmission quality. The algorithm deals with limiting constraint of transmitting power as well as maintaining sufficient transmission quality γ in each down link channel. If the transmission quality threshold γ (>0) is given, to maintain adequate transmission quality, mobile *i* requires

$$\Gamma_i \ge \gamma. \qquad (6)$$

The received bit energy to noise density ratio of mobile *i* served by a cell *k*, is lower bounded as

$$\left(\frac{E_b}{N_o}\right)_i \ge \Gamma_i \cong \frac{G_{ik}p_{ik}/R}{\left(\sum_{j=1}^{N} G_{ij}P_j + \eta_i\right)/W} \qquad (7)$$

where p_{ik} is the amount of transmitted power devoted to traffic signals for mobile *i* served in cell *k*, G_{ik} denotes the link gain on the path between the *i*th mobile and the *k*th cell sit, R is the information bit rate, N denotes number of cells, W is the total spread spectrum bandwidth occupied by CDMA signals, η_i denotes other interference sources, such as control signals including pilots as well as background noise due to spurious or thermal noise contained in W.

The transmitter capacity at the cell site is limited, for each cell *k*, the sum of allocated power is constrained by

$$P_k \cong \sum_{i \in I_k} p_{ik} \le T_k \qquad (8)$$

where T_k is the total power available traffic, I_k is the index set for the mobiles which are served by cell k,

The objective of the downlink power control is to determine the individual power level p_{ik} devoted to mobile *i* served by cell k under the constraint (6) and (8) using the measurement information $\mathbf{G} = \{G_{ik}\}$. The solution of the stated problem satisfies all users' E_b/N_o. Usually, the required $E_b/N_o = 5$ dB to ensure BER $\le 10^{-3}$ in the design of CDMA cellular downlink [6]. Fig.7 shows forward link cell site transmitter in which the power allocations to individuals $\phi_i = p_{ik}$. Fig.8 shows link geometry and link gain model.

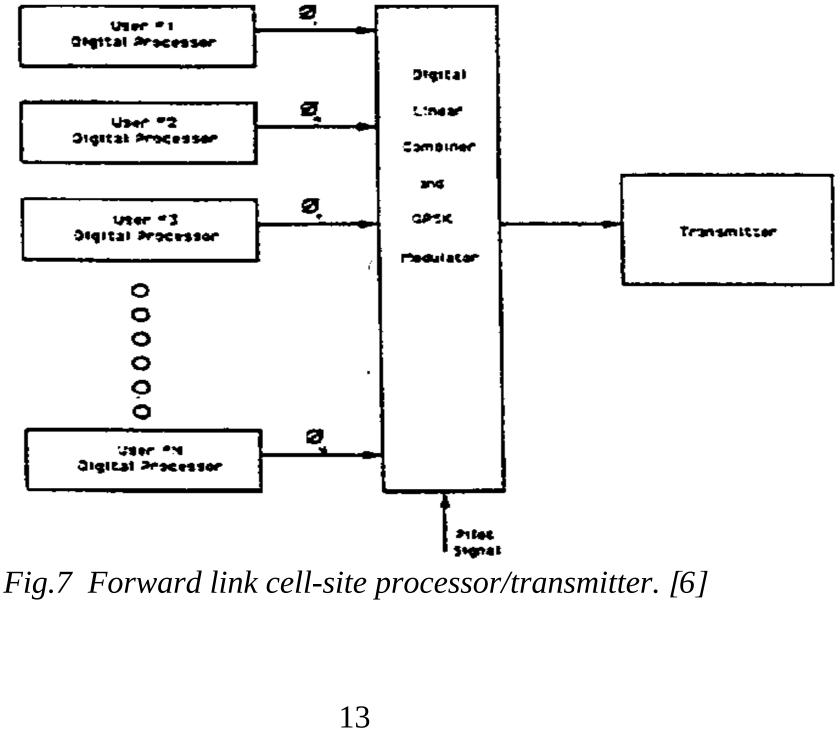


Fig.7 Forward link cell-site processor/transmitter. [6]

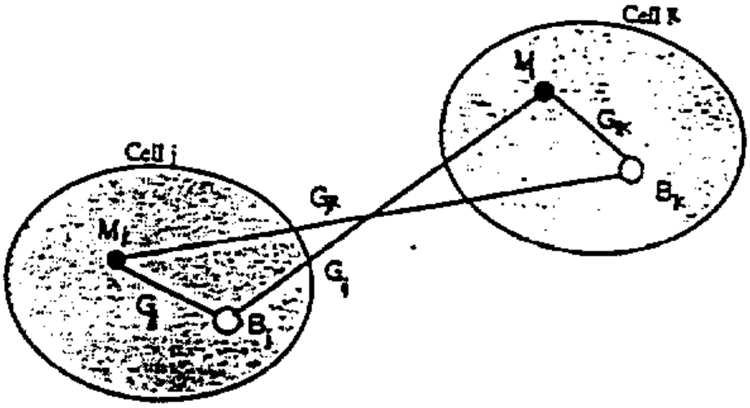


Fig.8 Link geometry and link gain model. [11]

The algorithm proposed in [15] consists of two parts: allocating and adjusting.

a. Allocation of individual power level

A method to allocate the pre-assigned cell-site power, P_k, fairly is to let the mobiles in the cell have an equal link quality, that is, the same value of Γ_i for all $i \in I_k$.
A balanced link quality for each cell is achieved by finding p_{ik}, $i \in I_k$, from solving the problem:

Link quality Balancing Problem for cell k (LBP_k):

$$\gamma_k = \max_{p_{ik}} \min_{i \in I_k} \left\{ \frac{G_{ik} p_{ik} / R}{\left(\sum_{j=1}^{N} G_{ij} P_j + \eta_i\right) / W}, i \in I_k \right\} \tag{9}$$

$$\text{Subject to} \quad \sum_{i \in I_k} p_{ik} = P_k \qquad \text{and } p_{ik} \geq 0 \qquad \text{for} \quad i \in I_k.$$

That is maximizing the minimum transmission quality among users served by cell.

A solution p_{ik} and the balanced link quality $\tilde{\gamma}_k$ are obtained by

$$\tilde{p}_{ik} = \frac{\phi_{ik}}{\Phi_k} P_k \quad \text{and} \quad \tilde{\gamma}_k = \frac{P_k}{\Phi_k}. \tag{10}$$

after substituting $\tilde{p}_{ik}$ for p_{ik} in (6), we have

$$\Gamma_i = \tilde{\gamma}_k, \qquad \text{for all } i \in I_k. \tag{11}$$

The base station does not need to know all the path gains and allocated power levels to users as the following: Each mobile should measure the total interference $\left(\sum_{j=1}^{N} G_{ij} P_j + \eta_i\right)$ it receives and transmits this value to the base station via a control channel. Assuming that each demodulator in the base-station can estimate the gain (G_{ik}) from the cell site to the serving mobile, the base station decide $\tilde{p}_{ik}$ without any information about the path gains and the power levels in the other cells.

If

$\tilde{\gamma}_k \geq \gamma$, then, satisfactory transmission quality for all mobiles in cell k.

$\tilde{\gamma}_l < \gamma$, then, the mobiles in cell *l* drop below the target, (i.e. non-supported cell).

$\tilde{\gamma}_h > \gamma$, then, the mobiles in cell *h* receive unnecessarily over-assigned traffic power from the cell site, (i.e. over-supported cell). Reducing this kind of wasting power is desirable to minimize the interference in the neighbor cells and then improve transmission quality in the non-supported cells.

b. Adjustment of the allocated power levels

Algorithm: Given the capacity limit of cell site transmitter T_k, k = 1,2,…..,N.

Step 0- Initialization: Balancing Single Cell Quality:
Determine I_k, k = 1,2,….,N. Set t = 0. For k = 1,2,…,N, with an initial cell site power level $P_k^0 = T_k$, find $p_{ik}^t = \tilde{p}_{ik}$ and $\Gamma_i^k = \tilde{\gamma}_k$ by solving LBP_k for for $i \in I_k$.

Determine

$$S_n^t = \{k : \tilde{\gamma}_k < \gamma, \quad 1 \leq k \leq N\} \tag{12}$$

$$S_s^t = \{k : \tilde{\gamma}_k = \gamma, \quad 1 \leq k \leq N\} \tag{13}$$

and

$$S_o^t = \{k : \tilde{\gamma}_k > \gamma, \quad 1 \leq k \leq N\} \tag{14}$$

Step 1- Adjusting the allocated power levels for over-sampled cells:

For $k \in S_o^t$, adjust the allocated power as

$$p_{ik}^{t+1} = \frac{p_i^k}{\Gamma_i^t}\gamma, \qquad i \in I_k \tag{15}$$

and let

$$P_k^{t+1} = \sum_{i \in I_k} p_{ik}^{t+1} \tag{16}$$

step 2- Re-allocating and updating cell status:

For all $k \in S_n^t \cup S_s^t$, let $P_k^{t+1} = P_k^t$, and find $p_{ik}^{t+1} = \tilde{p}_{ik}$ and $\Gamma_i^{t+1} = \tilde{\gamma}_k$ by solving LBP_k with P^{t+1}`s for $i \in I_k$.

Set S_n^{t+1} and S_s^{t+1} as in (12), (13), respectively. And let

$$S_n^t = S_o^t \cup \{k \in S_n^t \cup S_s^t : \tilde{\gamma} > \gamma\}. \tag{17}$$

Step 3- Termination:

If $S_o^{t+1} = \phi$ or $S_o^t = \phi$, then terminate.

Otherwise, set t=t+1 and go to step 1.

4.3 Reverse link feedback closed loop power control model

It is also called average power control [8]. It attempts to eliminate the slowly varying near-far and shadowing effects and it is affected by fast multipath fading process. To tackle this difficulty, a fixed-step power control that can accommodate the effects of rapid fading is proposed in [19]. The fixed step power control is performed at a higher rate than the rate of multipath fading. It is suggested that the power increment command updating rate is higher than 10 times the maximum fading rate. The power increment is determined on the basis of the deviation between the desired nominal power and the signal level received at the base station.

In this model (feedback closed loop power control [19] shown in fig.9) all the quantities are expressed in dB. Assuming that a power control bit is sent every T_p symbols for slightly increasing or decreasing in the transmitted power where T_p is the power control sampling period. The transmitted signal power p_j during the *j*th period is updated by a fixed step Δp every T_p symbols., The received signal power, during the *j*th period, at the base station's RAKE combiner output is $P_j + x_j$ where x_j represents the signal power variation due to channel losses and receiver processing. The received signal power is estimated using algorithm described below (sec.7.3.1)and compared to a preset threshold p_d. Based on the error $e_j = p_j + x_j - p_d$, a power control bit is generated to the mobile requesting an increase or decrease by Δp.

However, the decision to increase or decrease the received signal power is made by the base station, the up/down command is transmitted on the down link to the mobile so that it may adjust its transmitted power level accordingly. If the command is received in error, the opposite action will take place. This model accounts for extra loop kT_p which accounts for the two-way propagation delay and time delay involved in generating, transmitting, and executing the power command.

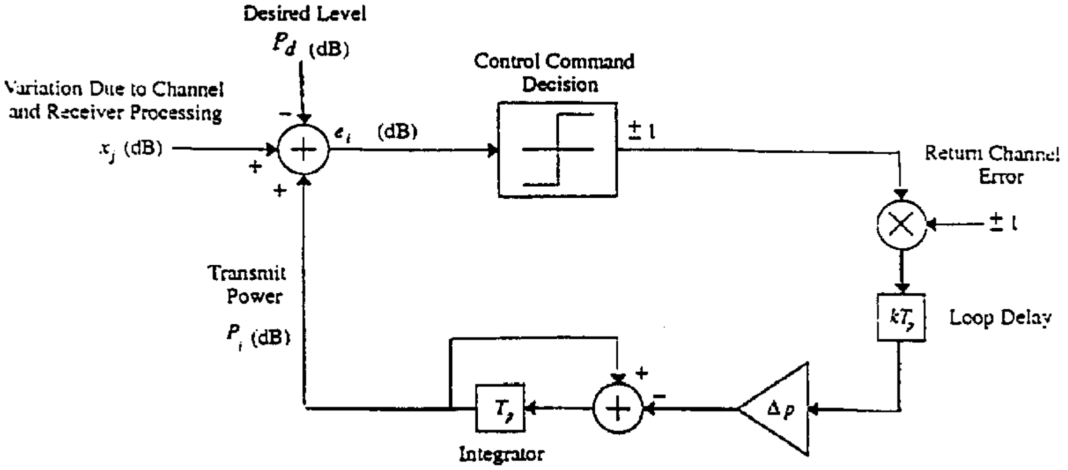


Fig.9 Feedback power control model. [19]

4.3.1 Received signal estimation Algorithm

The received signal power estimated at the base station in the way shown in fig.10, which is explained as follows :

On the average at relatively high SINR, the maximum of the decision variables $z_1^{(1)}, z_1^{(2)}, \ldots\ldots, z_1^{(M)}$ corresponds to the signal power plus interference-plus-noise power, since orthogonal of the M-ary signals [1] are used for modulation on the reverse link, The remaining M-1 variables corresponds to interference-plus-noise power only. A assuming that the fast fading remains almost constant over period T_p symbols in any power control sampling period. Therefore, if a hard decision is made to select the maximum of $z_1^{(1)}, z_1^{(2)}, \ldots\ldots, z_1^{(M)}$, then interference-plus-noise and signal powers over the T_p symbols in a power control period can be estimated as

$$\mu^2 = \frac{1}{T_p(M-1)} \sum_{i=1}^{T_p} \sum_{\substack{n=1 \\ n\neq n_{max}}}^{M} z_1^{(n)}(i) \qquad (18)$$

$$E_T = \frac{1}{T_p} \sum_{i=1}^{T_p} \max_{n=1:M}\left\{z_1^{(n)}(i)\right\} - \mu^2 \qquad (19)$$

The decision variables $z_1^{(1)}, z_1^{(2)}, \ldots\ldots, z_1^{(M)}$ are also passed to symbol-by-symbol M-ary decision device followed by a deinterleaver and a Viterbi convolutional decoder. The receiver uses the output bit sequence and other information from the convolutional decoder (such as the branch metrics) to get an estimate of the frame error rate (FER). Based on this estimated FER, the receiver selects the appropriate threshold to be used.

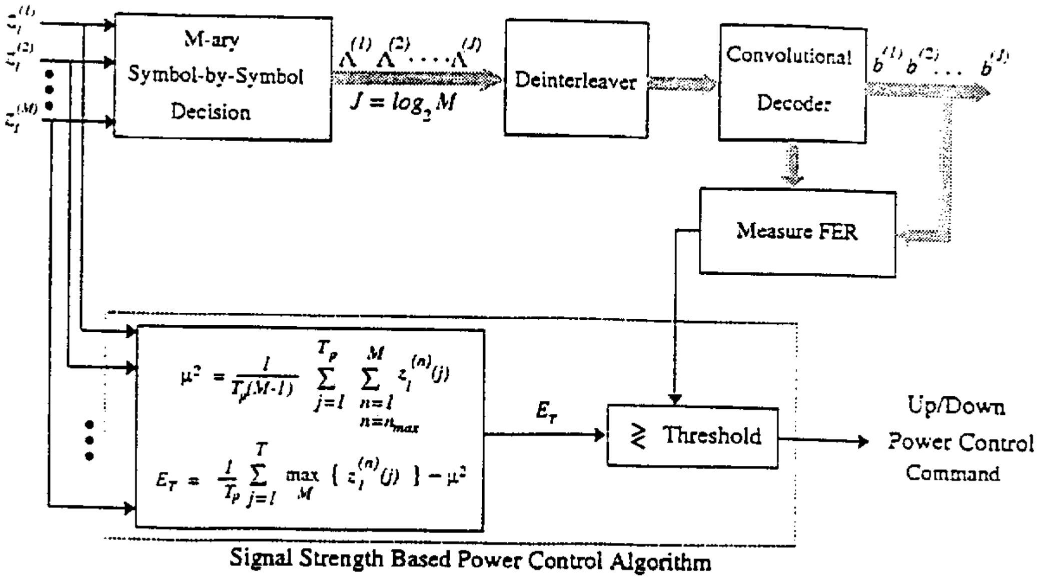


Fig. 10 Power control algorithm[16]

4.3.2 Performance of CLPC in CDMA system with base station antenna array

This study is presented in [16], where a single cell CDMA system was simulated. Assuming base station antenna array model proposed in [16], Signals received at the base station were generated using the channel and transmitted signal models described in [16]. The uncoded bit rate was assumed to be 9.6 kp/s. With a rate 1/3 convolutional code and M-ary orthogonal modulation with M=64, the symbol rate is 4800 symbol/sec. The processing gain is 256. Assuming the power control is sent every 1.25 ms. Assuming the total delay (including power measurement) is 1 T_p, The power step size is ∇p is 0.5 dB and angle spread ∇ is zero.

Fig.11 and 12 show the RAKE output received signal level waveform and the estimated distribution versus the simulated multipath fast fading f_d = 5 Hz and f_d = 100 Hz, respectively. From two figures One can see that closed loop power control eliminates most of the channel variations due to fast fading at low f_d, while at high f_d the received signal statistics after power control remain almost the same as that of the simulated multipath fast fading with only average power control.

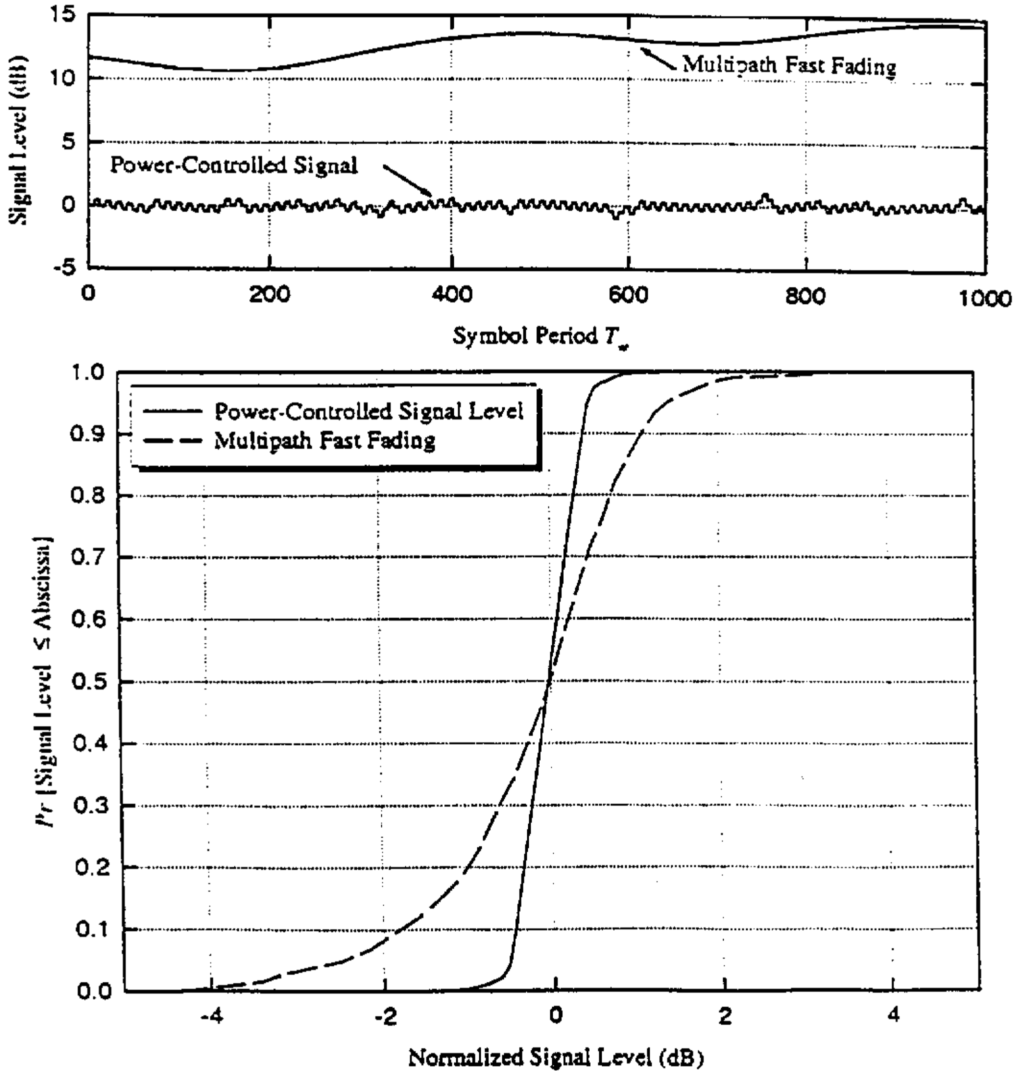
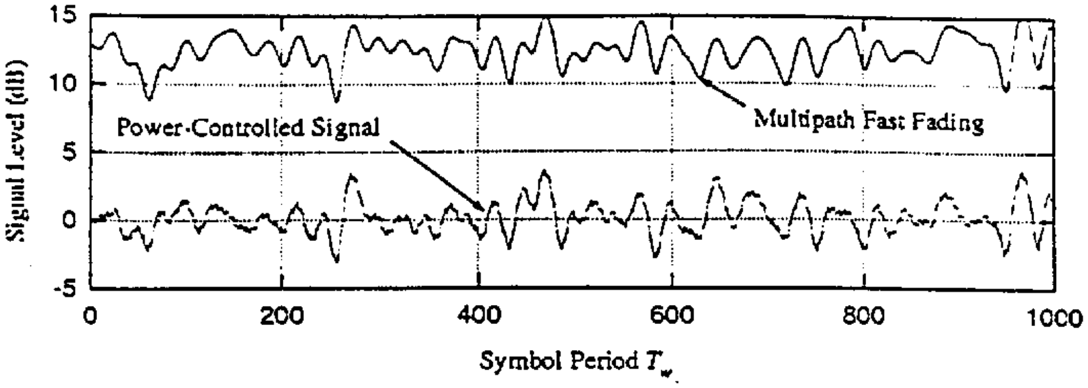
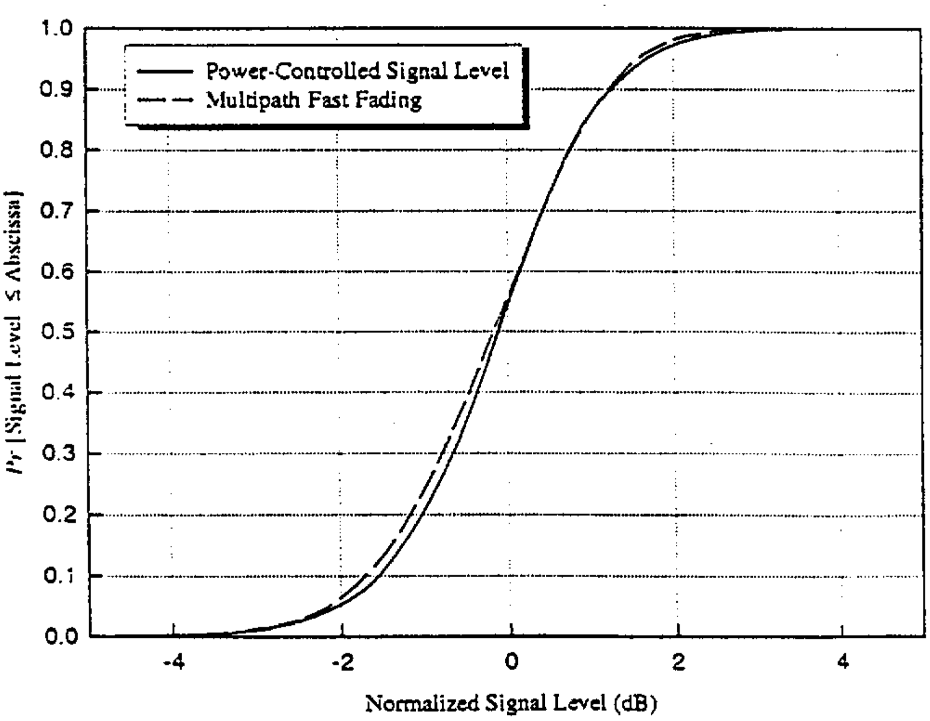


Fig.11 power controlled received signal vs. Simulated Rayleigh fading: f_d = 5 Hz, K = 5, L=4. K is number of paths, L is number of RAKE branches. [16]



(a) Signal waveform



(b) Normalized Signal level (dB)

Fig.12 Power-controlled received signal vs. Simulated Rayleigh fading: f_d=100 Hz, K= 5, L=4.K is number of paths, L is number of RAKE branches. [16]

Fig.13 shows the effect of the step size Δp on the power control error σ_E for Δp = 0.25, 0.5, and 1 dB. We can see that σ_E is lower with large step Δp and high f_d, a small step provides more precise control. The reason is that at high f_d the fading rate is too high and a large step size is necessary to track the fading. On the other hand, at low f_d the fading rate is slow enough to allow the control loop to track fading with a small step size.

Fig.14 and 15 plot the power control error σ_E against f_d for different values of Δ for K = 5 and 9, assuming antenna array size is 8λ and sensors are placed as ULA.
From these figures we can make the following observations. With zero angle spread, the number of antennas has no effect on the CLPC error σ_E. This is due to the fact that with zero angle spread Δ, the received signal in any multipath component will have the same fading at each antenna. Thus, the antenna array will not provide any space diversity for this multipath component. Also, for a given number of antennas K, as the angle spread Δ increases, the gain due to space diversity increases which will lead to a reduction in the power control error σ_E. (i.e. better CLPC performance).

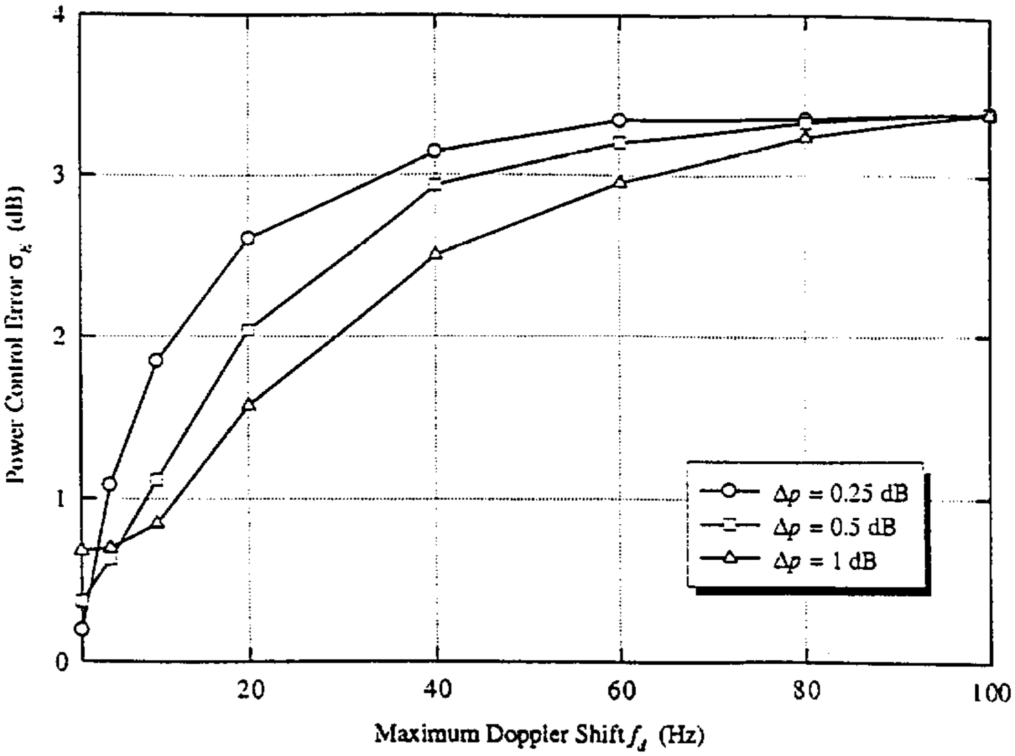


Fig.13 Power control error vs. Power step size, L = 2, K = 5. [16]

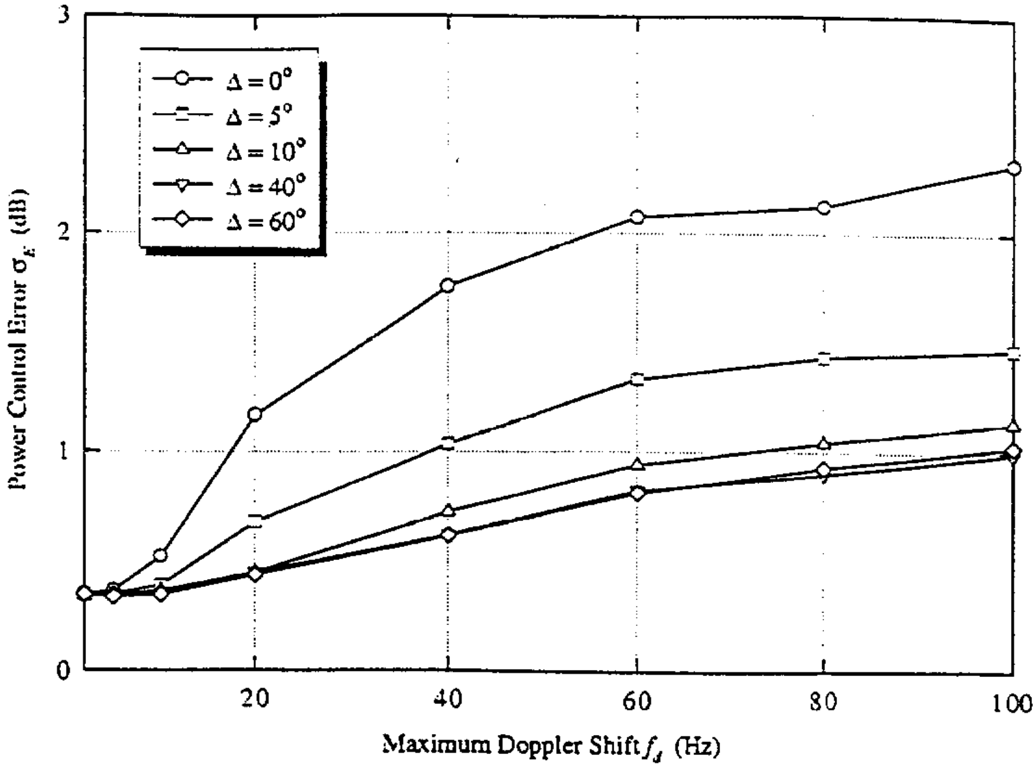


Fig.14 Power control error vs. angle spread, L = 2, K = 5, [16]

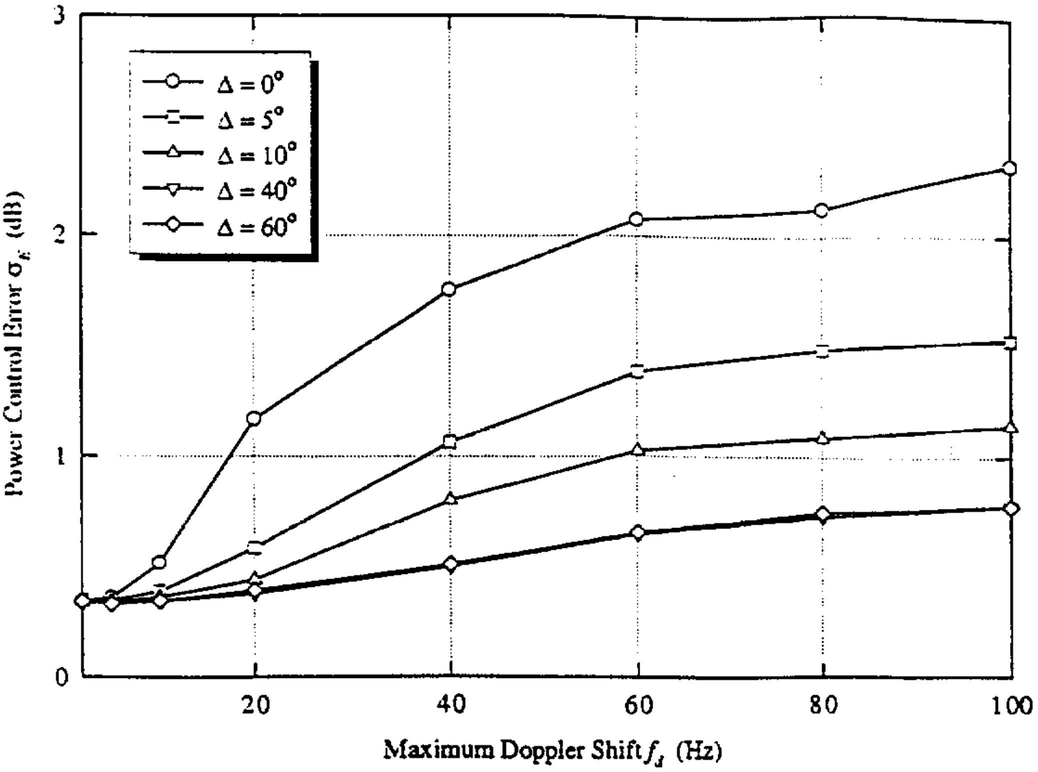


Fig.15 Power control error vs. Angle spread , L = 4, K = 9, [16]

5. EFFECT OF POWER CONTROL ON A CDMA SYSTEM CAPACITY

It has been pointed out in [4] that the forward link capacity with power control is smaller than the reverse link capacity. It is necessary to increase the number of users in the forward link to have similar capacity for both forward link and reverse link and to provide similar C/I ratio for acceptable performance.

5.1 Forward link capacity

5.1.1 nth-power-of-distance power control law

Considering the two tiers of cells, the forward link interference geometry is shown in fig.16. The forward link capacity is given by M(r, θ) is given by [17]

$$M(r,\theta)=\frac{\left[\left(C/I\right)_{req}+1\right]\cdot F_j}{\left(C/I\right)_{erq}\cdot f\left(r_o\right)\cdot x_I} \tag{20}$$

where

$$F_j=\begin{cases}\left(\dfrac{r_o}{R}\right)^n & \text{for } 0\le r\le r_o\\ \left(\dfrac{r}{R}\right)^n & \text{for } r_o\le r\le R\end{cases}. \tag{21}$$

$$f\left(r_o\right)=\frac{2}{n+2}+\frac{n}{n+2}\left(\frac{r_o}{R}\right)^n \tag{22}$$

x_I is the total interference factor. Since M depends on r, θ, r_o, to achieve at last the required C/I ratio in all locations, the minimum value of M(r, θ) is chosen as the system capacity of the forward link.

5.1.2 Optimum power control

For required C/I ratio, the capacity can be written as [17]

$$M=\frac{1}{\left(C/I\right)_{req}\cdot\dfrac{12}{\pi R^2\int_0^{30^o}\int_0^R x_I(r,\theta)\ r\ dr\ d\theta}} \tag{23}$$

Evaluating eq. (23) numerically, the approximate expressions are

for m=2, $$M=\frac{0.3424}{\left(C/I\right)_{req}} \tag{24}$$

for m=3, $$M=\frac{0.4921}{\left(C/I\right)_{req}} \tag{25}$$

for m=4, $$M=\frac{0.5794}{\left(C/I\right)_{req}} \tag{26}$$

for a give C/I ratio M is constant for users at any location. If M is fixed, C/I is a constant. The system can then provide uniform service for all users within the cell.

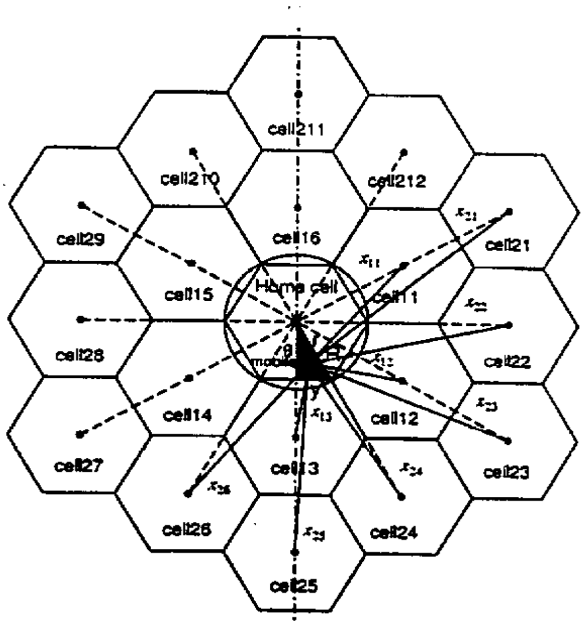


Fig.16 Forward link interference geometry[17]

Considering $(C/I)_{req} = 0.01792$, $M(r, \theta)$ is plotted in fig.17 for $r_o/R = 0.$ 0.6, 1.0 and $\theta = 0^0, 10^0, 20^0, 30^0$. Case A ($r_o/R = 1.0$) corresponds to the case when no power control is used. Case B ($r_o/R = 0$) corresponds to the power control scheme without threshold adjustment. Case C ($r_o/R = 0.6$) corresponds to the power control scheme with power threshold adjustment. In case A, M decreases as r/R increases because equal power is transmitted to users at any location within each cell. The signal received by the far end users becomes weak. To maintain the required C/I ratio, the number of users that can be supported will be decreased. In case B, capacity increases as r/R increases due to reduction of the transmitted power for the near-in users. Case A only benefits the close-in users and case B only benefits the far end users. Both cases are not acceptable for system design. Adjusting the transmitted power for the close-in users, we obtain curve C, which is the best case for path loss exponent m=4. The minimum value of $M(r,\theta)$ is 30.08 users/cell at $r/R = 1.0$ & $\theta = 30^0$, which is chosen as system capacity. When $r/R > 0.6$, the capacity increases to a maximum value and then decreases because the far-end users are more sensitive to the adjacent cell interference. From curves A, B, & C, capacity M is different for $\theta = 0^0, 10^0, 20^0, 30^0$, indicating that the capacity is also impacted by the direction of users.

Fig.18 plots the capacity M for different path loss exponents m=2, 3, 4 and $\theta = 0^0, 10^0, 20^0, 30^0$. Curves A, B and C are the case where the largest minimum capacity for each m is obtained. It can be observed that the capacity for m=4 is obviously larger than m=2 and m=3. This is due to the smaller impact the out-of-cell interference when the path loss becomes larger.

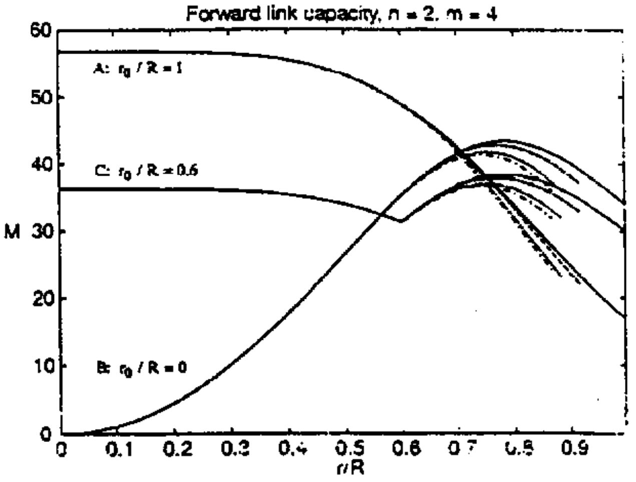


Fig. 17 Forward link capacity M versus r/R for n=2, m=4 and $\theta = 0^0$ *(-,-),*
$\theta = 10^0$ *(-,-),*$\theta = 20^0$ *(-,-),*$\theta = 30^0$ *(-,-),[17]*

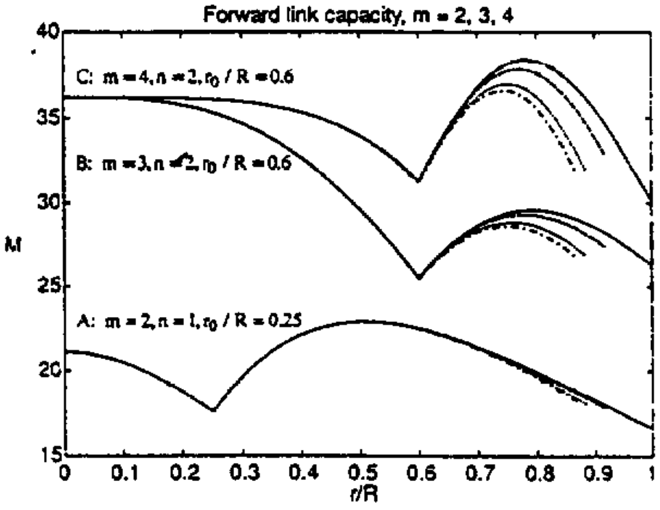


Fig. 18 Forward link capacity M versus r/R for $\theta = 0^0$ *(-,-),*
$\theta = 10^o$ *(-,-),*$\theta = 20^o$ *(-,-),*$\theta = 30^o$ *(-,-),[17]*

5.2 Reverse link capacity

For a required C/I ratio, $M_{R,}$ capacity of the reverse link with power control, has to satisfy [17]

$$M_R = \frac{\frac{1}{(C/I)_{req}} + 1}{\left[1 + I(n)_n\right]} \tag{27}$$

where I(n) is a constant, M_R is also a constant for users at different locations within the cell.

In table (2), the forward link capacity for the two power control schemes are compared with the reverse link capacity with power control. Adapting the optimum power control scheme, it can be found that the capacity of the forward link is slightly smaller than that of the reverse link, but they are very close. When m=4, employing the nth-power-of-distance power control scheme can achieve about 93 % of the optimum capacity and percentage of the cases m=2, and m=3 are 87 % and 93 % respectively.

Table (2), Forward link capacity and reverse link capacity with power control,[17]

	Path loss exponent m	m = 2	m = 3	m=4
Forward link capacity	*n*th-power-of-distance-power control law	16.63	25.48	30.08
	optimum distance and direction dependent power control law	19.11	27.46	32.33
Reverse link capacity	power control	19.43	27.87	32.53

6. THE EFFECT OF IMPERFECT POWER CONTROL IN CELLUAR CDMA SYSTEMS

When the power control is not ideal, the error is assumed to be log-normally distributed with standard deviation of σ (dB), [17] .

6.1 *n*th-power of distance power control error

The effect of power control error can be studied by multiplying the transmitted power by a log-normal random variable. The received power for a mobile is written as

$$\mathrm{Pr} = \mathrm{Pt} \cdot r^{-4} \cdot 10^{\frac{\gamma}{10}}$$

where Pt is the transmitter power. R is the distance between the transmitter and the receiver. γ is a zero mean Gaussian random variable with a standard deviation
σ = 0dB, the case is corresponding to perfect power control (i.e. for the case of n^{th} power of distance power control scheme). If power control is not perfect, σ is assumed to be 1~4 dB. The pdf of the received power is expressed as

$$f(pr) = \frac{1}{\sqrt{2\pi}} \exp\left\{ \frac{-\left[\log_{10}(\mathrm{Pr}) - \log_{10}(\overline{\mathrm{Pr}})\right]^2}{2\sigma^2} \right\} \qquad (28)$$

and the mean received power for a mobile is given by

$$\overline{\mathrm{Pr}} = \mathrm{Pt}.r^{-4}$$

Assuming that a service area is covered by two tiers of hexagonal cells (total 19 cells), each with a base station in the center. N mobiles are uniformly distributed in each cell. The interference model is shown in fig.19.

6.1.1 Forward link C/I ratio

In the presence of power control error, the total interference power received for the *j*th mobile in the home cell is

$$I_j = \sum_{i=0}^{18}\left[\sum_{k=1}^{N}\left(Pt_{ik}\cdot 10^{\frac{\gamma_{ik}}{10}}\right)\cdot x'_{ij}\right] - Pt_{0j}\cdot x_{0j}^{-4}\cdot 10^{\frac{\gamma_{0j}}{10}} \qquad (29)$$

where x_{ij} is the distance between *i*th base station and the *j*th mobile within the home cell. Pt_{ik} is the transmitted power for the *k*th mobile inside the *i*th cell under perfect control. The C/I ratio for the *j*th mobile in the home cell will be

$$C/I = \frac{Pt_{0j}\cdot x_{0j}^{-4}\cdot 10^{\frac{\gamma_{0j}}{10}}}{I_j}$$

6.1.2 Reverse link C/I ratio

In the reverse link, the total interference power received at the base station for the *j*th mobile within home cell becomes

$$I_j = \sum_{i=0}^{18}\sum_{k=1}^{N}\left[P_c\cdot\left(\frac{r_{ik}}{x'_{ik}}\right)^4\cdot 10^{\frac{\gamma_{ik}}{10}}\right] - P_c\cdot 10^{\frac{\gamma_{0j}}{10}} \qquad (30)$$

where x'_{ik} is the distance between the *k*th mobile in the *i*th cell and the home base station. r_{ik} is the distance between the *k*th mobile in cell *i* and its base station. The C/I ratio for the desired mobile is given by

$$C/I = \frac{P_c\cdot 10^{\frac{\gamma_{0j}}{10}}}{I_j}$$

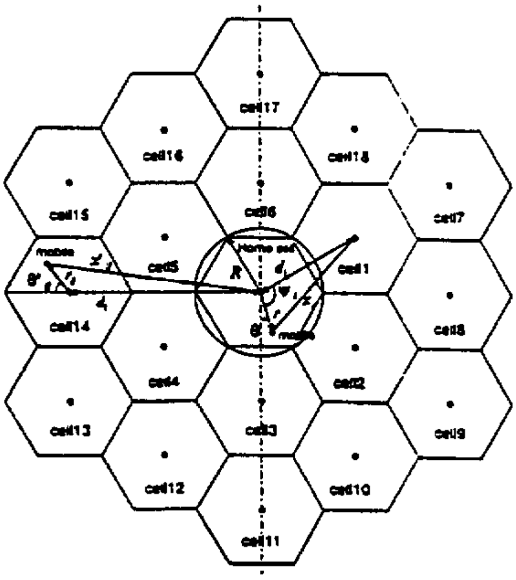


Fig.19 Forward link and reverse link interference model, [5].

6.1.3 Outage probability analysis

In mobile cellular systems, outage probability is generally used to evaluate the capacity. It is defined as the failing probability to achieve a required C/I ratio. It is well known that

$$\Pr\left[C/I < (C/I)_{req}\right] = \frac{1}{2} + \frac{1}{2}\operatorname{erf}\left[\frac{(C/I)_{req} - m_{CI}}{\sqrt{2}\sigma_{CI}}\right] \tag{31}$$

where $\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt.$

The mean C/I (in dB) is

$$\begin{aligned} m_{CI} &= 10\log_{10}(Pr) - 10\log_{10}(I) \\ &= 10\log_{10}(\overline{Pr}/\bar{I}) - \frac{\ln 10}{20}(\sigma^2 - \sigma_I^2) \end{aligned} \tag{32}$$

$\overline{Pr}/\bar{I}$ is the mean-carrier-power to mean-interference power ratio. The total interference is also approximately log-normal with standard deviation σ_I which depends on the location of the mobile in the forward link, σ_I is a function of the mobile changes. The variance C/I is

$$\sigma_{CI}^2 = \sigma^2 + \sigma_I^2 \tag{33}$$

The outage probability is obtained by

$$P_o = \int_\theta\int_r \Pr\left[C/I < (C/I)_{req}\right]\cdot f(r,\theta)\, r\, dr d\theta \tag{34}$$

where f(r,θ) stands for pdf for the location of a desired mobile. The double integral denotes one hexagonal cell coverage area.

Fig.20 Shows σ_I against r/R for the *n*th-power control when N=30 users/cell and θ =π/6, for required C/I=0.01792 (-17.47 dB), n=2, r_o/R=0.6. It can be seen that σ_I decreases as r/R increases due to the larger impact of the out of cell users. It is also noted that σ_I is higher for a larger σ.

The effect of imperfect power control is depicted in fig.21 for the forward and the reverse links. In the situation with perfect power control , σ = 0 dB. For the same capacity, the outage probability increases with increase in σ. When N=30 users/cell and using *n*th-power-of distance power control, P_o=0.13 for σ = 1dB, P_o=0.46 for σ = 3dB and P_o=0.55 for σ = 4dB. Obviously, to achieve a required outage probability, the capacity will be reduced due to the non-ideal power control.

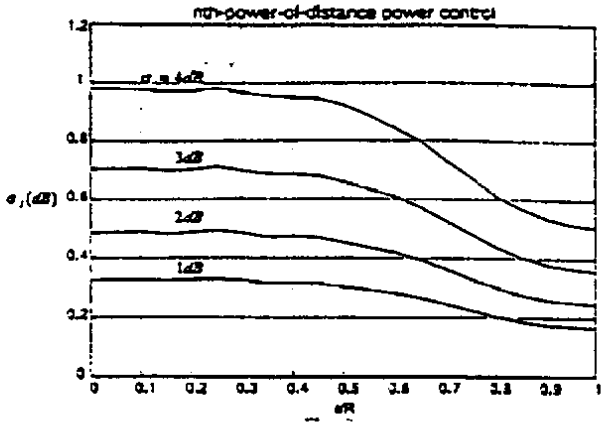
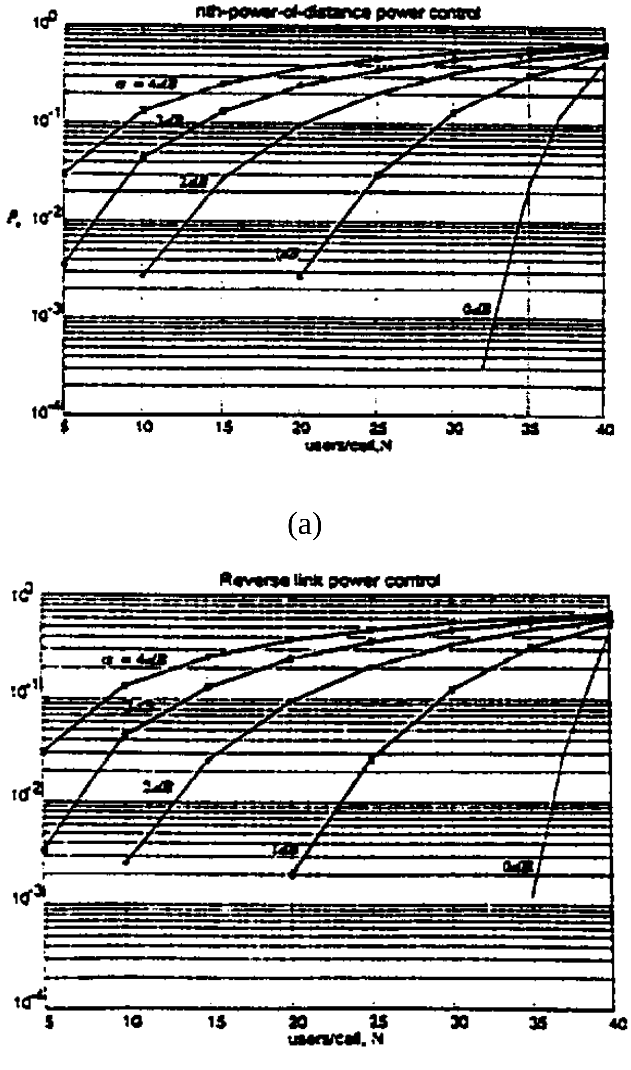


Fig.20 σ_I versus r/R for the forward link n^{th}-power-of-distance power control scheme[5]



(a)

(b*)*

Fig.21 Outage probability versus capacity (a) forward link n^{th}-power-of-distance power control (b)reverse link power control scheme [5]

10. CONCLUSION

This report has reviewed power control in CDMA cellular systems. Power control is essential to combat the near-far problem. Two mechanisms are needed to perform power control, they are open loop and closed loop, the later woks as " a fine tuning to the former ". Power control algorithms for both uplink and downlink has been presented. Power control has been shown to increase the call carrying capacity. The forward link capacity of a CDMA cellular network system has been presented with the two power control schemes: *n*th power-of-distance and optimum power control. The maximum capacities are presented for different path loss factors, and the optimum power control outperforms the *n*th power-of-distance scheme in all cases. The reverse link capacity is found to be slightly larger than that of the forward link with optimum power control for the same path loss exponent. The performance of power control algorithm is affected by power control error which is caused by power measurement error and delay in the power control process. The outage probability (which is generally used to evaluate the capacity) of the forward and reverse links in a CDMA cellular system with imperfect power control is illustrated that it is very sensitive to the power control error.

REFERENCES

[1] A. J. Viterbi, " CDMA principles of spread spectrum communications," Addison-Wesley 1995.

[2] J. G. Gipson, "The Communication Handbook," CRC Press, IEEE Press 1996.

[3] W. C. Y. Lee," Mobile Cellular Telecommunications, analog and digital systems" McGraw Hill, 1995.

[4] W. C. Y. Lee," Overview of cellular CDMA," IEEE Trans. On Veh. Technol., Vol. 40, No. 2, pp.291-302, May 1991.

[5] W. M. Tam & F. C. M. Lau, " Analysis of Imperfect Power control in CDMA Cellular systems", PIMRC 1997.

[6] K. S. Gilhousen, I.M. Jacobs, R. Padovani. A.J. Viterbi and C.E. Wheatly, " On the capacity of cellular CDMA system," IEEE Trans. Vehic. Technol., Vol. 40, No. 2, pp.303-312, May 1991.

[7] A. J. Viterbi, A. M. Viterbi and Ephraim Zehavi, " Performance of power-controlled wideband-terrestial digital communication," ," IEEE Trans. Vehicle. Technol., Vol. 41, No. 4 , pp.559-569, May 1991.

[8] Po-Rong Chang," Adaptive Fuzzy Power Control for CDMA Mobile Radio systems," IEEE Trans. Vehicle. Technol., Vol. 45, No. 2 , pp.225-236, May 1996.

[9] R. W. Nettleton and H. Aalavi " Power control for spread spectrum radio systems." In EEE Vehicle. Tech. Conference VTC-83, pp. 242-246, 1983.

[10] S. A. Grandhi, R. Vijayan, D. J. Goodman, and J. Zander " Centralized power control in cellular radio systems, " IEEE Trans. Vehicle. Technol., Vol. 42, No. 4, pp. 466-468, November 1993.

[11] J. Zander " Performance of optimum transmitter power control in cellular radio systems." IEEE Trans. Vehicle. Technol., Vol. 41, No. 1, pp. 57-62, February 1992.

[12] G. J. Foschini and Z. Miljanic " A simple distributed autonomous power control algorithm and its convergence "IEEE Trans. Vehicle. Technol., Vol. 42, No. 4, pp. 641-646, November 1993.

[13] R. D. Yates “ A framework for uplink power control in cellular radio systems” IEEE JASC 13(7): 1341-1347, September 1995.

[14] S. Ulukus and R. D. Yates “Power Control Using Stochastic Measurements” 34th Annual Allerton Conference on Communication, Control and Computing, October, 1996

[15] D. Kim “ Downlink power allocation and adjustment for CDMA cellular systems.” IEEE comm. Letters vol. 1, No. 4, July 1997.

[16] A. F. Naguib “ Adaptive antennas for CDMA wireless network” Ph.D. dissertation Stanford university, 1996.

[17] T. W. Man, F.C.M. Lau “Capacity Analysis of a CDMA Cellular System with Power Control Schemes” ICUPC '97.

[18] R. R. Gejji, “Forward-link power control on CDMA cellular systems, “IEEE Trans. Vehicle. Technol., Vol. 41, No. 4, pp. 532-536, November 1992.

[19] S. Ariyavisitakul “ Signal and interference statistical of CDMA system with Feedback power control “ IEEE trans. Vol. 41, No. 11, November 1993.

[20] M. Raitola “ CDMA overview “ report for Licentiate course on signal processing in communication S-38.220, Fall-97, Telecommunication lab. Helsinki University of Technology.

[21] Qualcomm home page. http://www.qualcomm.com/ProdTech/newmedia/ 31/10/97.

[22] CDMA Development Group home page. October 31, 1997. http://www.cdg.org/