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Impact of Adaptive Antenna Array and Transmit Power Control on Uplink Performance of a DS-CDMA Packet Cellular System

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Abstract The uplink performance of a direct-sequence code division multiple access (DS-CDMA) packet cellular system is limited by multi-access interference (MAI) from the other users. On one hand, adaptive antenna array (AAA) is a promising technique to increase the link capacity by suppressing the MAI of mobile radio communications systems. On the other hand, transmit power control (TPC) is an effective method to improve the performance further. However, the combination of AAA and TPC has always been considered difficult. In this study, a TPC algorithm for AAA-rake receiver is proposed. In this algorithm, the TPC and the weight vector calculation for AAA-rake receiver are separated. The outage probability of the received signal-to-interference plus noise power ratio (SINR) is evaluated by computer simulation and compared with coherent rake receiver using maximal ratio combining (MRC) to show that the proposed algorithm can yield a better performance.

Keyword DS-CDMA; adaptive antenna array; transmit power control; packet cellular system

1. Introduction

The demand for broadband packet services has been stronger and stronger in mobile communication systems. In a direct-sequence code division multiple access (DS-CDMA) system, multiple users transmit their packets using the same carrier frequency. Packets transmitted from different users suffer from different path losses, shadowing losses and multipath fading and are received by a base station (BS) with significantly different powers. This produces large multi-access interference (MAI) and therefore the link capacity degrades due to the packet collision [1].

Antenna diversity and Rake combining are well known techniques to improve the transmission performance [2, 3]. Another promising technique to suppress the MAI is the adaptive antenna array (AAA) [4]. By creating a narrow beam pointed towards the desired user and nulls in the directions of the interfering users, the total MAI experienced by the desired user's signal can be effectively suppressed. As a result, the system can accommodate a much larger number of users. In addition, employing the AAA can also reduce the outage probability at the cell edge and inside buildings, and extend the cell coverage. When used in the uplink (mobile-to-base), it can reduce the required mobile station (MS) transmit power and hence increase the battery life in terms of both talk time and standby time [4~11].

For a DS-CDMA cellular system, there is another important technique which is transmit power control (TPC) [12]. The transmit power of each MS is controlled so that the received instantaneous signal power is kept at the prescribed target value for all users. When TPC is used together with AAA, the beam former output signal's power is kept at the target value.

However, the array weight vector depends on not only the desired user's direction of arrival (DOA) and those of interfering users, but also the received desired and interfering signal powers. The array weight vector and MS's transmit power are dependent with each other. Therefore, application of TPC to uplink AAA is not so simple.

In this paper, we show that TPC and AAA can be carried out independently if some degree of imperfection is allowed to TPC. The outage probability of the signal-to-interference plus noise power ratio (SINR) of the uplink of a DS-CDMA cellular system using AAA and rake receiver (AAA-rake receiver) is evaluated by the computer simulation and compared with rake receiver using the maximal ratio combining (MRC-rake receiver) to show that the proposed algorithm can yield a better performance.

The remainder of this paper is organized as follows. Section 2 introduces the system model of the adaptive antenna array for DS-CDMA system. Section 3 proposes the TPC algorithm for AAA-rake receiver. Section 4 evaluates the outage probability and link capacity for a multi-cell system under an interference-limited condition by computer simulation. Section 5 gives the conclusions.

2. The Adaptive Antenna Array for DS-CDMA Packet Cellular System

In this paper, we consider a DS-CDMA packet cellular system with AAA and TPC based on the received signal power. Figure 1 illustrates its receiver structure. An antenna beam is formed for each discrete path. The signal output from each beam former is coherently combined.

The sum of the desired and interfering signals and the additive white Gaussian noise (AWGN) is received on each antenna. The received signal associated with the m-th antenna be expressed as

$$x_m(n)=\sum_{l'=0}^{L-1}\sqrt{2P_{t,0}A_{0\to j(0)}}\,h_{0\to j(0),m,l'}d_0(t)c_0(t-\tau_{i,l'})$$
$$+\sum_{i=1}^{19K-1}\sum_{l'=0}^{L-1}\sqrt{2P_{t,i}A_{i\to j(i)}}\,h_{i\to j(i),m,l'}d_i(t)c_i(t-\tau_{i,l'})$$
$$+n_m(t) \tag{1}$$

for m=0 ~ (M-1), where P_t and $h_{i\to j(i)}$ are the transmit power and the complex path gain, respectively. We assume a frequency-selective block fading channel having L discrete paths and τ_l is the time delay of the l-th path. $n_m(t)$ is the zero-mean complex Gaussian noise with variance $2N_0/T_c$, where N_0 is the single-sided power spectrum density of the AWGN. The subscripts i and l denote the user index and path index, respectively. Each user communicates with the best BS having the minimum propagation path loss including shadowing loss and fading gain. The best BS for the i-th user is indexed as $j(i)$, which can be represented as

$$j(i)=\arg\max_j\left\{A_{i\to j}\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}w^*_{m,l}\cdot h_{i\to j,m,l}\right\}, \tag{2}$$

where

$$A_{i\to j(i)}=r_{i\to j(i)}^{-\alpha}\cdot 10^{-\frac{\eta_{i\to j(i)}}{10}} \tag{3}$$

is the product of path loss and shadowing loss from i-th user to the $j(i)$-th BS, α is the path loss exponent, and $\eta_{i\to j(i)}$ is the shadowing loss in dB. In Eq.(1), $d(t)$ and $c(t)$ are the data-modulated symbol waveform and the spreading chip waveform, respectively, and are given by

$$d_i(t)=\sum_{n=0}^{N-1}d_{i,n}u(t/T-n)$$
$$c_i(t)=\sum_{q=0}^{N\cdot SF-1}c_{i,q}u(t/T_c-q) \quad , \tag{4}$$
$$u(x)=\begin{cases}1 & if\, 0<x\le 1\\ 0 & otherwise\end{cases}$$

where $\{d_{i,n}=\pm1;\ n=0\sim(N-1)\}$ is the data-modulated symbol sequence with i and m representing respectively the user index and the symbol position in a slot, $\{c_{i,q}=\pm1;\ q=0\sim(N\cdot SF-1)\}$ is the spreading chip sequence, T is the data symbol period, T_c is the spreading chip period, and $u(x)$ is the unit pulse given by $u(x)$=1 for x=(0~1] and 0 for otherwise. $SF=T/T_c$ is the spreading factor defined as the number of chips per data symbol.

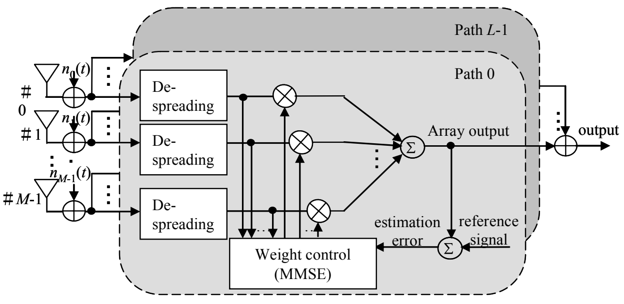

Fig.1 AAA-rake receiver.

The received signal is multiplied by the spreading sequence. The despreader output for the n-th symbol associated with the l-th discrete path is denoted by $r_{m,l}(n)$. The array input signal vector, the array weight vector, and the array output signal are denoted by $\mathbf{r}_l(n)$, $\mathbf{w}_l$ (n) and $y_l(n)$, respectively, and are given by

$$\mathbf{r}_l(n)=\left[r_{0,l}(n)\quad r_{1,l}(n)\quad\cdots\quad r_{(M-1,l}(n)\right]^T$$
$$\mathbf{w}_l=\left[w_{0,l}\quad w_{1,l}\quad\cdots\quad w_{(M-1),l}\right]^T \quad , \tag{5}$$
$$y_l(n)=\mathbf{w}_l{}^H\cdot\mathbf{r}_l(n)$$

where $(.)^{\mathrm{T}}$ denotes the transpose matrix and $r_{m,l}(n)$ is given by

$$r_{m,l}(n)=\frac{1}{SF}\sum_{t=n\cdot SF}^{(n+1)SF-1}x_m(t)c_0^*(t-\tau_{0,l}). \tag{6}$$

The AAA-rake combiner output $y(n)$ is given by

$$y(n)=\sum_{l=0}^{L-1}y_l(n)=\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}w^*_{m,l}\cdot r_{m,l}(n) \quad , \tag{7}$$

where $(.)^*$ denotes the complex conjugate operation.

3. Algorithm for AAA-rake Receiver

In optimal beam forming techniques, the weight vector is determined so that a cost function can be minimized. Typically, this cost function is inversely associated with the quality of the signal at the array output so that when the cost function is minimized, the quality of the signal is maximized at the array output. In this paper, we assume that the minimum mean square error (MMSE) method is used. The cost function to be minimized is

$$J(\mathbf{w}_l)=E\left[\left|\mathbf{w}_l^H\mathbf{r}_l(n)-d_0(t)\right|^2\right] \quad , \tag{8}$$

where d_0 is the desired signal. The set of weights which provides a Wiener solution is

$$\mathbf{w}_l=\mathbf{R}^{-1}_{xx,l}\mathbf{V}_{xr,l} \quad , \tag{9}$$

where the $\mathbf{R}_{xx,l}=E\left[\mathbf{r}_l(n)\mathbf{r}_l^H(n)\right]$ is the correlation matrix of the input data vector, and the $\mathbf{V}_{xr,l}=E\left[\mathbf{r}_l(n)d_0^*(t)\right]$ is the cross-correlation vector between the input data matrix $\mathbf{r}_l(n)$ and $d_0^*(t)$.

For our DS-CDMA packet cellular system with AAA-rake receiver, the received signal power $P_{r,i}$ at the $j(i)$-th BS after AAA-rake combining can be expressed as

$$P_{r,i}=P_{t,i}\cdot A_{i\to j(i)}\cdot\left|\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}w^*_{i,l,m}\cdot h_{i\to j(i),l,m}\right|^2. \tag{10}$$

The transmit power of each mobile station is controlled so that the received instantaneous array output signal power is kept at the prescribed target value P_{target} for all users. With the fast TPC, the i-th user's transmit signal power $P_{t,i}$ becomes

$$P_{t,i}=P_{target}\Bigg/\left(A_{i\to j(i)}\cdot\left|\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}w^*_{i,l,m}\cdot h_{i\to j(i),l,m}\right|^2\right). \tag{11}$$

From Eqs. (9) and (11), it can be seen that the array weight vector and the users' transmit power are related to each other. If the relationship of the array weight vector and the users' transmit power is not made clearly, the TPC for a DS-CDMA packet cellular system with AAA can not work. Therefore, in this paper, the transmit power of each mobile station is controlled so that not the received instantaneous array output signal power but the received rake combining signal power is kept at the prescribed target value P_{target} for all users. The AAA-rake receiver structure is illustrated in Fig. 2.

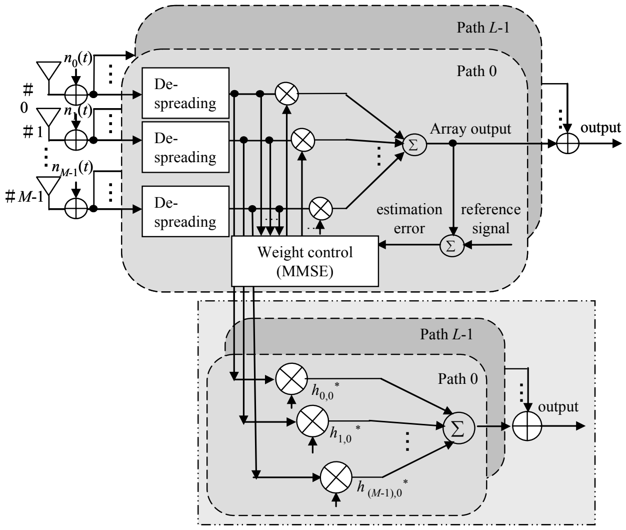

Fig.2 Structure of AAA-rake receiver with receive power measurement.

From this figure, it can be seen that controlling the array weight victor and the TPC can be carried out independently because the transmit power is only decided on their own channel condition.

4. Numerical and Simulation Results

Table 1 shows the simulation condition. We consider 19 cells with the center cell being the cell of interest. For BER=10^{-3} with BPSK modulation, the required SINR is about 10dB. In the following, γ_{req}=10dB will be used as a reference. When the interference is much larger than noise (i.e., $P_{r,0\to j(i)}/N \to \infty$), the effect of AAA-rake receiver on the outage probability will be clearly seen. Therefore, an interference-limited channel is assumed here. The path loss exponent α is set to be 3.5, the shadowing loss standard deviation σ is set to be 7.0. Block Rayleigh fading (the path gain due to fading stays constant during the reception of one packet) is assumed. The simulation condition is summarized in Table 1.

Table 1 Simulation condition

TPC	Fast TPC, slow TPC and no TPC
User location	Uniform distribution
Number of Antennas M	1,2,4
Target E_b/N_0	50dB
Path loss exponent α	3.5
Shadowing loss standard deviation η	7.0
Fading	Block Rayleigh L=16
Arrival angle Path spreading of paths	0°~ 360°
Spreading factor SF	16
Packet generation probability λ	0.05, 1.0
Required SINR γ_{req}	10dB
Allowable outage probability Q_{allow}	0.1

Without loss of generality, the 0-th user communicating with the 0-th cell (i.e., i=0 and $j(i)$=0) is considered. The distribution of the sum of interference and noise can be approximated as complex Gaussian distribution.

We consider K users per BS and infinite number of BSs. We can show that the instantaneous received SINR after AAA-rake combining is given by (the derivation is omitted for brevity)

$$\gamma_k=\frac{2\left(\frac{E_{b,0}}{N_0}\right)_t A_{0\to 0}\left|\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}w_{l,m}^*h_{0\to 0,l,m}\right|^2}{\left(\begin{array}{l}\frac{1}{SF}\left(\frac{E_{b,0}}{N_0}\right)_t A_{0\to 0}\left(\left(\sum_{l=0}^{L-1}\sum_{l'=0}^{L-1}\left|\sum_{m=0}^{M-1}w_{l,m}^*h_{0\to 0,l',m}\right|^2\right)-\sum_{l=0}^{L-1}\left|\sum_{m=0}^{M-1}w_{l,m}^*h_{0\to 0,l,m}\right|^2\right)\\+\frac{1}{SF}\sum_{i=1}^{\infty}\left(\frac{E_{b,i}}{N_0}\right)_t A_{i\to j(i)}\sum_{l=0}^{L-1}\sum_{l'=0}^{L-1}\left|\sum_{m=0}^{M-1}w_{l,m}^*h_{i\to j(i),l',m}\right|^2+\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}\left|w_{l,m}^*\right|^2\end{array}\right)} \tag{12}$$

For the single cell case, Eq.(9) reduces to

$$\gamma_k=\frac{2\left(\frac{E_{b,0}}{N_0}\right)_t A_{0\to 0}\left|\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}w_{l,m}^*h_{0\to 0,l,m}\right|^2}{\left(\begin{array}{l}\frac{1}{SF}\left(\frac{E_{b,0}}{N_0}\right)_t A_{0\to 0}\left(\left(\sum_{l=0}^{L-1}\sum_{l'=0}^{L-1}\left|\sum_{m=0}^{M-1}w_{l,m}^*h_{0\to 0,l',m}\right|^2\right)-\sum_{l=0}^{L-1}\left|\sum_{m=0}^{M-1}w_{l,m}^*h_{0\to 0,l,m}\right|^2\right)\\+\frac{1}{SF}\sum_{i=1}^{K-1}\left(\frac{E_{b,i}}{N_0}\right)_t A_{i\to 0}\sum_{l=0}^{L-1}\sum_{l'=0}^{L-1}\left|\sum_{m=0}^{M-1}w_{l,m}^*h_{i\to 0,l',m}\right|^2+\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}\left|w_{l,m}^*\right|^2\end{array}\right)} \tag{13}$$

Outage occurs if the transmission quality drops below the required quality of services (QoS). The interference protection ratio γ_{req} is the required SINR, which is defined as the minimum SINR that satisfies the required QoS. The outage probability Q is given by

$$Q=\mathrm{Prob}[\gamma<\gamma_{req}] \quad . \tag{14}$$

When the number of active users K per cell increases, the packet collision probability increases, thereby increasing the outage probability. The link capacity is defined as the maximum number of active users that satisfies the allowable outage probability Q_{allow} which is defined as the maximum outage probability that satisfies the system requirement.

We assume that K active users per cell are transmitting their packets at probability λ including the retransmit packets. At one instant, if the i-th user is transmitting a packet, then a_i=1; otherwise a_i=0. The 0-th user's instantaneous received SINR γ in Eq.(12) is given by

$$\gamma=\frac{2\left(\frac{E_{b,0}}{N_0}\right)_t A_{0\to 0}\left|\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}w_{l,m}^*h_{0\to 0,l,m}\right|^2}{\left(\begin{array}{l}\frac{1}{SF}\left(\frac{E_{b,0}}{N_0}\right)_t A_{0\to 0}\left(\left(\sum_{l=0}^{L-1}\sum_{l'=0}^{L-1}\left|\sum_{m=0}^{M-1}w_{l,m}^*h_{0\to 0,l',m}\right|^2\right)-\sum_{l=0}^{L-1}\left|\sum_{m=0}^{M-1}w_{l,m}^*h_{0\to 0,l,m}\right|^2\right)\\+\frac{1}{SF}\sum_{i=1}^{19K-1}a_i\left(\frac{E_{b,i}}{N_0}\right)_t A_{i\to j(i)}\sum_{l=0}^{L-1}\sum_{l'=0}^{L-1}\left|\sum_{m=0}^{M-1}w_{l,m}^*h_{i\to j(i),l',m}\right|^2+\sum_{l=0}^{L-1}\sum_{m=0}^{M-1}\left|w_{l,m}^*\right|^2\end{array}\right)}$$

. (15)

The uplink capacity is evaluated by the Monte-Carlo method in 5 steps as:

Step1: set K=0.
Step2: increase the value of K by one.
Step3: compute the SINR of Eq. (15).
Step4: obtain the outage probability of Eq. (14).
Step5: repeat the step 2 to step 4 until $Q \geq Q_{allow}$.

The maximum number of K that satisfies $Q < Q_{allow}$ is regarded as the link capacity. The single cell case is considered first and then, the simulation is extended to the multi-cell case.

4.1 Single-Cell Case

Figure 3 plots the outage probability as a function of the number K of active users. For comparison, the cases with slow TPC and no TPC are also plotted. It is observed that the performance of fast TPC outperforms that of slow TPC while the performance of slow TPC outperforms that of no TPC. This comparison has demonstrated that the proposed TPC schemes can improve the outage probability effectively.

Figure 3 also shows the performance of the fast/slow/no TPC with difference number of receive antennas. As a reference, the result obtained by using single antenna is also shown. An improvement in the performance can be observed when the number of antennas is increased.

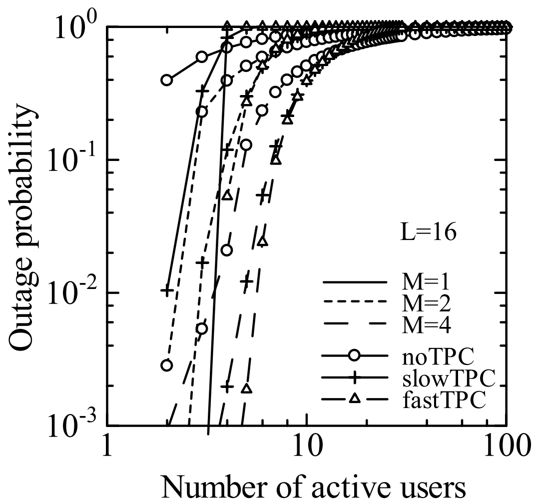

Fig.3 Impact of the number M of antennas.

The outage probability of SINR by using AAA-rake receiver is evaluated and compared with the rake receiver using maximal ratio combining (MRC-rake receiver). The simulation results with M=4 are shown in Fig. 4. It can be seen that the performance of AAA-rake receiver will be much better than the performance of MRC-rake receiver for all of the fast TPC, slow TPC and no TPC.

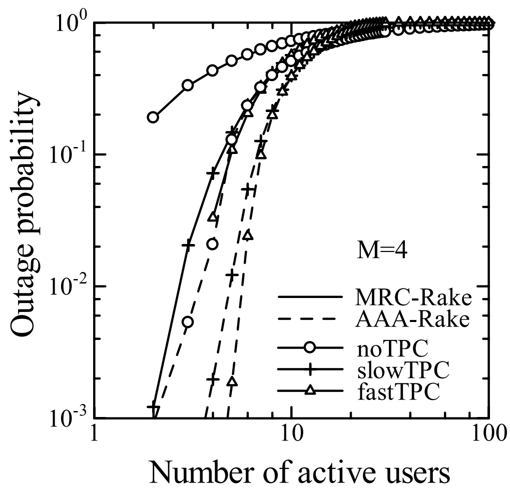

Fig.4 Comparison of MRC-rake receiver and AAA-rake receiver.

Figure 5 plots the link capacity with 10% outage (Qallow=0.1) as a function of the number of antennas. It is observed that, the link capacity with AAA-rake receiver increases rapidly with M while the link capacity with MRC-rake receiver only increases slightly with M.

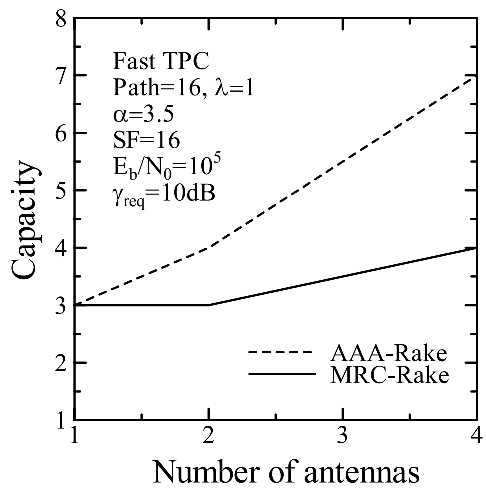

Fig.5 Capacity comparison between MRC-rake receiver and AAA-rake receiver.

Figure 6 plots the outage probability as a function of the packet generation probability λ. The simulation results with M=4 and L=16 have been given. And it can be seen that with decreasing the packet generation probability λ, better performance can be achieved.

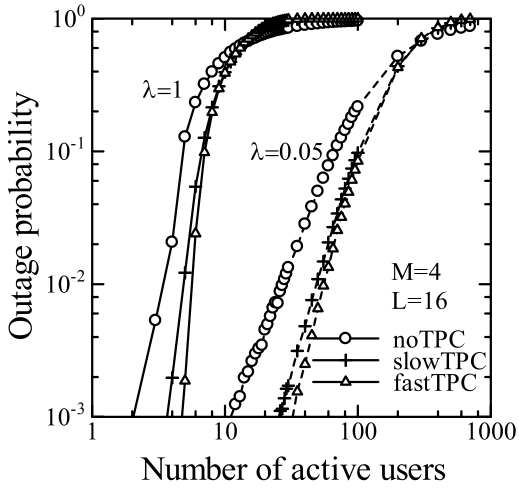

Fig.6 Impact of packet generation probability λ.

4.2 Multi-Cell Case

So far, the single-cell case has been considered. Next, the multi-cell case will be considered. In the multi-cell case, users from other cells become interference to the cell of interest and this interference will reduce the link capacity per cell. In this paper, up to the second tiers of the surrounding cells are considered (i.e., 19 cells are considered in the simulation).

Figure 7 plots the outage probability as a function of the number K of active users for multi-cell case. Similar to the single-cell case, the performance of fast TPC is better than no TPC and slow TPC. And it can be seen that with increasing the number of antennas, better performance can be achieved.

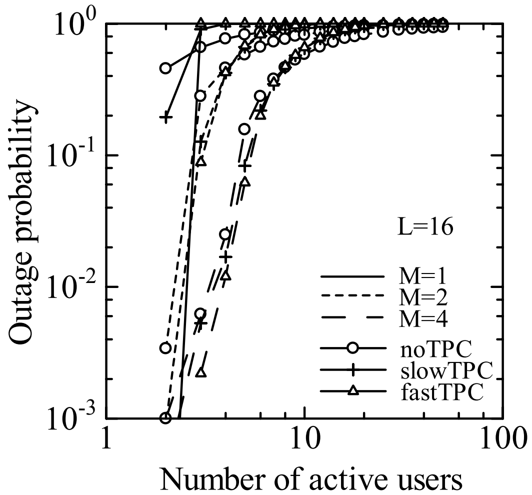

Fig.7 Impact of the number M of antennas for multi-cell case

The outage probability of SINR for multi-cell case by using AAA-rake receiver is evaluated and compared with the rake receiver using MRC-rake. The simulation results with M=4 are shown in Fig.8. And as the single-cell case, the AAA-rake receiver can provide much better performance than MRC-Rake receiver.

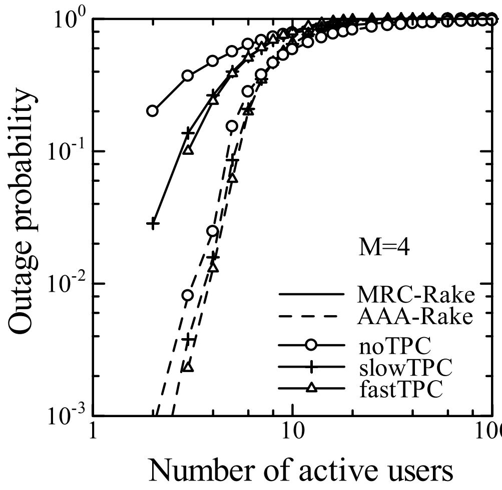

Fig.8 Comparison of MRC-rake receiver And AAA-rake receiver for multi-cell case

Figure 9 plots the outage probability as a function of the packet generation probability λ for multi-cell case. It can be seen that when the packet generation probability λ is decreased, better performance can be achieved.

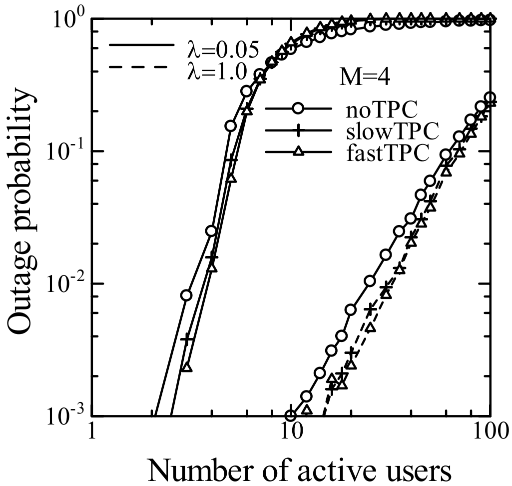

Fig.9 Impact of packet generation probability λ for multi-cell case

5. Conclusion

In this paper, a TPC algorithm for AAA-rake receiver has been proposed. The proposed algorithm has separated the array weight vector calculation and TPC into two independent procedures, which renders the algorithm simple as well as effective. The effectiveness of the proposed algorithm has been demonstrated by Monte-Carlo simulations in both single-cell and multi-cell cases.

References

[1] Z. S. Wang, E. Kudoh and F. Adachi, "Uplink link capacity of DS-CDMA packet mobile communication with Rake combining and transmit

power control," IEICE Trans. Commun., Vol. E86-B, No.7, pp. 2203-2206, July 2003.

[2] F. Adachi, M. Sawahashi, and H. Suda, "Wideband DS-CDMA for next-generation mobile communication system," IEEE Commun. Mag., Vol.36, pp. 56-59, Sept. 1998.

[3] S. Seo, T. Dohi, and F. Adachi, "SIR-based transmit power control of reverse link for coherent DS-CDMA mobile radio," IEICE Trans. Commun. Vol. E81-B No7, pp. 1508-1516, July 1998.

[4] 大鐘　武雄, 小川　恭孝, "アダプティブアレーと移動通信[I-Ⅳ]," 電子情報通信学会論文誌, Vol.81, No.12, 1998 年 12 月, Vol.82 No.1-3, 1999 年 1-3 月.

[5] 辻　宏之, 水野　光彦, "移動通信におけるアダプティブアンテナアレー技術の応用," 電子情報通信学会論文誌, A Vol. J82-A No.6 , pp.779-791, 1999 年 6 月.

[6] 菊間, "アダプティブアンテナ技術", オーム社出版, 2003.

[7] R. A. Monzingo and T. W. Miller, Introduction to adaptive arrays, John Wiley and Sons, New York, 1980.

[8] R. T. Compton, Adaptive antennas, Prentice Hall, Englewood Cliffs, 1988.

[9] L. C. Godara, "Application of antenna arrays to mobile communications, Part I: Performance improvement, feasibility, and system considerations," Proc. IEEE, vol. 85, no. 7, pp. 1029-1060, July 1997.

[10] L. C. Godara, "Application of antenna arrays to mobile communications, Part II: beam-forming and direction of arrival consideration," Proc. IEEE, vol. 85, no. 8, pp. 1195-1245, Aug. 1997.

[11] ITU-R Rec. M.1645, "Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-2000 (Question ITU-R 229/8)," Oct. 2002.

[12] 大野，安達，"DS-CDMA の上りリンク容量と送信電力"信学論，Vol. J79-B-Ⅱ，pp17-25，1996 年 1 月.