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LETTER

Effects of Power Control Error on the System User Capacity of DS/CDMA Cellular Mobile Radios

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SUMMARY User capacity of a DS/CDMA cellular mobile radio system employing transmitter power control (TPC) is investigated. Assuming log-normally distributed control error, outage probability is evaluated through computer simulations. The user capacity is dramatically decreased as the power control error increases. If the standard deviation is larger than about 2dB, the user capacity is decreased by more than 60%. It is shown that power control error with a standard deviation of less than or equal to 0.5dB is required to accommodate 90% of the maximum user capacity. The capacity decrease in the reverse and forward link channels due to non-uniform user distributions are also investigated. It is shown that if system users are densely distributed within the zone fringe whose thickness is 80% of the radius, the reverse link capacity is decreased by about 22%. The forward link capacity is comparatively insenstitive to non-uniform user distribution.

key words: *power control, CDMA, spread spectrum, user capacity, cellular system*

1. Introduction

Recently, applications of the direct sequence code division multiple access (DS/CDMA) scheme to digital cellular mobile and personal radio systems have attracted much attention because of the possibility of greatly increased system user capacity(1),(2). One difficult problem in applying the DS/CDMA scheme to cellular mobile radios is the near-far problem: received signals from transmitters close to the receiver are strong, while those from far transmitters are weak. Insufficient signal to interference power ratio (SIR) increases bit error rate (BER) which leads to degraded communication quality. On the other hand, excessive signal powers increase the interference to all the other users sharing the DS/CDMA channel. The system user capacity is maximized when all transmitted signals are received at the minimum power for the SIR. Therefore, transmitter power control (TPC) is essential in the DS/CDMA system to mitigate the near-far problem, and to increase system user capacity.

A TPC system including reverse link (mobile to base) and forward link (base to mobile) has been proposed by Ref. (3). It has been shown that, assuming the proposed TPC system has perfect power control accuracy, 40 users/cell can be supported in the 1.25 MHz bandwidth if the speech activation factor is 3/8. This user capacity can farther be tripled with sectored cell configuration (120° sector). Consequently, about 20 times the current user capacity of the North American analog system (30 kHz channel spacing) can be achieved (4). However, inaccurate power control decreases the user capacity, and it is important in DS/CDMA system design to evaluate the effects of imperfect TPC on the system user capacity.

Another factor which decrease user capacity is non-uniform user distribution within the radio zone. If a user is located in the zone fringe area, he is likely to increase reverse link (mobile to base) transmission power because of the attenuation in the received signal power due to the distance between the mobile and base stations. Also, the forward link (base to mobile) transmission power to a mobile user in the zone fringe area may have to be increased because the zone fringe area is prone to interference from the signals transmitted from the adjacent cell base station. Therefore, if users densely distribute in the zone fringe area, the results is that interference power increases for other users.

This letter presents simulation results for the user capacity estimation of a DS/CDMA cellular mobile radio system employing the TPC scheme proposed by Ref. (3), and shows by how much the inaccurate power control decreases the user capacity. Also, the capacity decreases in the reverse and forward link channels due to non-uniform user distributions are evaluated through computer simulations. Section 2 briefly summarizes the TPC scheme. Section 3 investigates the effects of the imperfect TPC. Section 4 presents the system user capacity under the non-uniform user distribution. Section 5 estimates the effect of the imperfect TPC combined with the non-uniform user distribution effect.

2. TPC Schemes

The TPC system is comprised of reverse link and forward link TPC's(5). The reverse link TPC ensures that all the signals transmitted by the mobile transmitters in the radio zone arrive at the base station with just the minimum power. This can be done by a combina-

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tion of open loop and closed loop control. In open loop control, each mobile station estimates the signal strength of the base station by measuring the received power of a broadcast pilot signal, and controls its transmission power. In closed loop control, the base station measures the received powers of the signals as transmitted by the mobile stations in the radio zone, and sends power control commands to them.

The forward link TPC controls the base station transmitter power such that each mobile receiver can receive the transmitted signals with the received SIR equal to or larger than the required minimum value. For this purpose, the transmission power to a mobile in the zone fringe is relatively increased because it is prone to interference from another cell's base stations; conversely, the transmission power for mobiles in the zone center is decreased.

Wideband transmission(6) leads to many propagation paths which can provide independent diversity branches to the receiver. Diversity reception reduces the envelope variation due to fading, and thus, deep fades typically encountered in narrow band transmission no longer appear. Therefore, it is a reasonable assumption that the envelope variation remains after power control is regarded as control error whose values are assumed to distribute over a certain distribution function (pdf). Hence, random variables distributed over the pdf were generated in the computer simulations, and used as the power control error.

3. Effects of Imperfect TPC

3.1 Reverse Link TPC

An ideal hexagonal cell layout as described in Fig. 1 is assumed. Every base station is assumed to transmit a pilot signal. Without the reverse link TPC the i-th mobile receiver receives the pilot signal transmitted from the j-th base station with power of

$$I_{ij} = T_p \cdot r_{ij}^{-\rho} \cdot 10^{(\eta/10)} \quad (1)$$

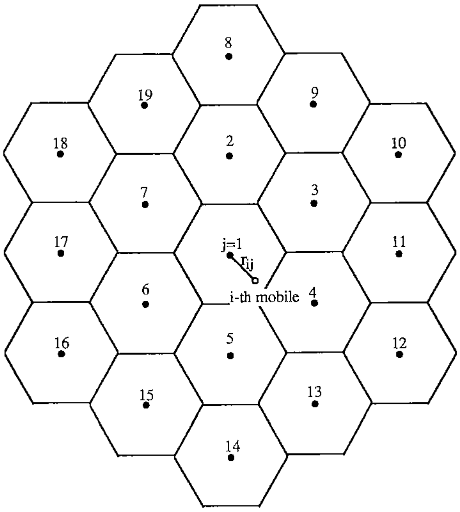

Fig. 1 Hexagonal cell layout.

where T_p is the transmitted pilot signal power of a base station, r_{ij} is the distance between the i-th mobile and the j-th base stations, ρ is the propagation constant, and η is a random variable corresponding to shadowing which is log-normally distributed with mean of 0 dB and a standard deviation of σ_S dB. The i-th mobile transmitter transmits signal to a base station whose pilot signal power received by the mobile receiver statisfies

$$A_i = \operatorname*{Max}_{j}(I_{ij}). \quad (2)$$

The reverse link TPC determines the transmission power of the i-th mobile so that the transmitted signal arrives at the j-th base station with power of

$$P_B(i, j) = \frac{I_{ij}}{A_i}. \quad (3)$$

However, because of imperfect TPC, the received power deviates from its correct value $P_B(i, j)$ as

$$P'_B(i, j) = \frac{I_{ij}}{10^{(\delta_i/10)} \cdot A_i} \quad (4)$$

where δ_i (in decibel) denotes the control error in the transmitter power. Fading envelope variation is assumed to be almost completely eliminated with broadband transmission, and the small remaining envelope variation is assumed to be included in the control error. The total amount of the interference power S received by the j-th base station is expressed as

$$S = \sum_{i=1}^{m \cdot n} \{\Psi_i \cdot P'_B(i, j)\} \quad (5)$$

where n is the number of the mobile stations in a cell, m is the number of the cells in the entire service area, and Ψ_i denotes the speech state: $\Psi_i = 1$ corresponds to the active state in which voice signal transmission is required, and $\Psi_i = 0$ corresponds to the non active state wherein no signal transmission is required. $\Psi_i = 1$ happens with a probability of α and $\Psi_i = 0$ with a probability of $1 - \alpha$. Since the received SIR in the reverse link is approximated as

$$\frac{1}{\mathrm{SIR}} \cong \frac{S}{P'_B(i, j)} \quad (6)$$

the required communication quality is realized if(3)

$$\frac{1}{\mathrm{SIR}} \leqq \frac{W}{R} \frac{1}{E_b/N_0} \quad (7)$$

where E_b/N_0 is the required signal energy per information bit-to-noise power spectral density ratio, W is the spread spectrum bandwidth and R is the information bit rate.

Assuming that in the computer simulations, system users were uniformly distributed in the service area, the i-th user location was determined as a two-dimensional uniformly distributed random variable with range covering all areas considered. Cells in the third rings of the hexagonal cell layout were considered ($m=19$ was assumed in the simulations). n users were uniformly located over each of the 19 cells. For each user location a log-normally distributed random variable $10^{\eta/10}$ with a standard deviation of σ_S (in decibel), which represents shadowing, was generated and multiplied by $r_{ij}^{-\rho}$. A uniformly distributed random variable with range of [0, 1) was generated to determine the speech state: $\Psi_i=1$ if the generated random variable is smaller than α, and $\Psi_i=0$ if it is larger than or equal to α. All users that satisfied Eq. (7) were counted up. This trial was repeated many times for each value of N. The probability that for a certain user, his reverse link communication quality was worse than required was evaluated.

Assuming that power control error $10^{\delta i/10}$ has a log-normal pdf with a standard deviation of σ_E (in decibel), another random variable having the log-normal pdf was generated, and used as the power control error term. Figure 2 shows the simulation result for system user capacity in the reverse link versus the average outage probability with σ_E as a parameter. We assumed the spread spectrum bandwidth was 1.25 MHz, the information bit rate was 8 kb/s, the speech activation factor α was 3/8 and the required E_b/N_0 was 7dB. The values of the propagation constant ρ and shadowing standard deviation σ_S used are $\rho=4$ and $\sigma_S=8$ dB. It is found from this figure that if $\sigma_E=0$ dB, the outage probability that the reverse link quality requirement of $E_b/N_0>7$ dB is not satisfied in a radio zone is about 1% when the system user capacity is 36 users/cell. This almost equals the value presented by Ref. (3). If $\sigma_E=0.5$ dB, the capacity is reduced to 32 users/cell. This is about a 10% reduction. The reduction is 31% for $\sigma_E=1$ dB, 61% for $\sigma_E=2$ dB, and 81% for $\sigma_E=3$ dB.

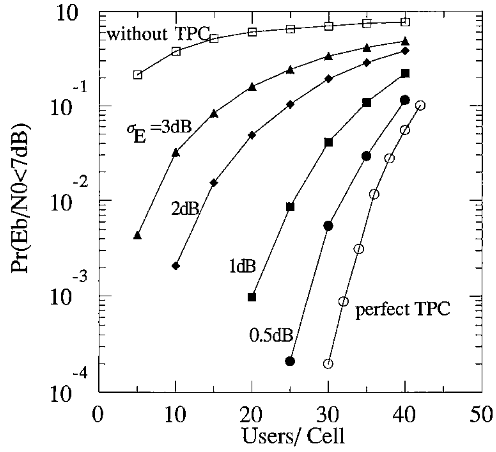

Fig. 2 Reverse link capacity under imperfect TPC.

The reverse link capacity without TPC, which is also plotted in Fig. 2, is significantly smaller than with TPC. This shows that TPC is indispensable.

3. 2 Forward Link TPC

The total amount of the received interference signal power each mobile station suffers from was controlled in the simulations to be equal to or larger than a minimum specified value. All the transmitted signals (including pilot signal) arrived at the i-mobile station with power $P_M(i, j)$ of

$$P_M(i, j)=T_t\cdot r_{ij}^{-\rho}\cdot 10^{(\eta/10)} \tag{8}$$

where T_t is total transmitted power (including pilot signal) from base station. We assume that before the forward link TPC is performed, $\phi_i \cdot 100\%$ of the j-th base station transmitter power was assigned to communicate with the i-th mobile station. The interference signal power is the sum of each of signal power arriving at the mobile receiver except that of the desired signal. If $\beta\cdot 100\%$ of the total transmission power is used for signal transmission to all the mobile stations communicating with the j-th base station ($1-\beta$ is used for the pilot signal transmission), the received SIR of the i-th mobile receiver is expressed as

$$\frac{1}{\text{SIR}}\cong\frac{\sum_{j=1}^{m}P_M(i, j)}{\beta\cdot\phi_i\cdot P_M(i, j)}. \tag{9}$$

Therefore, if the power ratio of the i-th receiver (ϕ_i) is modified to

$$\phi_i'=\frac{\phi_i}{\sum_{i=1}^{n}\Psi_i\cdot\phi_i} \tag{10}$$

by the forward link TPC and if this is done for all mobile receivers, they receive their desired signals with the same SIR. However, because of the control error, the power ratio ϕ_i' deviates from its correct value of Eq. (10) as

$$\phi_i'=\frac{10^{(\delta_i/10)}\cdot\phi_i}{\sum_{i=1}^{n}\Psi_i\cdot 10^{(\delta_i/10)}\cdot\phi_i} \tag{11}$$

where δ_i (in decibel) denotes the control error in the transmitter power assignment. Hence, the required forward link communication quality is realized if

$$\frac{1}{\text{SIR}}\cong\frac{\sum_{j=1}^{M}P_M(i, j)}{\beta\cdot\phi_i'\cdot P_M(i, j)}\leq\frac{W}{R}\frac{1}{E_b/N_0}. \tag{12}$$

As in the computer simulations for the reverse link TPC, system users were assumed to be uniformly distributed in the cell area. The random variables used in the forward link TPC simulation were generated in the same way as explained in the reverse link TPC

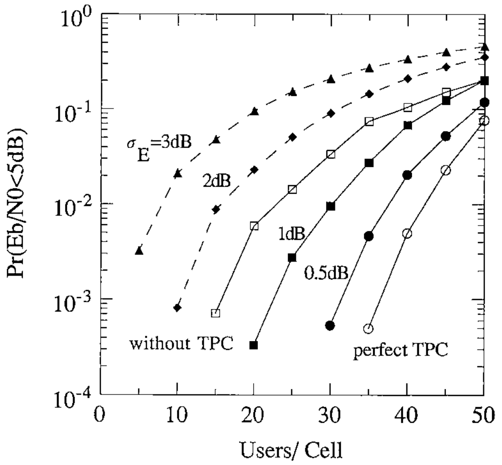

Fig. 3 Forward link capacity under imperfect TPC.

simulation. The users satisfying Eq. (12) in the forward link were counted up. This trial was repeated many times for each value of n. The probability that for a certain user, his forward link communication quality was worse than required was evaluated.

Figure 3 shows the simulation results for the system user capacity in the forward link versus the average outage probability with σ_E as a parameter. The required E_b/N_0 of 5 dB and the power ratio of $1-\beta=$ 0.2 for the pilot signal transmission were assumed. Other parameter values were the same as those used in the reverse link TPC simulation. The forward link capacity without TPC is also plotted. It is found from Fig. 3 that if $\sigma_E=0$ dB , the forward link capacity is larger than that presented by Ref. (3). This is probably, because the outage probability given by Ref. (3) is an upper-bound (Chernoff bound approach was used in Ref. (3), and that yields only a rough estimation). If $\sigma_E=0.5$ dB, the reduction in user capacity is about 10%. The reduction is 29% for $\sigma_E=1$ dB, 64% for $\sigma_E=2$ dB, and 83% for $\sigma_E=3$ dB. If $\sigma_E \geqq 2$ dB, no improvement in the forward link capacity is achieved over that without TPC. This implies that the variation in the received interference power from the surrounding cells is less than 2 dB.

4. Non-Uniform User Distribution

A mobile user in the zone fringe area is likely to increase his reverse link transmission power because of the attenuation in the received pilot signal power due to the distance between the mobile and base stations. Also, such a mobile user may require the forward link transmission power to be increased because the zone fringe area is prone to interference from signals transmitted from adjacent cell base stations. Therefore, if users are densely distributed in the zone fringe area, interference power to other cells in both reverse and forward links may increase, which will decrease user capacity. Computer simulations were conducted in order to estimate this effect on system user capacity.

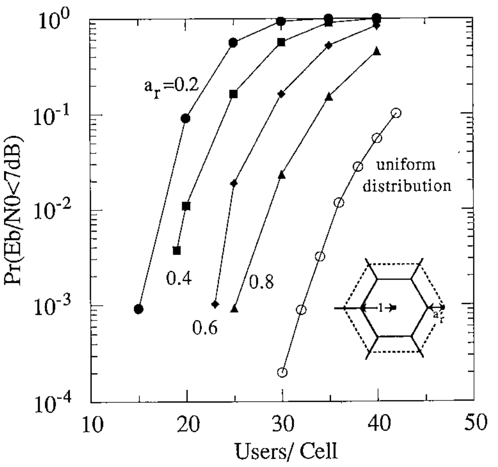

Fig. 4 Reverse link capacity under non-uniform user distribution.

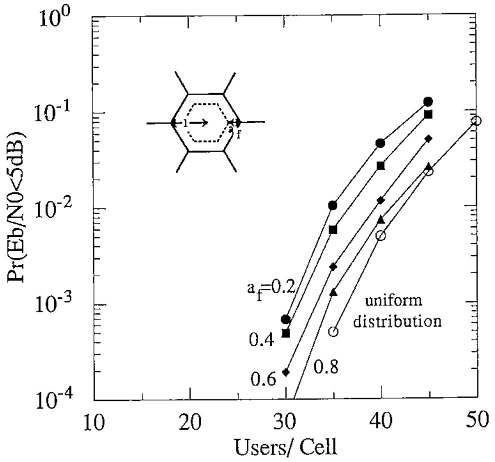

Fig. 5 Forward link capacity under non-uniform user distribution.

To simulate the effect of non-uniform user distribution we determined the effect on one cell from six surround cells, the users of which were concentrated into adjacent fringe zones as shown in the inset sketch in Fig. 4. User locations were taken as two dimensional random variables whose range covered the fringe zone. Figure 4 shows the simulation results for the reverse link capacity versus the average outage probability with the ratio a_r of the zone thickness to the cell radius as a parameter. It is found from this figure that if all users are densely distributed within the zone with $a_r=0.8$, the forward link capacity that yields 1% outage probability is reduced from 36 users/cell to 28 users/cell. This is about a 22% decrease. The capacity decrease due to the non-uniform user distribution is increased as the value of a_r becomes smaller.

For the forward link capacity estimation under non-uniform user distribution, the user location in a certain cell was determined as a two-dimensional uniformly distributed random variable ranging over the peripheral zone (see sketch in Fig. 5). For other cells, user locations were assumed to be uniformly distributed. Figure 5 shows the simulated system user capacity of the forward link versus the average outage probability with the ratio a_f of the zone thickness to cell radius as a parameter. Similar to the decrease in the reverse link capacity, the forward link capacity is also decreased by non-uniform user distribution. It is found from Fig. 5 that the decrease in the forward link capacity is not so dramatic as in the reverse link capacity decrease. The capacity decrease is about 2% when $a_f=0.8$.

5. Combined Effects

Effects of both imperfect TPC and non-uniform user distribution on the system user capacity were also estimated through computer simulations. Figure 6 shows the relative reverse link user capacity normalized by that for the uniform user distribution and $\sigma_E=$ 0dB versus a_r with σ_E as a parameter. It is found from Fig. 6 that the reverse link capacity decreases to half the maximum capacity when $\sigma_E=0.5$ dB and $a_r=0.4$. This reduction is much larger than the sum of the individual causes. The relative forward link user capacity versus a_f is shown in Fig. 7 with σ_E as a parameter. The capacity is normalized by that with $a_f=1$ and $\sigma_E=0$ dB. For each value of σ_E, the forward link capacity is comparatively less sensitive to the value of a_f than that of the reverse link capacity. When $\sigma_E=0.5$dB, about 80% the maximum capacity is maintained with all values of a_f examined.

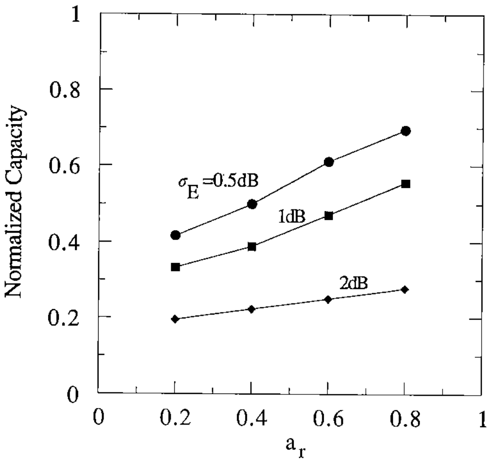

Fig. 6 Normalized reverse link capacity under imperfect TPC and non-uniform user distribution.

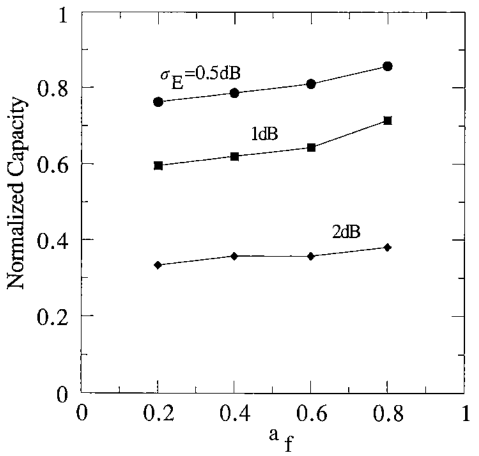

Fig. 7 Normalized forward link capacity under imperfect TPC and non-uniform user distribution.

6. Conclusions

The system user capacity of a DS/CDMA cellular mobile radio system employing TPC was evaluated through computer simulations. The user capacity was dramatically decreased as power control error increases. If the standard deviation was larger than about 2 dB, the user capacity was decreased by more than 60%. It has been shown that power control error with a standard deviation of less than or equal to 0.5 dB is required to realize 90% of the maximum user capacity. This implies that using a 1.25 MHz bandwidth with sectored cell configuration, 108 users/cell is possible with the DS/CDMA system if the power control accuracy is 0.5 dB or better. This capacity increase over the present North American analog system[(4)] is quite large. Therefore, the DS/CDMA cellular mobile radio system still remains a strong candidate for increasinguser capacity. This is only possible if the TPC scheme as a power control accuracy of at least 0.5dB.

The capacity decreases in the reverse and forward link channels due to non-uniform user distributions were also investigated. It has been shown that if system users are densely distributed within a fringe zone whose thickness is 80% of the cell radius, the reverse link capacity is decreased by about 22%. The forward link capacity is comparatively insensitive to non-uniform user distribution. It should be noticed that the desired signals transmitted from a mobile station in the zone fringe area can be received by several base stations, which suggests, at a sacrifice of complexity increase in radio channel control functions, the possibility of using site diversity reception. Site diversity would permit the transmitting power of the reverse link to be reduced so as to diminish interference to other users.

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