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Joint Effect of Transmit Power Control and Antenna Diversity on Spectrum Efficiency of a Cellular System

Fumiyuki ADACHI†, ***Regular Member***, **Akihito KATOH**†, ***and*** **Deepshikha GARG**†, ***Student Members***

SUMMARY This paper addresses a classic question about whether transmit power control (TPC) can increase the spectrum efficiency of a TDMA system and an FDMA cellular system as in the case of a DS-CDMA cellular system. Two types of TPC schemes are considered; one is slow TPC that regulates the distance dependent path loss and shadowing loss, while the other is fast TPC that regulates multipath fading as well as path loss and shadowing loss. In addition to TPC, antenna diversity reception is considered. The allowable interference rise factor χ, which is defined as the interference plus background noise-to-background noise power ratio, is introduced. The simple expressions for the signal-to-interference plus background noise power ratio (SINR) at the diversity combiner output using maximal-ratio combining (MRC) are derived to obtain the reuse distance by computer simulations. The impact of joint use of TPC and antenna diversity reception on the spectrum efficiency is discussed. It is found that the joint use of fast TPC and antenna diversity is advantageous and larger spectrum efficiency can be achieved than with no TPC. On the other hand, the use of slow TPC is found advantageous only for small values of standard deviation of shadowing loss; however, the improvement in the spectrum efficiency is quite small.
key words: *transmit power control, antenna diversity reception, cellular system, spectrum efficiency*

1. Introduction

Transmit power control (TPC) is indispensable in a direct sequence code division multiple access (DS-CDMA) cellular system to avoid the well-known near-far problem and to reduce the adverse effect of multipath fading [1], [2]. However, whether the use of TPC can improve the spectrum efficiency of other frequency-reusing cellular systems, e.g., TDMA and FDMA cellular systems, or not, is still left as an interesting question to be answered. In the TDMA and FDMA systems, the available radio channels are grouped into F groups, each group being assigned to a different cell. F is called the cluster size (in the DS-CDMA cellular system, $F = 1$ always) and is determined so that the probability of outage (the received signal quality falling below a prescribed threshold value) is kept at a design value [3]. The spectrum efficiency is inversely proportional to the cluster size F.

The interference from other co-channel cells and the background noise produces outage. When the received desired signal power fades due to multipath fading, outage due to the background noise occurs. However, outage due to interference occurs when the received interference power rises and/or the received desired signal power fades. This means that both outages should be treated together. In the practical system design, the allowable outage probability is split into two parts; one is due to co-channel interference and the other due to the background noise [4]. The allowable outage probability due to interference determines the reuse distance and the other due to the background noise determines the maximum transmit power (or the maximum cell size for the given transmit power). The use of TPC can regulate the variations in the received signal power both due to shadowing loss and multipath fading, resulting in reductions in the outage probability. However, since the use of TPC may increase the transmit power, it may not necessarily lead to increasing the spectrum efficiency. This is the motivation of this paper.

In this paper, both slow and fast TPC are considered. The slow TPC regulates the received signal power variations due to shadowing loss while the fast TPC regulates the received signal power variations due to both shadowing loss and multipath fading. In addition to TPC, antenna diversity reception is considered. The remainder of this paper is organized as follows. In Sect. 2, the frequency reuse concept of a cellular system is overviewed and a propagation model considered in this paper is presented. Section 3 derives the simple expressions for the signal-to-interference plus background noise power ratio (SINR) at the diversity combiner output to obtain the reuse distance by computer simulations. In this paper, we assume quadrature phase shift keying (QPSK) data modulation with ideal coherent demodulation to find the required SINR necessary for achieving the required BER. The computer simulation results are presented in Sect. 4. The impact of joint use of TPC and antenna diversity reception on the spectrum efficiency is discussed. Also discussed is the impact of shadowing loss correlation between the desired signal and co-channel interference. Section 5 draws some conclusions.

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†The authors are with the Department of Electrical and Communication Engineering, Graduate School of Engineering, Tohoku University, Sendai-shi, 980-8579 Japan.

Table 1 Allowable maximum reuse distance D/R to achieve the cluster size F.

F	1	3	4	7	9	12	13	16
D/R	1.32	3	3.46	4.58	5.20	6	6.24	6.93

2. Preliminaries

2.1 Frequency Reuse

If the total number of available channels is G and the cluster size is F, the number C of channels per cell is given by $C = G/F$. The spectrum efficiency is then, defined as $\mu = C/G = 1/F$. Assuming the hexagonal cell layout, F is related to the cell radius R and distance D between the nearest co-channel cells by [3]

$$F = \frac{1}{3}(D/R)^2. \tag{1}$$

F can take only limited integer numbers and $F = i^2 + j^2 + ij$, where i and j are positive integers. The allowable maximum reuse distance D/R is shown in Table 1. The value of D/R depends on the required transmission quality (often given as the bit error rate (BER)) and the propagation channel parameters (path loss exponent, shadowing loss standard deviation, multipath fading type, and diversity combining method) for the given modulation/demodulation scheme.

2.2 Propagation Channel Model

The mobile radio propagation channel can be modeled by the distance dependent path loss, log-normally distributed shadowing loss, and multipath fading [3]. Assuming frequency non-selective multipath Rayleigh fading, the received signal power P_R on a receive antenna at a distance d from a transmitting antenna can be represented as

$$P_R = P_T d^{-\beta} 10^{-\xi/10} |g|^2, \tag{2}$$

where P_T is the transmitting power, β is the path loss exponent, ξ is the shadowing loss, and g is the complex-valued path gain of multipath fading channel. ξ is a zero-mean Gaussian variable with standard deviation σ and g is a zero-mean complex Gaussian variable with unity variance. Then, the value of $|g|$ follows a Rayleigh distribution and that of $|g|^2$ is exponentially distributed [5]. The value of β ranges from 3 to 4 and that of σ ranges from 5 to 7 in a typical urban propagation environment [6].

3. Analysis

The reverse link is considered. To compute the interference power, only the six nearest co-channel cells that give predominant interference to the desired cell are considered; i = 0th cell is the cell of interest and i = 1st to 6th cells are the nearest co-channel cells surrounding the 0th cell. The worst case is that each mobile station communicating with its corresponding base station is located at the cell edge. This situation is illustrated in Fig. 1 and is assumed throughout this paper. Two types of TPC schemes are considered; one is slow TPC that regulates the distance dependent path loss and shadowing loss and the other is fast TPC that regulates multipath fading as well as path loss and shadowing loss. Antenna diversity assumes M-antenna maximal-ratio combining (MRC) [3] with independent Rayleigh fading experienced on each antenna.

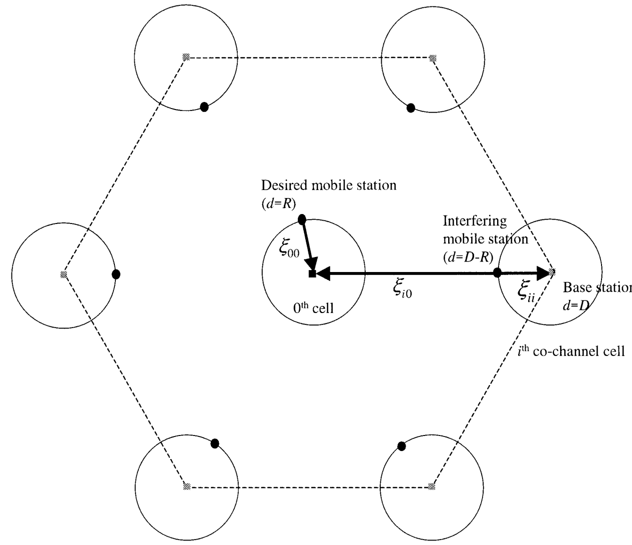


Fig. 1 Geographical relationship among 0th cell, interfering co-channel cells, and their communicating mobile stations.

3.1 No TPC

Letting P_T be the mobile transmit power which is the same for all mobile stations, the instantaneous desired signal power $S(m)$ and the instantaneous interference power $I(m)$ received on the mth antenna of the 0th cell base station are respectively given by

$$\begin{cases} S(m) = P_T R^{-\beta} |g_{00}(m)|^2 10^{-\xi_{00}/10} \\ I(m) = P_T (D-R)^{-\beta} \sum_{i=1}^{6} |g_{i0}(m)|^2 10^{-\xi_{i0}/10} \end{cases} \tag{3}$$

for $m = 0 \sim (M-1)$, where $g_{ij}(m)$ is the complex-valued path gain between the ith cell mobile station and the mth antenna of the jth cell base station and $\{g_{ij}(m)\}$ are statistically independent. ξ_{i0}, $i = 0 \sim 6$, represents the shadowing loss from an ith cell mobile station to the 0th cell base station of interest, where $\{\xi_{i0}\}$ are statistically independent.

The *local average* interference plus background noise power $\bar{I}$ (average is taken over a time interval during which the power variations due to multipath fading can be completely smoothed out but the shadowing loss remains constant) is given by

$$\bar{I} = \bar{I}(m) + N = P_T(D-R)^{-\beta}\sum_{i=1}^{6}10^{-\xi_{i0}/10} + N, \quad \text{for all } m, \tag{4}$$

where N is the background noise power. Assuming ideal MRC antenna diversity reception, the received signal on the mth antenna is multiplied by the complex conjugate of the path gain $g_{00}(m)$ of the desired signal and is combined with those of other antennas [3]. Assuming independent fading on different antennas, the instantaneous SINR at the MRC combiner output is given by

$$\lambda = \frac{\sum_{m=0}^{M-1} S(m)}{\bar{I}}. \tag{5}$$

Taking the average of Eq. (5) with respect to $g_{00}(m)$'s, the *local average* SINR, Λ, is obtained. Since $E[|g_{00}(m)|^2] = 1$ by definition, where $E[.]$ denotes ensemble average, we obtain

$$\Lambda = \frac{M(\tilde{S}/N)10^{-\xi_{00}/10}}{(\bar{I}/N)} = \frac{M(\tilde{S}/N)10^{-\xi_{00}/10}}{1 + (\tilde{S}/N)(D/R-1)^{-\beta}\sum_{i=1}^{6}10^{-\xi_{i0}/10}}, \tag{6}$$

where

$$\tilde{S}/N = (P_T/N)R^{-\beta} \tag{7}$$

is the median value of the local average received signal-to-background noise power ratio (SNR) *per antenna* at the cell edge.

Due to shadowing, the local average SINR Λ varies slowly. Outage occurs when the value of Λ falls below the required average SINR necessary to achieve the required BER. Since antenna diversity reception alters the fading statistics appearing at the MRC combiner output, the required average SINR at the MRC combiner output becomes a function of the diversity order M and it is denoted as $\Lambda_0(M)$ here. Introducing the allowable interference rise factor (defined as the interference plus background noise-to-background noise power ratio) χ (> 1), the total of median local average SNRs received on M antennas is $M\tilde{S}/N$ and is expressed as

$$M\tilde{S}/N = \chi_{no\_TPC}\Lambda_0(M). \tag{8}$$

It can be shown from Eqs. (6) and (7), that the outage occurs if

$$\chi_{no\_TPC}10^{-\xi_{00}/10} - 1 < \chi_{no\_TPC}\left[\frac{\Lambda_0(M)}{M}\right](D/R-1)^{-\beta}\sum_{i=1}^{6}10^{-\xi_{i0}/10}.$$

Note that if $\chi_{no\_TPC}10^{-\xi_{00}/10} - 1 < 0$, the outage always occurs. Letting the outage probability be Q, we obtain

$$\text{Prob}\left[\frac{M}{\Lambda_0(M)}(D/R-1)^{\beta} < H_{no\_TPC}\right] + \text{Prob}[H_{no\_TPC} < 0] = Q, \tag{9}$$

where

$$H_{no\_TPC} = \frac{\sum_{i=1}^{6}10^{-\xi_{i0}/10}}{10^{-\xi_{00}/10} - 1/\chi_{no\_TPC}}. \tag{10}$$

If the threshold value η_{no_TPC} is chosen so that $\text{Prob}[\eta_{no\_TPC} < H_{no\_TPC}] + \text{Prob}[H_{no\_TPC} < 0] = Q$, we obtain

$$\frac{D}{R} = 1 + \left[\frac{\Lambda_0(M)}{M}\eta_{no\_TPC}\right]^{1/\beta}, \tag{11}$$

from which we can compute the cluster size F_{no_TPC} using Eq. (1). For the special case of no shadowing (or the shadowing standard deviation $\sigma = 0$), i.e., $\xi_{i0} = 0$ for all i, Eq. (11) reduces to

$$\frac{D}{R} = 1 + \left[\frac{\Lambda_0(M)}{M}\frac{6}{1 - 1/\chi_{no\_TPC}}\right]^{1/\beta}. \tag{12}$$

It should be noted that the value of $\Lambda_0(M)/M$ is the required average SINR *per antenna*.

3.2 Slow TPC

Slow TPC regulates the power variations due to distance dependent path loss and shadowing; however, it cannot regulate those due to Rayleigh fading. The transmitted signal from the ith cell mobile station is received at M antennas of the i = 0th cell base station. Ideal SNR measurement is assumed. The mobile station transmit power to a base station at a distance of d is controlled in such a way that the local average received SNR at the MRC combiner output always becomes the target value $(\bar{S}/N)_t$, i.e.,

$$M(P_T/N)d^{-\beta}10^{-\xi_{ii}/10} = (\bar{S}/N)_t. \tag{13}$$

Substituting Eq. (13) with $d = R$ into Eq. (6), the local average SINR at the MRC combiner output becomes

$$\Lambda = \frac{(\bar{S}/N)_t}{\bar{I}/N}$$

$$= \frac{(\bar{S}/N)_t}{1+\dfrac{(\bar{S}/N)_t}{M}(D/R-1)^{-\beta}\sum_{i=1}^{6}10^{-(\xi_{i0}-\xi_{ii})/10}}. \quad (14)$$

The SINR at the MRC combiner output is the sum of the received SINR on each antenna. With slow TPC, the average SINR received on each antenna becomes one Mth of the target value. This leads to the reduction of the transmit power, thereby reducing the interference power received from a co-channel mobile station. This is clearly seen in Eq. (14). Since the slow TPC does not alter the fading statistics at the MRC combiner output from the case of no TPC, the required average SINR is the same as for the case of no TPC. Then, we express the TPC target value as

$$(\bar{S}/N)_t = \chi_{TPC}\Lambda_0(M), \quad (15)$$

where χ_{TPC} is the allowable interference rise factor with TPC.

Outage occurs if $\Lambda < \Lambda_0(M)$. Since $\chi_{TPC} > 1$, we obtain

$$\text{Prob}\left[\frac{M}{\Lambda_0(M)}(D/R-1)^{\beta} < H_{TPC}\right] = Q, \quad (16)$$

where

$$H_{TPC} = \frac{\sum_{i=1}^{6}10^{-\xi'_{i0}/10}}{1-1/\chi_{TPC}} \quad (17)$$

with $\xi'_{i0} = \xi_{i0} - \xi_{ii}$. If the threshold η_{TPC} is chosen such that $\text{Prob}[\eta_{TPC} < H_{TPC}] = Q$, we have

$$\frac{D}{R} = 1 + \left[\frac{\Lambda_0(M)}{M}\eta_{TPC}\right]^{1/\beta}. \quad (18)$$

It should be noted again that the value of $\Lambda_0(M)/M$ is the required average SINR per antenna. When shadowing does not exist, i.e., $\xi'_{i0} = 0$ or $\sigma = 0$, Eq. (18) reduces to

$$\frac{D}{R} = 1 + \left[\frac{\Lambda_0(M)}{M}\frac{6}{1-1/\chi_{TPC}}\right]^{1/\beta}. \quad (19)$$

Comparison of Eq. (19) and Eq. (12) implies that *the use of slow TPC is advantageous only for small values of* σ.

3.3 Fast TPC

Ideal fast TPC is assumed that can completely remove received signal power variations due to multipath fading as well as shadowing. The instantaneous transmit power of a mobile station is controlled by its communicating base station in such a way that the received SNR at the MRC combiner output is always kept at the target value $(S/N)_t$, i.e.,

$$(P_{T,i}/N)\alpha_{ii}^2 d^{-\beta}10^{-\xi_{ii}/10} = (S/N)_t, \quad (20)$$

where

$$\alpha_{ii} = \sqrt{\sum_{m=1}^{M}|g_{ii}(m)|^2} \quad (21)$$

is the equivalent path gain seen at the MRC combiner output and $g_{ii}(m)$ is the complex-valued path gain associated with the m-th antenna. $\{g_{ii}(m)\}$ are statistically independent complex Gaussian variables with unity variance.

The interference power from the i-th cell mobile station, which is received at m-th antenna of the 0th cell base station, is given by

$$I_i(m) = S(D/R-1)^{-\beta}|g_{i0}(m)|^2\alpha_{ii}^{-2}10^{-\xi'_{i0}/10}, \quad (22)$$

where $\xi'_{i0} = \xi_{i0} - \xi_{ii}$ as introduced in Eq. (17). The local average interference power is given by

$$\bar{I}(m) = \sum_{i=1}^{6}E[I_i(m)] = \frac{S}{M-1}(D/R-1)^{-\beta}\sum_{i=1}^{6}10^{-\xi'_{i0}/10}, \quad (23)$$

where we have used the following relationships [7]

$$\begin{cases} E[|g_{i0}(m)|^2] = 1 \\ E[\alpha_{ii}^{-2}] = 1/(M-1) \end{cases}. \quad (24)$$

The interference plus background noise power $\bar{I}$ is given by

$$\bar{I} = \bar{I}(m) + N = \frac{S}{M-1}(D/R-1)^{-\beta}\sum_{i=1}^{6}10^{-\xi'_{i0}/10} + N, \quad \text{for all } m. \quad (25)$$

Hence, with fast TPC, the SINR at the MRC combiner output is given by

$$\lambda = \frac{(S/N)_t}{\bar{I}/N} = \frac{(S/N)_t}{1+\dfrac{(S/N)_t}{M-1}(D/R-1)^{-\beta}\sum_{i=1}^{6}10^{-\xi'_{i0}/10}}. \quad (26)$$

When $M > 1$, the equivalent path gain, defined by Eq. (21), seen at the MRC combiner output does not become zero. From Eq. (24), the average SINR received on each antenna can be reduced by a factor of $M-1$. Therefore, the interference received from a mobile of a co-channel cell can be reduced when $M > 2$. Without diversity ($M = 1$), but with fast TPC, the transmit power must be increased significantly when the path gain approaches zero; thus, theoretically, the average transmit power becomes infinite. In order to avoid this situation, fast TPC must be jointly used with antenna diversity reception as in the case of a DS-CDMA cellular system [7].

Since fast fading can be completely removed by fast TPC, the required SINR at MRC combiner output is not anymore a function of the diversity order M and thus, denoted as λ_0. The outage occurs if $\lambda < \lambda_0$. We obtain

$$\text{Prob}\left[\frac{M-1}{\lambda_0}(D/R-1)^{\beta} < H_{TPC}\right] = Q, \tag{27}$$

where H_{TPC} is given by Eq. (17) and

$$(S/N)_t = \chi_{TPC}\lambda_0. \tag{28}$$

Since the threshold η_{TPC} that satisfies $\text{Prob}[\eta_{TPC} < H_{TPC}] = Q$ is the same for slow and fast TPC cases, we have

$$\frac{D}{R} = 1 + \left[\frac{\lambda_0}{M-1}\eta_{TPC}\right]^{1/\beta}. \tag{29}$$

When shadowing does not exist, i.e., $\xi'_{i0} = 0$ or $\sigma = 0$, Eq. (29) reduces to

$$\frac{D}{R} = 1 + \left[\frac{\lambda_0}{(M-1)}\frac{6}{(1-1/\chi_{TPC})}\right]^{1/\beta}. \tag{30}$$

Comparison of Eq. (30) and Eq. (19) is interesting. When antenna diversity is used ($M > 1$), the condition

$$\frac{M}{M-1} < \frac{\Lambda_0(M)}{\lambda_0} \tag{31}$$

holds since $\Lambda_0(M) \gg \lambda_0$. This suggests that the joint use of fast TPC and antenna diversity (i.e., $M > 1$) is always advantageous for small values of σ.

3.4 Impact of Shadowing Correlation

Same obstacles near-by a mobile station affect shadowing loss experienced at a communicating base station and that experienced at other co-channel base stations. This causes ξ_{i0} and ξ_{ii} to be correlated. When the correlation between ξ_{i0} and ξ_{ii} is ρ, the standard deviation of $\xi'_{i0} = \xi_{i0} - \xi_{ii}$ reduces to $\sigma' = \sqrt{2(1-\rho)}\sigma$, i.e., the correlated shadowing is equivalent to the uncorrelated shadowing but with a standard deviation reduced by a factor of $\sqrt{2(1-\rho)}$. The shadowing correlation was considered for capacity estimation of a power controlled DS-CDMA cellular system [8] as well as for a FDMA (TDMA) cellular system with no TPC [4]. In general, as the value of ρ increases, the random path losses to the communicating base station and co-channel base stations tend to vary in a similar manner. With TPC, this helps to reduce the interference power received at the base station of interest. An extreme case is that $\rho = 1$ and is equivalent to the no shadowing case.

In this paper, the reverse link is considered. The analytical treatment presented in this paper can be applied to the forward link case. However, the following should be remembered. The value of shadowing correlation on the forward link may be different from that on the reverse link. For example, let us consider the no TPC case. The outage probability on the forward link is impacted by the shadowing correlation between the desired signal and co-channel interference, *observed at a mobile station*. Hence, obstacles nearby a mobile station contribute to shadowing correlation. On the other hand, what affects the outage probability on the reverse link is the shadowing correlation between the desired signal and co-channel interference, *observed at the base station*. Hence, what contribute to this shadowing correlation are obstacles nearby the base station. Since the base station antenna is, in general, high enough, the shadowing correlation on the reverse link is lower compared to that on the forward link. Therefore, with no TPC, the above-discussed benefit from shadowing correlation cannot be expected on the reverse links. However, when TPC is used, shadowing correlation both observed at a mobile and a base station contribute to the outage probability. This is an interesting problem for further study.

4. Numerical Computation

We assume the path loss exponent of $\beta = 3.5$, and the outage probability of 0.1. If handoff between two base stations is taken into account, the outage probability corresponding to the single cell case is $Q = \sqrt{0.1} = 0.32$. The cluster size is calculated for the various values of σ, χ, and M. The required BER is set at $P_b = 0.001$ and 0.01. Since, in this paper, we are interested in the joint use of TPC and antenna diversity, channel coding is not considered.

With no TPC and slow TPC, the Rayleigh-faded interference is characterized by a complex Gaussian process when observed over a time interval, during which the shadowing is considered constant. Therefore, the sum of six Rayleigh faded interference waveforms can be combined with the background noise and the combined process becomes a new complex Gaussian process. This means that the theoretical BER expressions in Ref. [5] can be applied to our case. Equation (7A.20) of Ref. [5, Appendix 7A] is represented using the average SNR on each antenna. By replacing the average SNR in Eq. (7A.20) of [5, Appendix 7A] with the average SINR, Λ, at the MRC combiner output and remembering that the average SINR at the MRC combiner output is M times that on each antenna, P_b can be computed from

$$P_b=\frac{1}{2}\left[1-\frac{\mu}{\sqrt{2-\mu^2}}\sum_{k=0}^{M-1}\binom{2k}{k}\left(\frac{1-\mu^2}{4-2\mu^2}\right)^k\right] \quad (32)$$

for no TPC and slow TPC, where

$$\mu=\sqrt{\frac{\Lambda/M}{1+\Lambda/M}}. \quad (33)$$

From Eqs. (32) and (33), the required SINR Λ_0 can be numerically obtained for $P_b = 0.001$ and 0.01. On the other hand, when fast TPC is applied, the received faded co-channel interference is not anymore a Gaussian process since the transmit power from a co-channel cell mobile station varies due to fast TPC. However, here, the sum of six interferences is modeled as a complex Gaussian process based on the central limit theorem and combined with the background noise. The BER expression for fast TPC is the same as that without fading and is given by

$$P_b=(1/2)\mathrm{erfc}\sqrt{\lambda/2}. \quad (34)$$

From Eq. (34), the required SINR λ_0 can be computed for $P_b = 0.001$ and 0.01. The numerical results for λ_0 and Λ_0 are listed in Table 2 for slow TPC and fast TPC, respectively.

The cumulative distribution function (CDF) curves of H were found by Monte Carlo simulations. From the simulated CDF curves of H, the values of η are found for computing the achievable reuse distance D/R. The simulated values of η are listed in Tables 3 and 4 for the cases of no TPC and TPC, respectively. Then, the values of D/R are computed and the results are plotted in Figs. 2–5.

Table 2 Values of Λ (dB) and λ (dB) for various values of required BER P_b and diversity order M.

P_b		10^{-2}	10^{-3}
Slow TPC	M=1	Λ_0=16.9 dB	27.0 dB
	2	11.5	17.1
	3	9.9	14.3
	4	9.2	13.1
	5	8.8	12.3
Fast TPC		λ_0=7.3 dB	9.8 dB

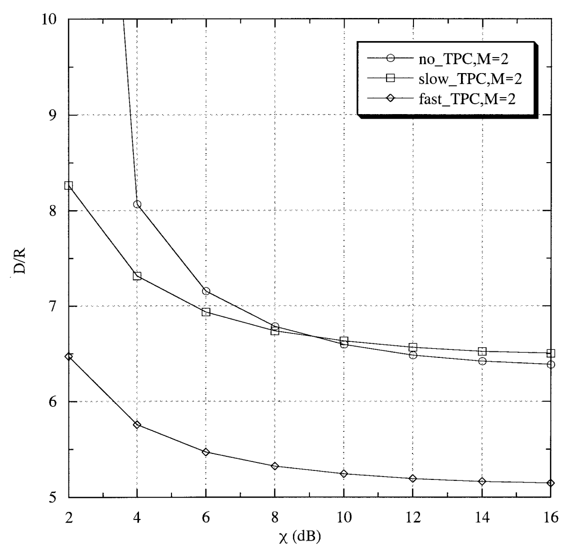
Table 3 η for no TPC.

χ (dB) \ σ	4	6	8
5	27.2	70.9	279.2
10	16.1	31.6	70.8
∞	13.5	24.8	49.4

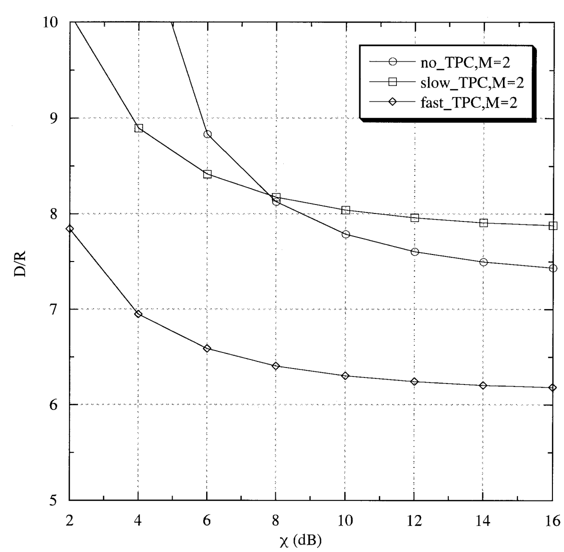
First, the impact of the selection of χ is discussed. Increasing the transmit power makes the channel to be interference-limited and this reduces the reuse distance

Table 4 η for TPC when $\rho = 0$.

χ(dB) \ σ	4	6	8
5	21.7	47.3	113.7
10	16.4	35.9	86.3
∞	14.8	32.3	77.5

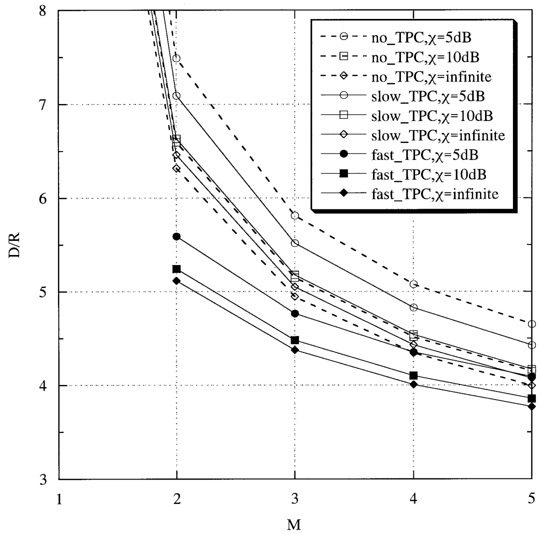


(a) $\sigma = 4$

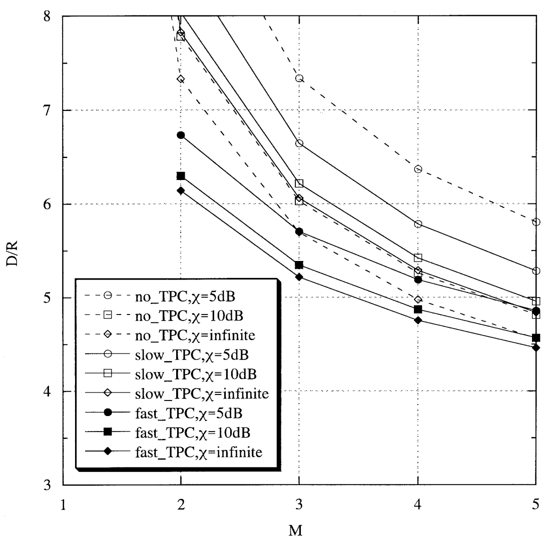


(b) $\sigma = 6$

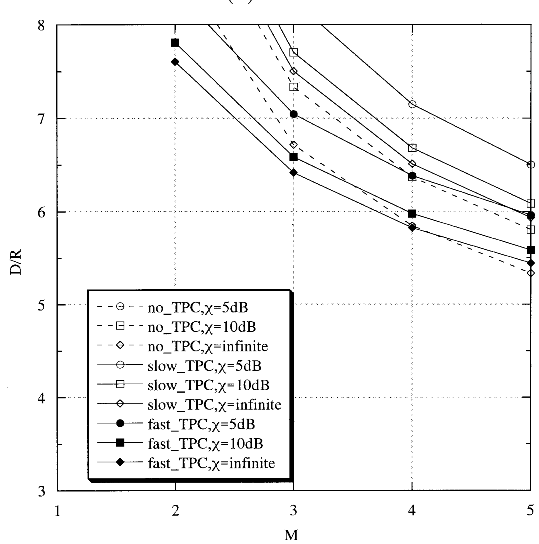
Fig. 2 Impact of allowable interference rise factor χ. $\rho = 0$, $M = 2$, and $P_b = 0.001$.



(a) $\sigma = 4$

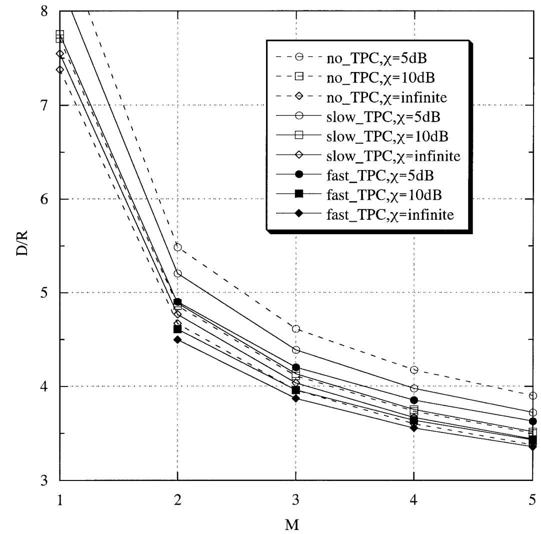


(b) $\sigma = 6$

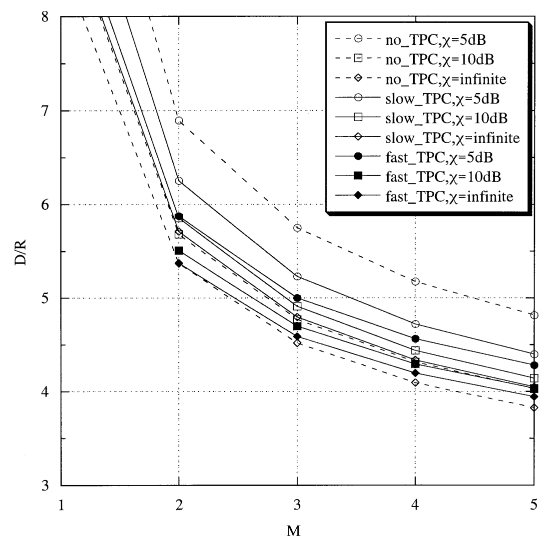


(c) $\sigma = 8$

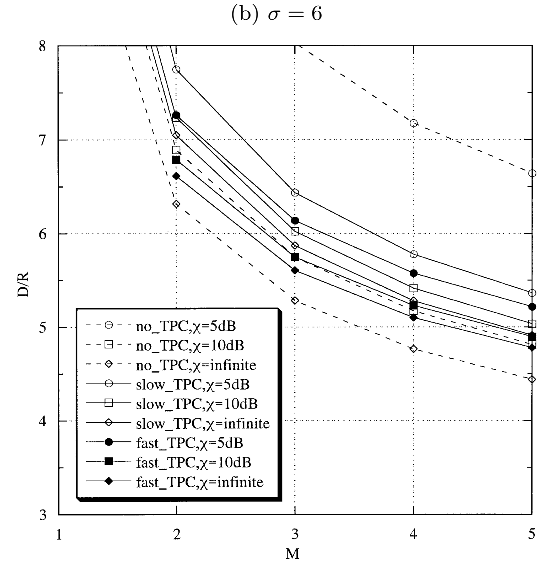
Fig. 3 D/R as a function of M for $\rho = 0$ and $P_b = 0.001$.



(a) $\sigma = 4$

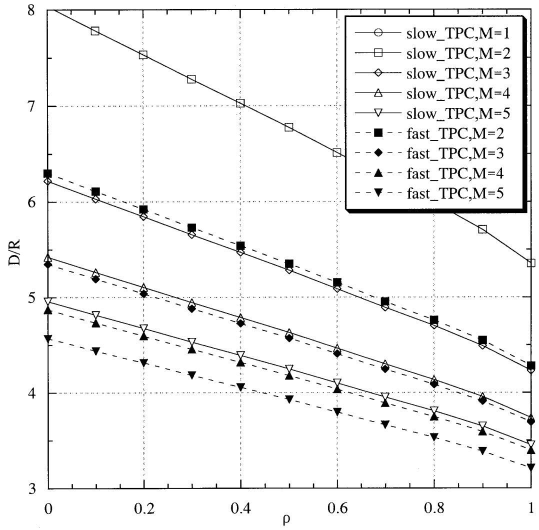


(b) $\sigma = 6$

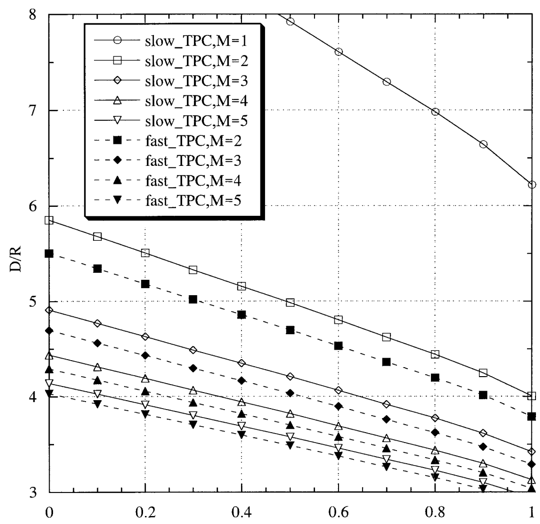


(c) $\sigma = 8$

Fig. 4 D/R as a function of M for $\rho = 0$ and $P_b = 0.01$.



(a) $P_b = 0.001$



(b) $P_b = 0.01$

Fig. 5 D/R as a function of ρ with M as a parameter. $\sigma = 6$ and $\chi = 10$ dB.

Table 5 η for TPC as a function of ρ when $\sigma = 6$ and $\chi = 10$ dB.

ρ	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
η	35.9	31.6	27.7	24.1	20.9	18.0	15.3	12.9	10.8	8.8	6.7

(thus, the cluster size). Increasing the value of χ can do this (e.g., see Eqs. (20) and (28)). Figure 2 plots the achievable reuse distances D/R as a function of χ for $\rho = 0$, $M = 2$, and $P_b = 0.001$. It is clearly seen from Fig. 2 that when $\sigma = 4$, the joint use of fast TPC and antenna diversity is always advantageous; however, the use of slow TPC is advantageous only for small values of χ. As the value of χ increases from 2 dB to 5 dB, fast TPC can reduce the reuse distance D/R from 6.5 to 5.6 (the cluster size can be reduced from $F = 16$ to 12) at the cost of increasing the transmit power by 3 dB. As the value of χ increases from 5 dB to 10 dB, D/R reduces from 5.6 to 5.2 (i.e., $F = 12$ to 9) with fast TPC. However, further increase in the value of χ can reduce the reuse distance only slightly and hence, does not help to reduce the cluster size. Similar results can be observed for $\sigma = 6$.

Next, impact of the diversity order M is discussed. It is seen from Fig. 3 that when $M = 2$, $\sigma = 4$ and $\chi = 10$ dB, the reuse distance of $D/R = 5.2$ (i.e., cluster size of $F = 9$) is possible with fast TPC, while $D/R = 6.6$ (i.e., $F = 16$) with no TPC. When M increases to 3, $D/R = 4.5$ (i.e., $F = 7$) with fast TPC, while $D/R = 5.1$ (i.e., $F = 9$) for no TPC. However, seen from Fig. 4 is that as the required BER becomes larger, e.g., $P_b = 0.01$, the advantage of using fast TPC tends to be lost. Also seen from Fig. 3 is that the advantage of the use of fast TPC tends to be lost as the value of σ increases. When $\sigma = 8$, the use of fast TPC cannot be advantageous. However, this may not be true if the shadowing loss correlation exists. This is because the shadowing correlation can reduce the equivalent standard deviation σ' as discussed in Sect. 3.3. The impact of shadowing loss correlation ρ is discussed below.

For the given value of σ, as the value of ρ increases, the equivalent standard deviation σ' becomes smaller and this leads to the reduction in the values of η. This is shown in Table 5 for $\chi = 10$ dB and $\sigma = 6$. The achievable reuse distance is plotted as a function of ρ in Fig. 5. Clearly seen from Fig. 5 is that the presence of the shadowing loss correlation can reduce the reuse distance. When antenna diversity is used, the value of D/R with no TPC was found to be 15.7, 7.3, 5.7, 5.0, and 4.6 when $M = 1, 2, 3, 4$, and 5, respectively in the case of $P_b = 0.001$. For the case of $M = 2$ and $\sigma = 6$, $D/R = 5.2$ (i.e., $F = 9$) can be achieved with fast TPC when $\rho = 0.6$, while $D/R = 6.3$ (i.e., $F = 16$) is only possible when $\rho = 0$. Furthermore, it can be seen from Fig. 5 that even slow TPC can be advantageous if $\rho > 0.2$ when $M = 2$. A similar trend can be seen for $P_b = 0.01$. These results suggest that the shadowing loss correlation is a very important factor to determine the reuse distance when TPC is used.

5. Conclusions

In this paper, simple expressions for the SINR at the diversity combiner output using MRC were derived to obtain the reuse distance by computer simulations. The impact of joint use of TPC and antenna diversity reception on the spectrum efficiency was discussed. The allowable interference rise factor χ was introduced. Larger interference rise factor means that the channel tends to become interference-limited and the outage is produced mostly by interference, thereby being able to reduce the cluster size. However, the use of too large interference rise factor requires too large transmit power for a given cell size and this may not be practical. The results obtained in this paper can be summarized as follows:

(a) The introduction of the allowable interference rise factor allows the flexible design of a cellular system. A system can be designed either with emphasis on increasing the spectrum efficiency or emphasis on reducing the transmit power by changing the allowable interference rise factor.
(b) The use of slow TPC is advantageous only for small values of χ (e.g., $\chi = 5\,\text{dB}$) and small values of σ (e.g., $\sigma = 6$) when the shadowing correlation ρ is close to zero, but the improvement is quite small.
(c) The joint use of fast TPC and antenna diversity (i.e., $M > 1$) is advantageous for small values of σ (e.g., $\sigma = 6$) if the shadowing correlation is close to zero.
(d) Advantage of the joint use of fast TPC and antenna diversity tends to be lost for large required BER (i.e., $P_b = 0.01$) if the shadowing correlation is close to zero.
(e) Presence of shadowing correlation helps to reduce the reuse distance when TPC is used. Therefore, the measurement of shadowing correlation in various propagation environments is very important for system design.

The results obtained in this paper encourage the use of fast TPC and antenna diversity reception in a TDMA or an FDMA cellular system when the shadowing correlation is present and may provide theoretical foundations for the system design. In practical systems, fast TPC requires the transmission of power control command to raise or lower the mobile transmit power at a much higher rate than the multipath fading rate. In a TDMA system, however, the power control command can be transmitted only once in each TDMA frame; e.g., the transmission rate of power control command may be in the order of 50–100 per sec. This suggests that the variations in the received signal power due to fading cannot be completely regulated in a fast fading environment resulting in degraded spectrum efficiency. The effect of channel coding on the spectrum efficiency with TPC is not discussed in this paper. It is well known [9] that fast TPC and channel coding work complementarily against fading; the former works satisfactorily in slow fading while the latter does in fast fading. The joint effect of fast TPC and channel coding on the spectrum efficiency is left for an interesting future study. As discussed in Sect. 3.4, the impact of shadowing correlation on the forward link and reverse link outage probabilities is different. Detailed analysis of the impact of shadowing correlation is also left for an interesting future work.

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Fumiyuki Adachi received his B.S. and Dr.Eng. degrees in electrical engineering from Tohoku University, Sendai, Japan, in 1973 and 1984, respectively. In April 1973, he joined the Electrical Communications Laboratories of Nippon Telegraph & Telephone Corporation (now NTT) and conducted various types of research related to digital cellular mobile communications. From July 1992 to December 1999, he was with NTT Mobile Communications Network, Inc. (now NTT DoCoMo, Inc.), where he led a research group on wideband/broadband CDMA wireless access for IMT-2000 and beyond. Since January 2000, he has been at Tohoku University, Sendai, Japan, where he is a Professor of Electrical and Communication Engineering at Graduate School of Engineering. His research interests are in CDMA and TDMA wireless access techniques, CDMA spreading code design, Rake receiver, transmit/receive antenna diversity, adaptive antenna array, bandwidth-efficient digital modulation, and channel coding, with particular application to broadband wireless communications systems. From October 1984 to September 1985, he was a United Kingdom SERC Visiting Research Fellow in the Department of Electrical Engineering and Electronics at Liverpool University. From April 1997 to March 2000, he was a visiting Professor at Nara Institute of Science and Technology, Japan. He has written chapters of three books: Y. Okumura and M. Shinji, eds., "Fundamentals of mobile communications" published in Japanese by IEICE, 1986; M. Shinji, ed., "Mobile communications" published in Japanese by Maruzen Publishing Co., 1989; and M. Kuwabara, ed., "Digital mobile communications" published in Japanese by Kagaku Shinbun-sha, 1992. He was a co-recipient of the IEICE Transactions best paper of the year award 1996 and again 1998. He is an IEEE Fellow and was a co-recipient of the IEEE Vehicular Technology Transactions best paper of the year award 1980 and again 1990 and also a recipient of Avant Garde award 2000.

Akihito Katoh received his B.S. degree in communications engineering from Tohoku University, Sendai, Japan, in 2001. Currently, he is a graduate student at the Department of Electrical and Communications Engineering, Tohoku University. His research interests include the theoretical aspects of link capacity estimation problem and adaptive transmit power control in the cellular mobile communications systems.

Deepshikha Garg received her B.E. degree in Electrical and Electronics engineering (specialization in Telecommunications) from Kathmandu University, Kathmandu, Nepal in 1998. Currently, she is a graduate student in the Department of Electrical and Communications Engineering, Tohoku University, Sendai, Japan. Her research interests include power control, channel coding, and ARQ techniques, especially for wireless communications.