Throughput analysis of DS-CDMA Wireless Packet Access using Frequency-domain Equalization and Random TPC

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***Abstract*— Recently, we proposed a random transmit power control (TPC) to increase the uplink capacity of DS-CDMA wireless packet access using Rake combining. Furthermore, we evaluated the combined effect of random TPC and inter-path interference (IPI) cancellation and showed that a significant throughput improvement can be achieved if the IPI is sufficiently suppressed. Frequency-domain equalization (FDE) is a promising technique to suppress the IPI. In this paper, we derive an expression for the received signal-to-interference plus noise power ratio (SINR) for a DS-CDMA wireless packet access using FDE and random TPC. Using the derived SINR expression, we evaluate its throughput performance by numerical computation. We compare the throughput using Rake combining with that using FDE to discuss the IPI suppression effect of FDE. It is shown that the throughput using MMSE-FDE approaches that achievable using rake combining w/perfect IC.**

Keywords-component; Wireless packet access, capture effect, transmit power control, IPI cancellation, frequency-domain equalization, DS-CDMA

I. INTRODUCTION

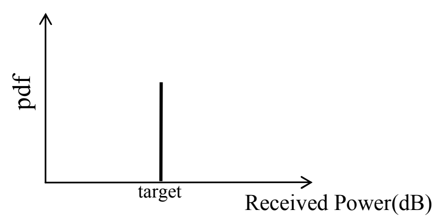
In wireless packet communication, since users transmit their packets randomly, packet collision occurs, thereby decreasing the system throughput. When the received signal power difference among colliding packets is small, all packet transmissions fail. Otherwise, a packet with larger received signal power can survive and thus the throughput increases. This is known as the capture effect [1],[2]. In [3], we applied the random transmit power control (TPC) to obtain the controlled capture effect for DS-CDMA wireless packet access.

In wireless packet communication, as the transmission rate increases, the number of resolvable propagation paths increases and hence, the inter-path interference (IPI) gets stronger, thereby severely reducing the throughput performance. If the IPI is partially suppressed by an interference canceller [4] or an equalizer [5], the throughput increases. We have shown that a combined use of IPI canceller and random TPC provides a significant improvement in the throughput of DS-CDMA slotted ALOHA [6]. Recently, frequency-domain equalization (FDE) [7],[8] has been attracting much attention to improve the single-carrier transmission performance in a frequency-selective channel. In this paper, we evaluate the throughput improvement achievable with the use of FDE and random TPC in DS-CDMA slotted ALOHA.

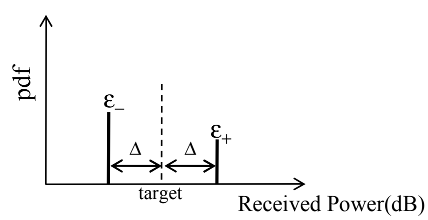
The remainder of this paper is organized as follows. Sect. II introduces random TPC and derives the system throughput. Sect. III derives an expression for the received signal-to-interference plus noise power ratio (SINR) using FDE and random TPC. Sect. IV evaluates the throughput performance and discusses the effect of FDE and random TPC. Sect. V gives some conclusions.

II. RANDOM TPC AND SYSTEM THROUGHPUT

Fig.1 shows the probability density function (pdf) of the received signal power for the random TPC and the fast TPC. With the random TPC, the transmit power is controlled so that the signal power received at the base station becomes $P_{\text{target}} \pm \Delta$ dB with a probability of $\varepsilon_{\pm}$ ($\varepsilon_{+}+\varepsilon_{-}=1$), where Δ denotes forced power fluctuation in dB.



(a)Fast TPC



(b)Random TPC

Fig.1 Pdf of received signal power.

In wireless packet access, the automatic request (ARQ) is necessary. We assume slotted ALOHA and an infinite number of retransmissions. For the given chip rate and packet length N in bits, the slot duration is proportional to the spreading factor SF. The original packet occurrence rate λ_{SF} per slot, when spreading factor is SF, is given by

$$\lambda_{SF} = SF \cdot \lambda_0 , \tag{1}$$

where λ_0 is the original packet occurrence rate (excluding the retransmitted packets) for SF=1. The packet occurrence rate λ including the retransmitted packets ($\lambda = \lambda_{SF}$ + retransmitted packet rate) is given by

$$\lambda = \frac{\lambda_{SF}}{1 - p(Q,\lambda)} , \tag{2}$$

where $p(Q,\lambda)$ is the average packet error rate when Q active users exist and given by

$$p(Q,\lambda)=\sum_{q=0}^{Q-1} p(q)\cdot\binom{Q-1}{q}\lambda^{q}(1-\lambda)^{Q-1-q}\ , \qquad (3)$$

where $p(q)$ is the conditional packet error rate when q interfering packets collide and $\binom{Q-1}{q}=\frac{(Q-1)!}{q!(Q-q-1)!}$ is the binomial coefficient. The system throughput S is given by

$$S=G\{1-p(Q,\lambda)\}\,, \qquad (4)$$

where G is the traffic normalized by the slot duration of SF=1 as

$$G=\frac{\lambda Q}{SF}\,. \qquad (5)$$

If $p(q)$ is known, $p(Q,\lambda)$ for the given λ can be evaluated by using Eq.(3). We search for λ which satisfies Eq.(2) by the iterative computation method [9]. This gives $p(Q,\lambda)$ for the given λ_0. Once $p(Q,\lambda)$ is obtained, the system throughput S is computed using Eq.(4).

First, we derive $p(q)$. We introduce the threshold SINR γ_{th} and approximate the instantaneous packet error rate $p(\gamma_q)$ for the given SINR γ_q as

$$p(\gamma_q)=\begin{cases}0 & \text{if } \gamma_q\ge\gamma_{th}\\ 1 & \text{otherwise}\end{cases}\,. \qquad (6)$$

Since γ_q is a random variable, the conditional packet error rate $p(q)$ is given by

$$p(q)=E[p(\gamma_q)]\,. \qquad (7)$$

III. Numerical Expression of Received SINR using FDE

We assume a single-cell environment with ideal channel estimation and ideal TPC. Below, an expression for γ_q to compute the conditional packet error rate $p(q)$ is derived for a combined use of FDE and random TPC.

The transmit chip sequence $s_i(t)$ of i-th user can be expressed, using the equivalent baseband representation, as

$$s_i(t)=\sqrt{2P_i}\,d_i\left(\left\lfloor\frac{t}{SF}\right\rfloor\right)c_i(t)\,, \qquad (8)$$

where P_i is the transmit power, $d_i(.)$ is the data symbol, $\lfloor x\rfloor$ represents the largest integer smaller than or equal to x, and $c_i(t)$ is the orthogonal spreading code with the spreading factor SF. The resulting chip sequence is divided into a sequence of chip blocks of N_c chip each, where N_c is the block size (in chips) of fast Fourier transform (FFT). The last N_g chips of N_c-chip block is copied and inserted into the guard interval (GI) placed at the beginning of the block as a cyclic prefix. GI-inserted chip block is transmitted.

A frequency-selective block fading channel having L discrete paths is assumed. After the removal of GI, the received signal $\{r(t);t=0\sim N_c-1\}$ at the base station is given by

$$r(t)=\sum_{i=0}^{q}\sum_{l=0}^{L-1}\sqrt{A_i}\,h_i^{(l)}s_i\left((t-\tau_i^{(l)})\bmod N_c\right)+n(t)\,, \qquad (9)$$

where A_i is given as

$$A_i=r_i^{-\alpha}10^{-\frac{\eta_i}{10}} \qquad (10)$$

with r_i, α, η_i, $h_i^{(l)}$, q, and $n(t)$ denoting respectively the distance between the i-th user and the base station, the path loss exponent, the shadowing loss in dB, the complex l-th path gain, the number of interfering users, and the complex Gaussian noise with the single-sided power spectrum density N_0.

The GI-removed received chip block $\{r(t);t=0\sim N_c-1\}$ is decomposed into N_c frequency components by N_c-point FFT. The k-th frequency component $R(k)$ is given by

$$\begin{aligned}R(k)&=\sum_{t=0}^{N_c-1}r(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\ &=\sum_{i=0}^{q}\sqrt{A_i}\,H_i(k)S_i(k)+\Pi(k)\end{aligned}\,, \qquad (11)$$

where $S_i(k)$ is the signal component, $H_i(k)$ is the channel gain and $\Pi(k)$ is the noise component and they are given as

$$\begin{cases}S_i(k)=\sum_{t=0}^{N_c-1}s_i(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\\ H_i(k)=\sum_{l=0}^{L-1}h_i^{(l)}\exp\left(-j2\pi k\frac{\tau_i^{(l)}}{N_c}\right)\\ \Pi(k)=\sum_{t=0}^{N_c-1}n(t)\exp\left(-j2\pi k\frac{t}{N_c}\right)\end{cases}. \qquad (12)$$

Without loss of generality, the i=0th user is considered as the desired user. FDE is carried out as follows.

$$\hat{R}_0(k)=R(k)w_0(k)\,, \qquad (13)$$

where $w_0(k)$ is the FDE weight. In this paper, we use the minimum mean square error (MMSE) weight and the zero forcing (ZF) weight [8]. They are given as

$$w_0(k)=\begin{cases}\dfrac{H_0^*(k)}{\sum_{i=0}^{q}P_iA_i|H_i(k)|^2+SF\dfrac{N_0}{T_s}} & \text{MMSE}\\ \dfrac{H_0^*(k)}{|H_0(k)|^2} & \text{ZF}\end{cases}\,, \qquad (14)$$

where T_s is data symbol duration. After FDE, N_c-point IFFT is applied to $\{\hat{R}_0(k);k=0\sim N_c-1\}$ to obtain the time-domain chip sequence $\{\hat{r}_0(t);t=0\sim N_c-1\}$. Finally, despreading is applied to $\{\hat{r}_0(t);t=0\sim N_c-1\}$ to obtain a soft decision symbol associated with $d_0(n)$ as

$$
\begin{aligned}
\hat{d}_0(n) &= \frac{1}{SF}\sum_{t=nSF}^{(n+1)SF}\hat{r}_0(t)c_0^*(t) \\
&= \frac{\sqrt{2P_0A_0}}{N_c}\left(\sum_{k=0}^{N_c-1}\hat{H}_0(k)\right)d_0(n) \\
&+ \frac{\sqrt{A_0}}{SF\cdot N_c}\sum_{t=n\cdot SF}^{(n+1)\cdot SF-1}\left[\sum_{k=0}^{N_c-1}\hat{H}_0(k)\left\{\sum_{\substack{\tau=0\\ \neq t}}^{N_c-1}s_0(\tau)\exp\left(j2\pi k\frac{t-\tau}{N_c}\right)\right\}\right]c_0^*(t) \\
&+ \frac{1}{SF\cdot N_c}\sum_{t=n\cdot SF}^{(n+1)\cdot SF-1}\left[\sum_{k=0}^{N_c-1}\left\{w_0(k)\sum_{i=1}^{q}\sqrt{A_i}H_i(k)S_i(k)\right\}\exp\left(j2\pi k\frac{t}{N_c}\right)\right]c_0^*(t) \\
&+ \frac{1}{SF\cdot N_c}\sum_{t=n\cdot SF}^{(n+1)\cdot SF-1}\left[\sum_{k=0}^{N_c-1}\hat{\Pi}_0(k)\exp\left(j2\pi k\frac{t}{N_c}\right)\right]c_0^*(t)
\end{aligned}
\quad , \tag{15}
$$

where the first, second, third, and forth terms represent the desired signal, IPI, multi-access interference (MAI), and noise, respectively. $\hat{H}_0(k)$ is the equivalent channel gain and $\hat{\Pi}_0(k)$ is the equivalent noise. They are given as

$$
\begin{cases}
\hat{H}_0(k) = H_0(k)w_0(k) \\
\hat{\Pi}_0(k) = \Pi(k)w_0(k)
\end{cases} . \tag{16}
$$

The desired signal power P_s, IPI power σ^2_{IPI}, MAI power σ^2_{MAI}, and noise power σ^2_{noise} are respectively given by

$$
\begin{cases}
P_s = 2P_0A_0\left|\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\hat{H}_0(k)\right|^2 \\
\sigma^2_{IPI} = \dfrac{P_0A_0}{SF}\left[\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\left|\hat{H}_0(k)\right|^2 - \left|\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\hat{H}_0(k)\right|^2\right] \\
\sigma^2_{MAI} = \dfrac{1}{SF}\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\left|w_0(k)\right|^2\sum_{i=1}^{q}A_iP_i\left|H_i(k)\right|^2 \\
\sigma^2_{noise} = \dfrac{N_0}{T_s}\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\left|w_0(k)\right|^2
\end{cases} . \tag{17}
$$

The received SINR γ_q can be derived from Eq. (17) as

$$
\gamma_q = \frac{P_s}{\sigma^2_{IPI}+\sigma^2_{MAI}+\sigma^2_{noise}}, \tag{18}
$$

The transmit power P_i of the i-th user is given by

$$
P_i = \begin{cases}
\dfrac{P_{target}}{r_i^{-\alpha}10^{-\frac{\eta_i}{10}}\displaystyle\sum_{l=0}^{L-1}\left|h_i^{(l)}\right|^2} & \text{for fast TPC} \\
\dfrac{P_{target}10^{\frac{\Delta}{10}\delta_i}}{r_i^{-\alpha}10^{-\frac{\eta_i}{10}}\displaystyle\sum_{l=0}^{L-1}\left|h_i^{(l)}\right|^2} & \text{for random TPC}
\end{cases} , \tag{19}
$$

where P_{target} is the TPC target and δ_i (=1 or -1) represents the power state. δ_i takes ±1 with the probability of $\varepsilon_\pm$, where $\varepsilon_+ + \varepsilon_- = 1$. Substituting Eq.(19) into Eq.(18), the received SINR is given as

$$
\gamma_{ff,q} = \frac{2\Gamma_{target}\left|\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\hat{H}_0(k)\right|^2}{\left[\begin{aligned}&\frac{\Gamma_{target}}{SF}\left[\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left|\hat{H}_0(k)\right|^2-\left|\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{H}_0(k)\right|^2\right] \\ &+\frac{\Gamma_{target}}{SF}\frac{\sum_{l=0}^{L-1}\left|h_0^{(l)}\right|^2}{N_c}\sum_{k=0}^{N_c-1}\left|w_0(k)\right|^2\left\{\sum_{i=1}^{q}\frac{\left|H_i(k)\right|^2}{\sum_{l=0}^{L-1}\left|h_i^{(l)}\right|^2}\right\}+\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left|w_0(k)\right|^2\end{aligned}\right]}
$$

for FDE + fast TPC (20)

and

$$
\gamma_{fr,q} = \frac{2\Gamma_{target}\left|\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\hat{H}_0(k)\right|^2}{\left[\begin{aligned}&\frac{\Gamma_{target}}{SF}\left[\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left|\hat{H}_0(k)\right|^2-\left|\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{H}_0(k)\right|^2\right] \\ &+\frac{\Gamma_{target}}{SF}\frac{\sum_{l=0}^{L-1}\left|h_0^{(l)}\right|^2}{N_c}\sum_{k=0}^{N_c-1}\left|w_0(k)\right|^2\left\{\sum_{i=1}^{q}\frac{\left|H_i(k)\right|^2}{\sum_{l=0}^{L-1}\left|h_i^{(l)}\right|^2}10^{\frac{\Delta}{10}(\delta_i-\delta_0)}\right\}+\frac{1}{N_c}10^{-\frac{\Delta}{10}\delta_0}\sum_{k=0}^{N_c-1}\left|w_0(k)\right|^2\end{aligned}\right]}
$$

for FDE + random TPC, (21)

where $\Gamma_{target}=P_{target}T_s/N_0$. For comparison, the received SINR using Rake combining is given as

$$
\gamma_{rf,q} = \frac{2\Gamma_{target}}{\left[\dfrac{\Gamma_{target}}{SF}(1-\beta)\left\{1-\dfrac{\sum_{l=0}^{L-1}\left|h_0^{(l)}\right|^4}{\left(\sum_{l=0}^{L-1}\left|h_0^{(l)}\right|^2\right)^2}\right\} + \dfrac{\Gamma_{target}}{SF}q+1\right]}
$$

for Rake + fast TPC (22)

and

$$
\gamma_{rr,q} = \frac{2\Gamma_{target}}{\left[\dfrac{\Gamma_{target}}{SF}(1-\beta)\left\{1-\dfrac{\sum_{l=0}^{L-1}\left|h_0^{(l)}\right|^4}{\left(\sum_{l=0}^{L-1}\left|h_0^{(l)}\right|^2\right)^2}\right\} + \dfrac{\Gamma_{target}}{SF}\displaystyle\sum_{i=1}^{q}10^{\frac{\Delta}{10}(\delta_i-\delta_0)}+10^{-\frac{\Delta}{10}\delta_0}\right]}
$$

for Rake + random TPC, (23)

where β is IPI cancellation factor introduced in [5].

IV. COMPUTER SIMULATION

The system throughput is evaluated for the given original packet occurrence rate λ_0 and Q by Monte Carllo numerical computation method. Table 1 shows the simulation condition. We assume the interference-limited channel ($\Gamma_{target}\to\infty$) and ideal TPC. The system throughput using FDE, taken into account the GI insertion loss, is given as

$$S=\frac{G}{1+\dfrac{N_g}{N_c}}\{1-p(Q,\lambda)\}. \quad (24)$$

Table 1 Simulation condition

Packet	Length	N=512bits
	Allowable SINR	γ_{th}=10dB [5]
	Normalized original packet occurrence rate	λ_0=0.05
Transmitter	Data modulation	BPSK
	Chip block length	N_c=256chips
	GI length	N_g=16chips
	Spreading factor	SF=1, 8
	Transmit power control (TPC)	Ideal fast TPC Ideal random TPC (Δ=12dB,ε=0.6)
Propagation channel	Fading	Block Rayleigh
	Power delay profile	L=16-path uniform
Receiver	Frequency -domain equalization	MMSE, ZF
	Channel estimation	Ideal

The effect of FDE on the system throughput is shown in Figs. 2 and 3.

First, we discuss the simulation result obtained when SF=8. It is seen from Fig.2 that the throughput using MMSE-FDE is only slightly worse than that using rake combining with perfect IPI cancelation (w/perfect IC). This slight throughput degradation is due to the residual IPI after FDE and the GI insertion loss. On the other hand, ZF-FDE gives almost the same throughput as rake combining without IPI cancellation (β=0). This is because of MAI enhancement due to the ZF weight.

Comparing Fig.2 (a) with Fig.2 (b) shows that the use of random TPC (Fig.2 (b)) achieves larger throughput than the use of fast TPC (Fig.2 (a)) since capture effect is obtained by random TPC.

Next, we discuss the simulation result obtained when SF=1. It is seen from Fig.3 that the throughput using rake (β=0) is always 0 because of large IPI. On the other hand, when fast TPC is used, the MMSE-FDE, ZF-FDE and rake w/perfect IC (β=1) achieve almost the same throughput performance. When SF=1, no packet is received correctly if packet collision occurs. As understood from Eq. (14), IPI can be perfectly suppressed (we are assuming ideal channel estimation) in the interference-limited condition if MMSE or ZF-FDE is used. As a result, MMSE and ZF-FDE achieve almost the same throughput as rake w/perfect IC (β=1). The slight throughput degradation from rake w/perfect IC (β=1) is due to the GI insertion loss. When SF=1, the throughput with random TPC (Fig.3 (b)) is lager than that with fast TPC (Fig.3 (a)) due to the capture effect.

Comparing Fig.2 with Fig.3 shows that when FDE is used, SF=1 achieves larger throughput than SF=8.

V. CONCLUSION

In this paper, we evaluated by computer simulation the uplink system throughput of DS-CDMA wireless packet access using slotted ALOHA. It was shown that the throughput using MMSE-FDE approaches that achievable using rake combining w/perfect IC. In this paper, we assume interference-limited channel and single-cell environment. The throughput performance in a multi-cell environment is the interesting future topic.

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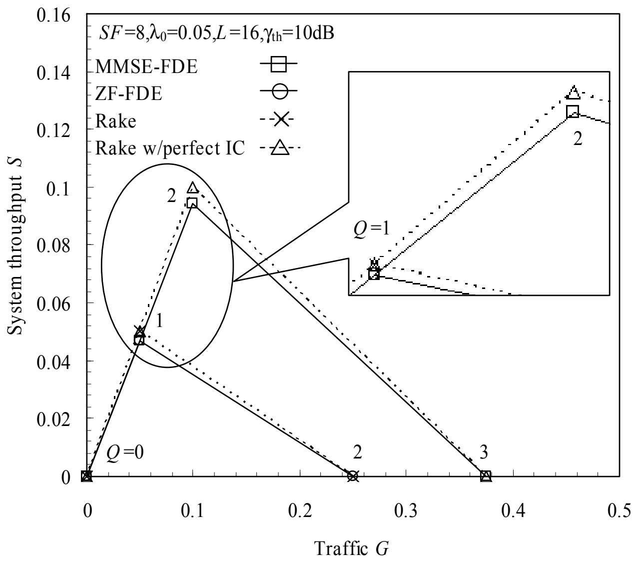
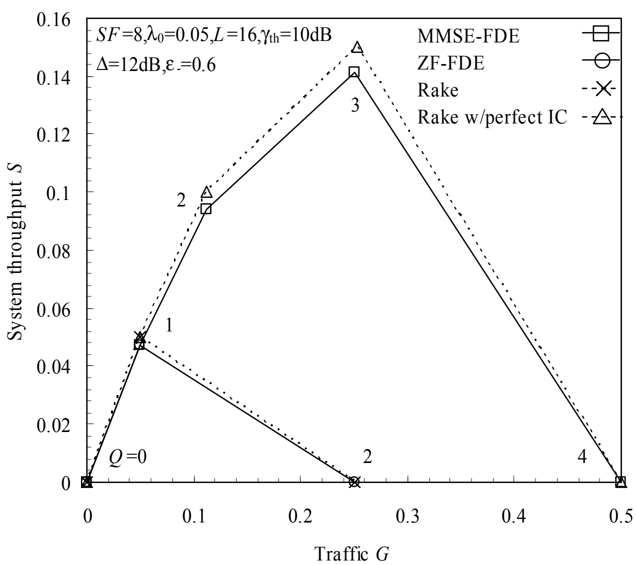
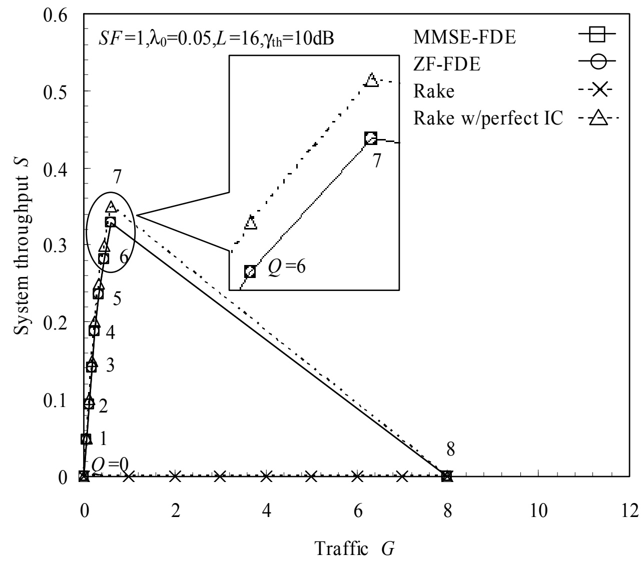


(a)Fast TPC

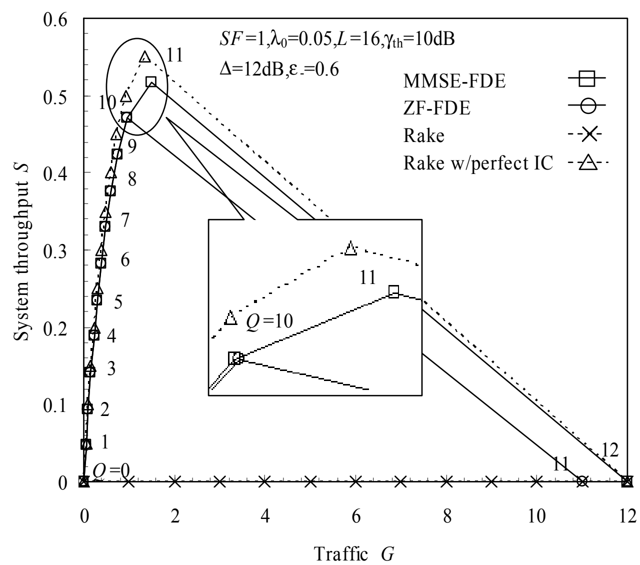


(b)Random TPC

Fig.2 System throughput when SF=8



(a)Fast TPC



(b)Random TPC

Fig.3 System throughput when SF=1