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LETTER

Application of Random Transmit Power Control to DS-CDMA/TDD Packet Mobile Radio

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SUMMARY A random transmit power control (TPC) is applied to DS-CDMA/TDD packet mobile radio, which controls the transmit power so as to intentionally vary the received signal power in order to obtain the large capture effect. The uplink capacity with the random TPC in a frequency-selective fading channel is evaluated by computer simulation. The simulation results show that the random TPC provides larger link capacity than slow TPC.
key words: *DS-CDMA, packet communication, capture effect, transmit power control, link capacity*

1. Introduction

In a packet mobile communications system, a packet with larger power can survive when multiple packets collide. This is known as the capture effect [1]. In direct sequence code division multiple access (DS-CDMA), transmit power control (TPC) and Rake combining are necessary to reduce the multiple access interference [2]. There are two types of TPC: fast TPC and slow TPC [3]. Since fast TPC keeps the instantaneous received signal power constant, no capture effect is expected. On the other hand, slow TPC keeps intact the instantaneous received signal power variations due to multipath fading, thereby yielding a larger capture effect. Therefore, slow TPC achieves a larger link capacity than fast TPC [4]. However, as the number of resolvable propagation paths increases, the received power variations become less due to the increased effect of Rake combining and thus, the capture effect obtainable by slow TPC decreases.

If the transmit power can be controlled so as to intentionally vary the received signal power, a sufficient capture effect can be obtained irrespective of the number of the propagation paths. The random TPC [5]–[9] proposed and studied for non-spread narrowband systems can be applied to DS-CDMA. We apply a binary random TPC (which is the simplest version of multi-level random TPC). When applying a binary random TPC, we should notice the following important differences between a DS-CDMA system and a non-spread narrowband system:
(1) For DS-CDMA, all users share the same carrier frequency, the link capacity is limited by the multi-user interference. Therefore, if the TPC target deviation $\pm\Delta$ is increased too much in order to increase the capture effect, larger multi-user interference is produced, thereby decreasing the link capacity. Hence, the optimum value of Δ for DS-CDMA should be smaller than that for non-spread narrowband system.
(2) The number of users simultaneously transmitting their signals is much larger in the DS-CDMA system than in the narrowband system. Since the probability of $\varepsilon_\pm$ for a TPC target of $\pm\Delta$ affects the multi-user interference, the optimum probability may also be different for two systems.
(3) In a DS-CDMA system, path diversity effect is obtained by Rake combining, which resolves the propagation paths with different time delays and coherently combines them. However, due to asynchronism among different paths, inter-path interference is produced. Therefore, it is necessary to take into account the inter-path interference as well as the path diversity effect for link capacity evaluation.

In this letter, we theoretically derive an expression for the received signal-to-interference power ratio (SIR) taking into account both path diversity effect and inter-path interference. Then, we evaluate the uplink capacity by Monte-Carlo numerical computation method to find the optimum Δ and probability $\varepsilon_\pm$. Furthermore, we evaluate the impact of spreading factor SF and number L of paths.

The remainder of this letter is organized as follows. Section 2 presents the random TPC for DS-CDMA/TDD. Section 3 presents the throughput computation method under an interference-limited condition. Section 4 evaluates the link capacity by computer simulation. Section 5 gives some conclusions.

2. Random TPC for DS-CDMA/TDD

First, fast TPC based on the received signal power is considered. Assuming an ideal Rake receiver based on maximal ratio combing (MRC), the received signal power P_R at the base station after Rake combining can be expressed as

$$P_R = P_T \cdot r^{-\alpha} \cdot 10^{-\frac{\eta}{10}} \sum_{l=0}^{L-1} \left|\xi^{(l)}\right|^2, \tag{1}$$

where P_T represents the mobile station transmit power, r the distance between the base and mobile stations, α the path loss exponent, η the shadowing loss in dB, $\xi^{(l)}$ the complex path gain of the lth path, and L the number of paths. It is assumed that $E\left[\sum_{l=0}^{L-1}\left|\xi^{(l)}\right|^2\right] = 1$, where E[·] denotes the ensemble average operation. With fast TPC, the base station

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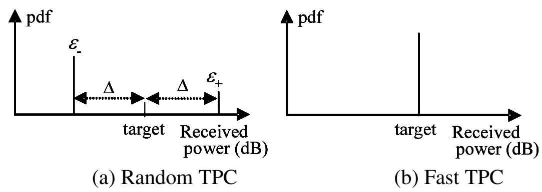

Fig. 1 Pdf of received signal power.

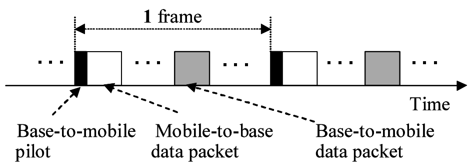

Fig. 2 Timing structure of uplink and downlink.

received signal power P_R is kept at $P_R = P_{\text{target}}$, where P_{target} is the TPC target. Therefore, the mobile station transmit power with fast TPC becomes

$$P_T = P_{\text{target}} \left[r^{-\alpha} \cdot 10^{-\frac{\eta}{10}} \cdot \sum_{l=0}^{L-1} \left| \xi^{(l)} \right|^2 \right]^{-1}. \tag{2}$$

When the fast TPC is applied, all users' signals are received with the same power P_{target} at the base station. Hence, no capture effect is obtained.

With the binary random TPC, the mobile station intentionally varies its transmit power by $\pm\Delta$ dB, with the probability of $\varepsilon_\pm$ ($\varepsilon_+ + \varepsilon_- = 1$), from its nominal power P_T given by Eq. (2). By doing so, the signal power received at the base station from a certain user becomes $P_{\text{target}} \pm \Delta$ dB with a probability of $\varepsilon_\pm$. Figure 1 shows the probability density function (pdf) of the received signal power for the random TPC and the fast TPC.

The transmit power $\tilde{P}_T$ with random TPC is given by

$$\tilde{P}_T = P_T \cdot 10^{\pm \frac{\Delta}{10}}, \tag{3}$$

where P_T is given by Eq. (2). To determine $\tilde{P}_T$, the value of $\left[r^{-\alpha} \cdot 10^{-\frac{\eta}{10}} \cdot \sum_{l=0}^{L-1} \left| \xi^{(l)} \right|^2 \right]^{-1}$ must be known. In this letter, a TDD system is considered, in which the uplink (mobile-to-base) and downlink (base-to-mobile) propagation channels are reciprocal since the same carrier frequency is used. Figure 2 illustrates the timing structure of uplink and downlink. The base station broadcasts periodically pilot signals with the known power of P_{BTp} and the mobile station measures its received power, which is denoted by P_{MRp}. The value of P_{BTp}/P_{MRp} is $\left[r^{-\alpha} \cdot 10^{-\frac{\eta}{10}} \cdot \sum_{l=0}^{L-1} \left| \xi^{(l)} \right|^2 \right]^{-1}$. Hence, $\tilde{P}_T$ in Eq. (3) is given by

$$\tilde{P}_T = P_{\text{target}} \left(\frac{P_{BTp}}{P_{MRp}} \right) 10^{\frac{\pm\Delta}{10}}. \tag{4}$$

In this way, the mobile station can determine its transmit power by itself.

3. Throughput Computation Method

In this letter, the throughput computation method for fast TPC presented in [4] is utilized and an interference-limited channel is assumed.

In a packet communications system, automatic repeat request (ARQ) is used. Assuming an infinite number of retransmissions (infinite delay is allowed before successful transmission of a packet), the throughput S is given by

$$S = 1 - p(K, \lambda), \tag{5}$$

where $p(K, \lambda)$ is the average packet error rate, with K and λ being the number of active users and the packet occurrence rate, respectively. The outage occurs if the throughput is less than the required value. The outage probability Q is defined as

$$Q = \text{Prob}[S < S_{\text{req}}], \tag{6}$$

where S_{req} is the required throughput. The link capacity is defined as the maximum number of active users that satisfies $Q \le Q_{\text{allow}}$ the allowable outage probability.

For the throughput computation, it is necessary to find $p(K, \lambda)$. We assume that the occurrence rate of original packets is the same for all active users and is denoted by λ_0. The total packet occurrence rate λ is [1+packet retransmission rate] $\times\ \lambda_0$. When TPC is used, packet errors occur equally likely for all active users and thus, λ is given by

$$\lambda = \frac{\lambda_0}{1 - p(K, \lambda)}. \tag{7}$$

Assuming that the original and retransmitted packets are randomly produced, $p(K, \lambda)$ can be computed as

$$p(K, \lambda) = \sum_{k=0}^{K-1} p(k) \cdot \begin{pmatrix} K-1 \\ k \end{pmatrix} \lambda^k (1 - \lambda)^{K-1-k}, \tag{8}$$

where $p(k)$ is the conditional packet error rate when k interfering packets collide, and $\binom{K-1}{k} = \frac{(K-1)!}{k!(K-k-1)!}$ is the binomial coefficient.

Assuming a slotted packet transmission and a block fading (the fading stays almost constant over a packet), $p(k)$ can be computed using

$$p(k) = 1 - (1 - p_b(\gamma_k))^N, \tag{9}$$

where $p_b(\gamma_k)$ is the average conditional bit error rate (BER) when k interfering packets collide, and N is the number of bits in a packet. γ_k represents the instantaneous received signal-to-interference power ratio (SIR). If it is assumed that data modulation is coherent binary phase shift keying (BPSK) and that the interference due to colliding packets can be approximated as a Gaussian process, $p_b(\gamma_k)$ is given by [10]

$$p_b(\gamma_k) = \frac{1}{2} erfc \sqrt{\frac{\gamma_k}{2}}, \tag{10}$$

where $erfc(x) = (2/\sqrt{\pi}) \int_x^\infty e^{-t^2} dt$ is the complimentary error function.

A frequency-selective block fading channel having L

discrete paths is assumed. Below, we derive an expression for γ_k to compute the packet error rate $p(k)$ using Eqs. (9) and (10). In equivalent baseband representation, the received signal $r_j(t)$ at the jth base station can be expressed as

$$r_j(t) = \sum_{i=0}^{k-1} \sqrt{2\tilde{P}_{Ti} r_{i\_j}^{-\alpha} 10^{-\frac{\eta_{i\_j}}{10}}} \sum_{l=0}^{L-1} \xi_{i\_j}^{(l)} d_i(t - \tau_{i\_j}^{(l)}) \cdot c_i(t - \tau_{i\_j}^{(l)}), \quad (11)$$

where $\tilde{P}_{Ti}$, η_{i_j}, $d_i(t)$ and $c_i(t)$ are the transmit power, the shadowing loss in dB, the data-modulated symbol waveform and the spreading chip waveform, respectively, and $\xi_{i\_j}^{(l)}$ and $\tau_{i\_j}^{(l)}$ are the complex path gain and the time delay of the lth path respectively, associated with ith user seen at the jth base station. Each user communicates with the best base station having the minimum propagation loss. The best base station for the ith user is indexed as $j(i)$, where

$$j(i) = \arg\max_j \left\{ r_{i\_j}^{-\alpha} 10^{-\frac{\eta_{i\_j}}{10}} \sum_{l=0}^{L-1} \left| \xi_{i\_j}^{(l)} \right|^2 \right\}. \quad (12)$$

Time dependency of the path gain is dropped for the sake of simplicity. The received signal power $P_{Rake,i\_j(i)}$ after Rake combing at the $j(i)$th base station is given by

$$P_{Rake,i\_j(i)} = \tilde{P}_{Ti} r_{i\_j(i)}^{-\alpha} 10^{-\frac{\eta_{i\_j(i)}}{10}} \sum_{l=0}^{L-1} \left| \xi_{i\_j(i)}^{(l)} \right|^2. \quad (13)$$

When random TPC is applied, the ith user transmit power $\tilde{P}_{Ti}$ is given by

$$\tilde{P}_{Ti} = \frac{P_{\text{target}} 10^{\frac{\delta_i \Delta}{10}}}{r_{i\_j(i)}^{-\alpha} 10^{-\frac{\eta_{i\_j(i)}}{10}} \sum_{l=0}^{L-1} \left| \xi_{i\_j(i)}^{(l)} \right|^2}, \quad (14)$$

where δ_i (=1 or −1) represents the power state. $\delta_i = \pm 1$ gives the received signal power of $P_{\text{target}} \pm \Delta$ dB, with the probability of $\varepsilon_\pm$, respectively, where $\varepsilon_+ + \varepsilon_- = 1$.

Without loss of generality, the 0th user communicating with the 0th cell (i,e., i=0 and $j(i)$=0(0)) is considered. We can show that the instantaneous received SIR γ_k after Rake combining is given by (for the brevity, its derivation is omitted)

$$\gamma_k = \frac{2SF}{\left(1 - \frac{\sum_{l=0}^{L-1} \left| \xi_{0\_0(0)}^{(l)} \right|^4}{\left(\sum_{l=0}^{L-1} \left| \xi_{0\_0(0)}^{(l)} \right|^2 \right)^2} + \sum_{i=1}^{k-1} \left[\left(\frac{r_{i\_0}}{r_{i\_j(i)}} \right)^{-\alpha} \cdot 10^{-\frac{\eta_{i\_0} - \eta_{i\_j(i)}}{10}} 10^{-\Delta \frac{\delta_i - \delta_0}{10}} \frac{\sum_{l=0}^{L-1} \left| \xi_{i\_0}^{(l)} \right|^2}{\sum_{l=0}^{L-1} \left| \xi_{i\_j(i)}^{(l)} \right|^2} \right] \right)}, \quad (15)$$

where SF is the spreading factor. For the single cell case, Eq. (15) reduces to

$$\gamma_k = \frac{2SF}{\left(1 - \frac{\sum_{l=0}^{L-1} \left| \xi_{0\_0}^{(l)} \right|^4}{\left(\sum_{l=0}^{L-1} \left| \xi_{0\_0}^{(l)} \right|^2 \right)^2} + \sum_{i=1}^{k-1} 10^{-\Delta \frac{\delta_i - \delta_0}{10}} \right)}. \quad (16)$$

4. Computer Simulation

Table 1 shows the simulation parameters. The uplink capacity is evaluated by the Monte-Carlo simulation using the following procedure:

Step 1: set K=1.
Step 2: increase the value of K by one.
Step 3: obtain the throughput S of Eq. (5).
Step 4: obtain the outage probability Q of Eq. (6).
Step 5: repeat step 2 to step 4 until $Q \geq Q_{\text{allow}}$. The maximum number of K that satisfies $Q \leq Q_{\text{allow}}$ is the link capacity C.

The single-cell case is considered first and then, the simulation is extended to the multi-cell case, where perfect TDD frame synchronization among base stations is assumed.

4.1 Single-cell Case

Figure 3 plots the normalized link capacity C/SF as a function of Δ with ε_- as a parameter for $L = 2$. For comparison, the cases with slow and fast TPC are also plotted. When Δ=0 dB, the link capacity with random TPC is the same as that with the fast TPC. As Δ becomes larger, the link capacity increases due to increasing capture effect obtained by controlled power variations and approaches its maximum when Δ=3 dB. When Δ increases beyond 3 dB, however, the link capacity starts to decrease since the increasing multi-user interference offsets the capture effect. It

Table 1 Simulation parameters.

User location		Uniform distribution
Propagation channel	Fading	Block Rayleigh
	Number of paths	L=1~16
Transmitter and receiver	Data mod. and demod.	BPSK with coherent detection
	Spreading factor	SF=1~512
Packet	Length	N=512 bits
	Data packet generation probability	λ_0=0.05
QoS	Required throughput	S_{req}=0.9
	Allowable outage probability	Q_{allow}=0.1

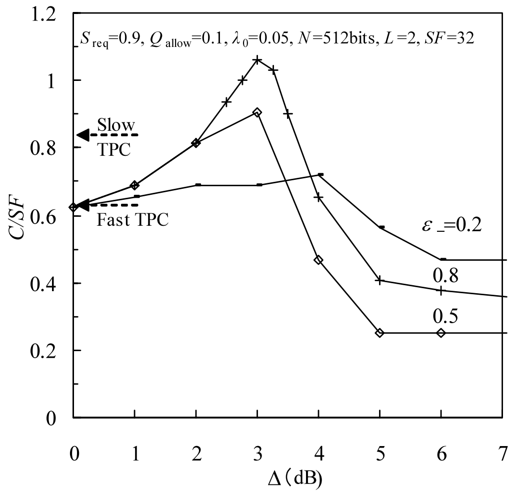

Fig. 3 Impact of Δ. Single-cell case.

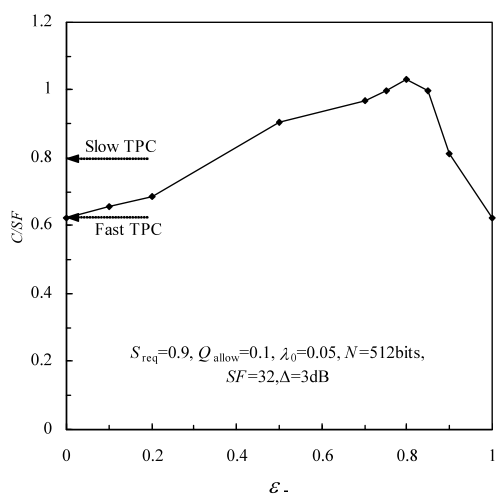

Fig. 4 Impact of ε_-. Single-cell case.

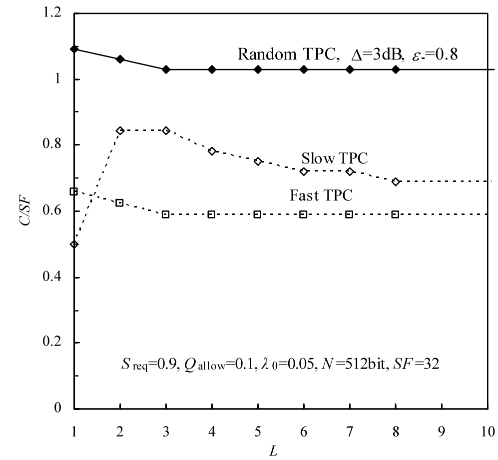

Fig. 5 Impact of number L of paths. Single-cell case.

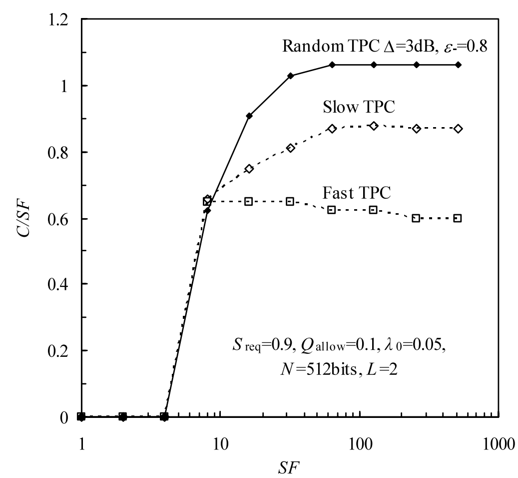

Fig. 6 Impact of SF. Single-cell case.

can be seen that the random TPC achieves a larger link capacity than slow TPC when Δ=3 dB and ε_-=0.8. The optimum Δ for DS-CDMA is 3 dB. On the other hand, in the case of a narrow band system, the optimum Δ is 5 dB [5]. In a DS-CDMA system, since all users share the same carrier frequency, the user of too large Δ produces large multi-user interference. Hence, the optimum Δ that maximizes the link capacity is smaller than that of the narrow band system.

Figure 4 plots the normalized link capacity C/SF as a function of ε_- for $\Delta = 3$ dB and SF=32. When ε_-= 0 or 1, since the received signal power is constant, the same normalized link capacity as with fast TPC is obtained. As ε_- increases, the link capacity becomes larger due to the increasing capture effect and it is maximized at $\varepsilon_- = 0.8$.

Figure 5 plots the normalized link capacity C/SF as a function of L for $\Delta = 3$ dB, $\varepsilon_- = 0.8$ and SF=32. For comparison, the cases with slow and fast TPC are also plotted. For the case of slow TPC, the link capacity is sensitive to L since the degree of the received power fluctuations after Rake combining depends on L. However, random TPC always obtains a larger link capacity than both slow and fast TPC irrespective of L.

Figure 6 plots the normalized link capacity as a function of SF. When $SF \leqq 4$, the link capacity is almost zero because of large inter-path interference for all TPC schemes. When $SF > 8$, the random TPC provides the largest link capacity. When $SF > 64$, the normalized link capacity almost remains constant since the impact of inter-path interference is negligible.

Figure 7 plots the normalized link capacity as a function of packet length N. As N becomes larger, the normalized capacity decreases because the required SIR increases. However, it can be found that the random TPC always provides a larger capacity than slow TPC and fast TPC irrespective of N.

4.2 Multi-cell Case

So far, the single-cell case has been considered. In the multi-cell case, users communicating with other cells give interference to the cell of interest and this reduces the link capacity per cell compared to the single-cell case. In this letter, up to

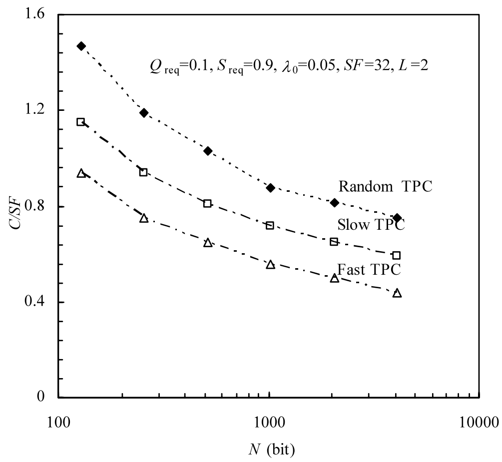

Fig. 7 Impact of packet length N. Single-cell case.

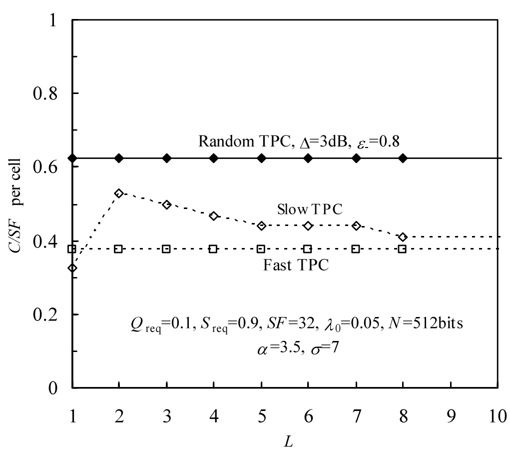

Fig. 8 Impact of number L of paths. Multi-cell case.

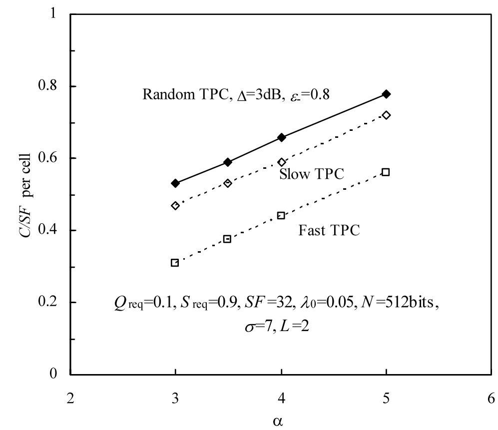

Fig. 9 Impact of path loss exponent α. Multi-cell case.

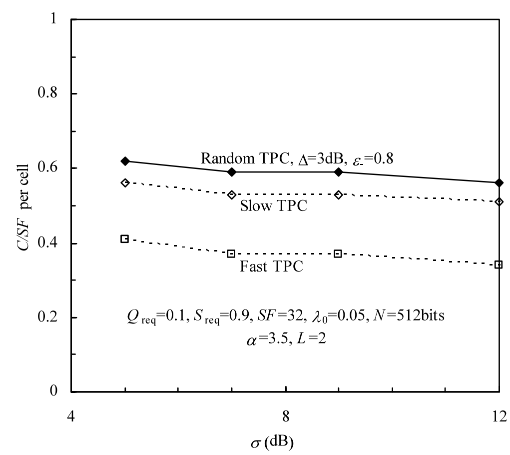

Fig. 10 Impact of standard deviation σ of shadowing loss. Multi-cell case.

the second tiers of the surrounding cells are considered (i.e., 19 cells are considered in the simulation).

Figure 8 plots the normalized link capacity per cell as a function of the number L of propagation paths. Similar to the single-cell case, the link capacity with random TPC is almost insensitive to L.

For the single-cell case, the path loss and shadowing loss do not have any impact on the link capacity (this can be understood from Eq. (16)). However, this is not true for the multi-cell case. Figure 9 plots the normalized link capacity per cell as a function of the path loss exponent α. As α becomes larger, the link capacity increases. This is because the interference power from the other cell users decreases as α becomes larger. Figure 10 plots the normalized link capacity per cell as a function of the standard deviation σ of the log-normally distributed shadowing loss. As σ becomes larger, the link capacity tends to decrease, but is almost insensitive to σ. Possible reason of this is discussed below. As σ becomes larger, the received signal power fluctuation also becomes larger. Hence, the site selection diversity effect, which is obtained by the selection of the best base station, contributes to increasing the capacity. However, on the other hand, as σ increases, the probability of large interference may increase. This contributes to decreasing the capacity. As a consequence, the capacity becomes almost insensitive to σ.

All the above results confirm that similar to the single cell case, the random TPC can always achieve a larger capacity than fast and slow TPC in a multi-cell case as well.

5. Conclusions

We applied the binary random TPC to DS-CDMA/TDD packet mobile radio. We evaluated the uplink link capacity by Monte-Carlo numerical computation. The results obtained in this letter can be summarized as follows:

(a) The random TPC was found to achieve a larger link capacity than slow TPC and fast TPC irrespective of the number L of propagation paths.

(b) The optimum TPC deviation Δ that maximizes the link capacity was found to be smaller than that of a non-spread narrow band system. This is because all users share the same carrier frequency, and hence the use of too large Δ produces large multi-user interference.

(c) When spreading factor $SF > 64$, the normalized link capacity remains almost constant since the impact of inter-path interference is negligible.

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