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***Abstract*—We evaluated the average throughput of two types of W-CDMA systems with Multiple-input-multiple-output and adaptive modulation and coding by numerical simulation and theoretic analysis. One system employs space-time transmit diversity, another implements per antenna rate control. In both systems the modulation levels and Turbo coding rates are dynamically adjusted depending on the channel conditions. The channels are assumed to be Rayleigh fading channels. Closed-form expressions are derived for the average throughput of both systems. The simulation results prove the accuracy of the analysis.**

***Index Terms*— W-CDMA, MIMO, HSDPA, AMC, STTD, PARC, throughput.**

I. Introduction

High speed downlink packet access (HSDPA) is a key feature in the 3rd generation wireless communication standard wideband code division multiple access (W-CDMA) [1]. This technology provides high data rate transmission (up to 8-10 Mbps, and 20 Mbps for Multiple-input-multiple-output (MIMO) systems) in W-CDMA downlink to support multimedia services. Several key technologies, such as adaptive modulation and coding (AMC), hybrid automatic request(HARQ), and MIMO, are used in HSDPA to achieve this goal.

AMC is used to support multiple rate transmission for different types of multimedia services. In AMC, the modulation level and coding rate are set by the channel condition. If the mobile user is close to the base station and the signal-to-interference-plus-noise ratio (SINR) is high, the base station can transmit date at high data rate by using higher modulation level and coding rate. Since generally speaking the wireless communication channels are fading and changing with time and location, higher average throughput is achievable by employing AMC instead of using fixed modulation level and coding rate.

For its advantage, the performance of AMC has been evaluated by simulation for various W-CDMA systems with HSDPA [2] [3]. While system simulation can provide performance evaluation of the average throughput of AMC, it is time consuming. On the other hand, most of the MIMO system analysis focuses on capacity evaluation, which does not take into account of the practical system aspects, such as the practical availability of modulation and coding rate. As far as we know, there is no closed-form expression for the average throughput of W-CDMA system with AMC.

In this paper we derive the expression for the average throughput of W-CDMA systems with AMC over Rayleigh fading channel. We focus on two types of W-CDMA systems, one employs Space Time Transmit Diversity (STTD) [1] [3], which implements space-time block code (STBLC), another employs per-antenna rate control (PARC) [2]. Here, we consider 2 transmit antennas and multiple receive antennas in our analysis. Our expressions show the relation between the average throughput and the system configurations such as number of receive antennas, signal-to-noise ratio and the thresholds at which the modulation level and coding rate are selected. We show that the results yielded by our expressions are very close to those yielded by simulation. However, the complexity of using our expressions to evaluate the average throughput is far less than those of simulations. Hence they are helpful for system analysis.

The rest of the paper is organized as follows: the system model is laid out in Section II. The throughput derivation for STTD and PARC systems is carried out in Section III. Numerical results are demonstrated in Section IV, and conclusions are provided in Section V.

II. System Model

We consider the W-CDMA systems with AMC in the physical layer. Only the closest related modules of the real W-CDMA system are taken into consideration. Fig. 1 is the diagram of a system with STTD, and Fig. 2 shows the diagram of a system with PARC. Fig. 1 and Fig. 2 will be discussed in more detail later. Both systems have 2 transmit antennas and L receive antennas, where $L \geqslant 1$ for STTD system and $L \geqslant 2$ for PARC system. The basic modules of the transmitters are:

1. Turbo encoder, which consists of rate 1/3 turbo encoder, puncturer and repeater. The overall code rate, which can be $1/4, 1/3$ or $3/4$, is determined by the puncturing or repeating rate.

2. Modulator, which maps the binary data from the encoder to QPSK, 16QAM or 64QAM symbols.

3. Multicode spreader, which spreads the symbols into chips with multiple Orthogonal Variable Spread Factor (OVSF) codes.

The basic modules of the receivers are multicode despreader, demodulator and turbo decoder.

The parameters for simulation and analysis are shown in Table I. Those parameters are recommended by [1].

Similar as defined in [2] and [3], the available modulation level and coding rate set (MCS) is shown in Table II. The modulation level and coding rate are selected based on the SINR at receiver output as indicated in Fig. 1 and Fig. 2. In the systems, the receiver feeds back the selection of MCS rather than the SINR values. Since we assume the channel information is perfectly known at the receiver, the output SINRs are calculated through the channel information instead of estimation.

The throughput is often expressed as a function of the ratio I_{or}/I_{oc}, where I_{or} is the total transmitted power density, and

Carrier frequency	2GHz
Spreading factor	16
Number of multicodes	10
Frame length	2ms
CPICH power	10%
Ec/Ior	70%
Fading model	One path Rayleigh
Correlation model	i.i.d.
Channel estimation	Perfect
Feedback delay	0
Feedback error	0%
Code	Turbo code

TABLE I
PARAMETERS FOR SIMULATION AND ANALYSIS

I_{oc} is the interference plus noise power density. In simulation and analysis, $I_{oc}$is represented by the power density of the interference plus noise added by the channel. For convenience it is often assumed that $I_{or} = 1$. In Table I, $Ec/Ior = 70\%$, which indicates 70% of the transmit power is allocated to desired signal. For the case of systems with 2 transmit antennas, the power density on each transmit antenna will be $0.7/2$, and the variance of the interference plus noise incurred in the channel is $1/10^{(I_{or}/I_{oc})/10}$ (assuming the unit of I_{or}/I_{oc} is dB). When multiple OVSF codes are used, in order to keep the power density on each transmit antenna to be $0.7/2$, the power density of each spread signal must be $(0.7/2)$ divided by the number of multicodes, i.e., $(0.7/2)/(\text{Number of multicodes})$.

As mentioned before, the MCS is selected based on the output SINR. The criterion is to choose such a MCS that the output frame error rate (FER) is less than 10%. However, the relation between the FER and the SINR for W-CDMA systems is very complicated and cannot be expressed in closed forms. Therefore it has to be obtained by numerical approaches. Fortunately, the simulation results can be applied to any W-CDMA systems of similar structures. The curves of FER versus SINR for different MCS are shown in Fig. 3. Here, 1 transmit antenna and 1 receive antenna are assumed in simulations. From Fig. 3, we choose the thresholds of SINR as shown in Table 2. For example, if the output SINR is greater than $y_2 = 1.25$ dB and less than $y_3 = 4.5$ dB, then to ensure the FER is less than 10%, the MCS will be chosen as QPSK modulation with 1/2 coding rate, which has a throughput T_2 of 2.4Mbps.

The channel between the transmitter and receiver is assumed to be Rayleigh fading channel and is represented by the channel matrix $\mathbf{H} = [h_{i,j}]_{L\times 2}$, where $h_{i,j}$ is the channel gain between the j-th transmit antenna and the i-th receive antenna. We also assume that the $h_{i,j}$ for different i and j is independent to each other.

III. THROUGHPUT ANALYSIS

In this section, we derive the expressions for the average throughput for W-CDMA systems with AMC over Rayleigh fading channel. Since the throughput is determined by the output SINR, the critical part is to find the cumulative distribute function (CDF) or the probability density function(PDF) of SINR.

A. Throughput Analysis for STTD system

The diagrams of the W-CDMA system that employs STTD is shown in Fig. 1. At the transmitter, the output symbols from modulator are first space-time block coded, and then spread using multiple OVSF codes. At the receiver, the received signal are first de-spread, then sent to the STBLC decoder, whose output is demodulated and turbo decoded.

According to the orthogonal property of OVSF codes and the structure of STBLC [4], after despreading, the received signal at time 1 on receive antenna l is

$$r_{l,1} = \sqrt{P_s}\left(h_{l,1}x_1 + h_{l,2}x_2\right) + n_{l,1} \quad (1)$$

where

$$P_s = \frac{0.7}{2}\frac{1}{\text{Number of multicodes}} = \frac{0.7}{20}. \quad (2)$$

The variance of the noise is $\sigma^2 = E\left[|n_{l,1}|^2\right] = \frac{1}{\text{Spreading factor}}\frac{1}{10^{(I_{or}/I_{oc})/10}} = \frac{1}{16}\frac{1}{10^{(I_{or}/I_{oc})/10}}$. Note that the number of multicodes and the spreading factor are given by Table I.

Similarly, the received signal at time 2 on receive antenna l is

$$r_{l,2} = \sqrt{P_s}\left(h_{l,1}\left(-x_2\right)^* + h_{l,2}x_1^*\right) + n_{l,1}. \quad (3)$$

Using STBLC decoder, the transmitted symbols x_1 and x_2 can be detected from the received signal $r_{l,1}$, $r_{l,2}$ ($l = 1, 2, \cdots, L$).The output SINR of the detected x_1 and x_2 is [4]

$$\gamma_{\text{STTD}} = \frac{P_s}{\sigma^2}\sum_{l=1}^{L}\left(|h_{l,2}|^2 + |h_{l,1}|^2\right). \quad (4)$$

The SINR γ_{STTD} is the summation of the square of Gaussian variables. It has a Chi-square distribution and its CDF is [5, Equ. (2.1-114)]

$$\begin{aligned} F(y) &= \Pr\left(\gamma_{\text{STTD}} < y\right) \\ &= 1 - \exp\left(-\frac{y}{\gamma}\right)\sum_{k=0}^{2L-1}\frac{1}{k!}\left(\frac{y}{\gamma}\right)^k \quad \text{for } y \geq 0 \end{aligned} \quad (5)$$

where

$$\gamma = \frac{P_s}{\sigma^2} = \frac{0.7 \times 16}{2 \times 10} \times 10^{(I_{or}/I_{oc})/10}. \quad (6)$$

From Table II, when $y_i < \gamma_{\text{STTD}} < y_{i+1}$, the throughput of the system is T_i. Therefore the average throughput of the STTD system is

$$\begin{aligned} T_{STTD} &= \sum_{i=1}^{7}\Pr\left(y_i < \gamma_{\text{STTD}} < y_{i+1}\right)T_i \\ &= \sum_{i=1}^{7}\left[F_Y\left(y_{i+1}\right) - F_Y\left(y_i\right)\right]T_i. \end{aligned} \quad (7)$$

Index i	1	2	3	4	5	6	7
Threshhold y_i (dB)	-1.9	1.25	4.5	6.5	10.2	14	16.2
Modulation & Code rate	QPSK $1/4$	QPSK $1/2$	QPSK $3/4$	16QAM $1/2$	16QAM $3/4$	64QAM $5/8$	64QAM $3/4$
Throughput T_i (Mbps)	1.2	2.4	3.6	4.8	7.2	9.0	10.8

TABLE II
THRESHHOLDS OF SINR

B. Throughput Analysis for PARC system

For the PARC system shown in Fig. 2, the input data are first de-multiplexed into two streams. Each stream is independently encoded and modulated with its own coding rate and modulation level. At the receiver, received signal are first despread, then the symbols that corresponding to the first transmitted antenna are detected first using Minimum Mean Square Error (MMSE) principle, next the detected symbols are demodulated, turbo decoded, to obtain the detected binary data. These binary data are re-encoded to generated the transmitted symbols from the first transmit antenna, just as in the transmitter. The regenerated symbols are deducted from the received signal in the interference canceller module. From the received signal after interference cancellation, Maximum Ratio Combining(MRC) is used to detect the symbols for the second transmit antenna. The MCS for the first and the second transmit antenna are determined by the SINR of their detected symbols as marked in Fig. 2.

It should be pointed out that the PARC system we discussed in this paper is slightly different from the system presented in [2]. Our system always uses two transmit antennas to transmit data, whereas under certain condition the system in [2] only use one of the two transmit antennas to transmit data.

As shown in Fig. 2, the received signal after despreading is

$$\mathbf{r} = \sqrt{P_s}\mathbf{H}\mathbf{x} + \mathbf{n} \tag{8}$$

where $\mathbf{r} = \begin{pmatrix} r_1 & r_2 \end{pmatrix}^T, \mathbf{x} = \begin{pmatrix} x_1 & x_2 \end{pmatrix}^T, \mathbf{n} = \begin{pmatrix} n_1 & n_2 \end{pmatrix}^T$, and the superscript T denotes transposition of a vector. For future use, Define vectors $\mathbf{h}_1$ and $\mathbf{h}_2$ as the first and the second column of the channel matrix $\mathbf{H}$, i.e., $\mathbf{H} = \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 \end{bmatrix}$. P_s is defined in (2). The covariance matrix of the noise is $E\left[\mathbf{n}\mathbf{n}^\dagger\right] = \sigma^2\mathbf{I}_L$, where the superscript $\dagger$ denotes Hermitian transposition; σ^2 is defined in the previous section and $\mathbf{I}_L$ is an identity matrix of rank L.

To analyze the theoretical throughput, we need to find the joint PDF of the SINR for the detected symbols from the first and the second transmit antenna. In doing that, we first derive expressions for the SINR of the detected symbols.

1) Expressions for SINR: The symbols x_1, which is from the first antenna, is detected first using the MMSE principle. It is well known that MMSE is equivalent to the optimum combining detection scheme discussed in [6]. From [6] we know the detected symbols for x_1 is

$$\widehat{x}_1 = \frac{1}{\sqrt{P_s}\mathbf{w}^\dagger\mathbf{H}}\mathbf{w}^\dagger\mathbf{r} \tag{9}$$

where $\mathbf{w} = \mathbf{R}^{-1}\mathbf{h}_1$ is the optimum combining weight; $\mathbf{R} = \mathbf{P}_s\mathbf{h}_2\mathbf{h}_2^\dagger + E\left[\mathbf{n}\mathbf{n}^\dagger\right]$ is the covariance matrix of interference plus noise for x_1. In (9), $\frac{1}{\sqrt{P_s}\mathbf{w}^\dagger\mathbf{H}}$ is a normalized factor that does not affect the output SINR. The SINR for the detected $\widehat{x}_1$ is [6]

$$\gamma_1 = \frac{P_s}{P_s\sum_{l=1}^{L}|h_{l,2}|^2 + \sigma^2}|g_1|^2 + \frac{P_s}{\sigma^2}\sum_{m=2}^{L}|g_m|^2 \tag{10}$$

where g_m for $m = 1, \cdots, L$ is a complex Gaussian random variable that has the same distribution as $h_{m,1}$, i.e., with zero mean and unit variance.

On condition that x_1 is perfectly detected and cancelled from the received signal $\mathbf{r}$, the output of the interference cancellation module in Fig. 2 is

$$\mathbf{r}_2 = \mathbf{r} - \sqrt{P_s}\mathbf{h}_1x_1 = \sqrt{P_s}\mathbf{h}_2x_2 + \mathbf{n}. \tag{11}$$

Using MRC detection scheme, the detect symbol for x_2 is [5]

$$\widehat{x}_2 = \frac{1}{\sqrt{P_s}\mathbf{h}_2^\dagger\mathbf{h}_2}\mathbf{h}_2^\dagger\mathbf{r}_2, \tag{12}$$

where $\frac{1}{\sqrt{P_s}\mathbf{h}_2^\dagger\mathbf{h}_2}$ is a normalized factor. It can be easily shown that the SINR for the detected $\widehat{x}_2$ is

$$\gamma_2 = \frac{P_s}{\sigma^2}\mathbf{h}_2^\dagger\mathbf{h}_2 = \frac{P_s}{\sigma^2}\sum_{l=1}^{L}|h_{l,2}|^2. \tag{13}$$

With the definition of γ_2 in (13) and γ in (6), the SINR γ_1 in (10) can be expressed as

$$\gamma_1 = \frac{\gamma}{\gamma_2 + 1}|g_1|^2 + \gamma\sum_{m=2}^{L}|g_m|^2. \tag{14}$$

2) Expressions for PDF of SINR: In order to evaluate the average throughput, we need to derive the jointed PDF $p_{\gamma_1,\gamma_2}(\gamma_1, \gamma_2)$ of γ_1 and γ_2, which can be obtained by using

$$p_{\gamma_1,\gamma_2}(\gamma_1, \gamma_2) = p_{\gamma_2}(\gamma_2)\,p_{\gamma_1|\gamma_2}(\gamma_1|\gamma_2) \tag{15}$$

where $p_{\gamma_2}(\gamma_2)$ is the PDF of γ_2, and $p_{\gamma_1|\gamma_2}(\gamma_1|\gamma_2)$ is the PDF of γ_1 conditioned on γ_2.

The SINR γ_2 in (13) is the summation of the square of Gaussian variables. It has a Chi-square distribution and its PDF is [5, Equ. (2.1-110)]

$$p_{\gamma_2}(\gamma_2) = \frac{\gamma_2^{L-1}}{(L-1)!\gamma^L}\exp\left(-\frac{\gamma_2}{\gamma}\right). \tag{16}$$

The conditional PDF $p_{\gamma_1|\gamma_2}(\gamma_1|\gamma_2)$ can be derived from its corresponding moment generating function (MGF) $M_{\gamma_1|\gamma_2}(s)$. $p_{\gamma_1|\gamma_2}(\gamma_1|\gamma_2)$ and $M_{\gamma_1|\gamma_2}(s)$ are Laplace transform pair. By modifying the result in [6, Eq. 10.52], we can get the MGF for our case as

$$M_{\gamma_1|\gamma_2}(s) = \left(\frac{1}{1-\gamma s}\right)^{L-1} \frac{1}{1-\frac{\gamma}{\gamma_2+1}s}. \tag{17}$$

Using the Laplace Transform pair in [7, Eq. (21)], after some manipulations, we get the conditional PDF of γ_1 as

$$\begin{aligned} & p_{\gamma_1|\gamma_2}(\gamma_1|\gamma_2) \\ = \; & (-1)^{L-2} \frac{1}{\gamma} \frac{(\gamma_2+1)}{\gamma_2^{L-1}} \exp\left(-\frac{\gamma_2+1}{\gamma}\gamma_1\right) + \exp\left(-\frac{\gamma_1}{\gamma}\right) \\ & \frac{1}{\gamma^{L-1}} \sum_{l=1}^{L-1} \frac{(-\gamma)^{l-1}}{(L-1-l)!} \frac{(\gamma_2+1)}{\gamma_2^{l}} \gamma_1^{L-1-l} \end{aligned} \tag{18}$$

Substituting (16) and (18) into (15), we obtain the joint PDF of γ_1 and γ_2 as

$$\begin{aligned} & p_{\gamma_1,\gamma_2}(\gamma_1,\gamma_2) \\ = \; & (-1)^{L-2} \frac{(\gamma_2+1)}{(L-1)!\gamma^{L+1}} \exp\left(-\frac{\gamma_2}{\gamma}\right) \\ & \exp\left(-\frac{\gamma_2+1}{\gamma}\gamma_1\right) + \frac{1}{(L-1)!\gamma^{2L-1}} \sum_{l=1}^{L-1} \frac{(-\gamma)^{l-1}}{(L-1-l)!} \\ & \gamma_1^{L-1-l} \exp\left(-\frac{\gamma_1}{\gamma}\right) \exp\left(-\frac{\gamma_2}{\gamma}\right) \left(\gamma_2^{L-l} + \gamma_2^{L-l-1}\right) \end{aligned} \tag{19}$$

3) Expression for throughput: To express throughput in equation, we first define the probability that γ_1 and γ_2 fall in the area $w_0 < \gamma_1 < w_1, z_0 < \gamma_2 < z_1$ as

$$\begin{aligned} & P(w_0, w_1, z_0, z_1) \\ = \; & \Pr(w_0 < \gamma_1 < w_1, z_0 < \gamma_2 < z_1) \\ = \; & \iint_{w_0<\gamma_1<w_1, z_0<\gamma_2<z_1} p_{\gamma_1,\gamma_2}(\gamma_1,\gamma_2)\, d\gamma_1 d\gamma_2. \end{aligned} \tag{20}$$

Substituting (18) in (20) and after some straightforward manipulations, we have

$$\begin{aligned} & P(w_0, w_1, z_0, z_1) \\ = \; & (-1)^{L-1} \left[\exp\left(-\frac{w_1}{\gamma}\right) S\left(0, \frac{w_1+1}{\gamma}, z_0, z_1\right) \right. \\ & \left. -\exp\left(-\frac{w_0}{\gamma}\right) S\left(0, \frac{w_0+1}{\gamma}, z_0, z_1\right)\right] \\ & + \frac{1}{(L-1)!\gamma^{2L-1}} \sum_{l=1}^{L-1} \frac{(-\gamma)^{l-1}}{(L-1-l)!} \\ & \left[S\left(L-l, \frac{1}{\gamma}, z_0, z_1\right) + S\left(L-l-1, \frac{1}{\gamma}, z_0, z_1\right)\right] \\ & S\left(L-l-1, \frac{1}{\gamma}, w_0, w_1\right) \end{aligned} \tag{21}$$

where the function $S(\cdot,\cdot,\cdot,\cdot)$ is defined as

$$\begin{aligned} & S(n, a, x_0, x_1) \\ = \; & \exp(-ax_0) \sum_{k=0}^{n} \frac{n!}{(n-k)!a^{k+1}} \left(x_0^{n-k} - x_1^{n-k}\right) \end{aligned} \tag{22}$$

From Table II, when $y_i < \gamma_1 < y_{i+1}$ and $y_1 < \gamma_2 < \infty$, the throughput we get from the first transmit antenna is T_i; when $y_1 < \gamma_1 < \infty$ and $y_i < \gamma_2 < y_{i+1}$, the throughput we can get from the second transmit antenna is T_i as well. Therefore the average throughput of the PARC system is

$$\begin{aligned} & T_{PARC} \\ = \; & \sum_{i=1}^{7} [\Pr(y_i < \gamma_1 < y_{i+1},\ y_1 < \gamma_2 < \infty) T_i + \\ & \Pr(y_1 < \gamma_1 < \infty,\ y_i < \gamma_2 < y_{i+1}) T_i] \\ = \; & \sum_{i=1}^{7} [P(y_i, y_{i+1}, y_1, \infty) + P(y_1, \infty, y_i, y_{i+1})] T_i. \end{aligned} \tag{23}$$

Though they may look complicated, the average throughput expressions (7) and (23) are very easy to implement in software and the time they take to evaluate is negligible comparing to simulation.

IV. Numerical Results

In this section we provide both analysis results and simulation results. The analysis results were calculated using (7), (23) and the related expressions. Fig. 4 shows the throughput versus I_{or}/I_{oc} for $L = 2$ receive antennas. Fig. 5 shows the throughput versus I_{or}/I_{oc} for $L = 4$ receive antennas. The analysis results match the simulation results in both figures. That proves we can use the analytical expressions to evaluate the throughput instead of resorting to the time-consuming Monte Carlo simulation.

V. Conclusions

In this paper, we derived the expressions of the average throughput for W-CDMA systems in the physical layer implementing AMC over diversity channel with Rayleigh fading. The expressions are closed-form, and are easy and fast to evaluate. The validity of these expressions have been proved by simulation results.

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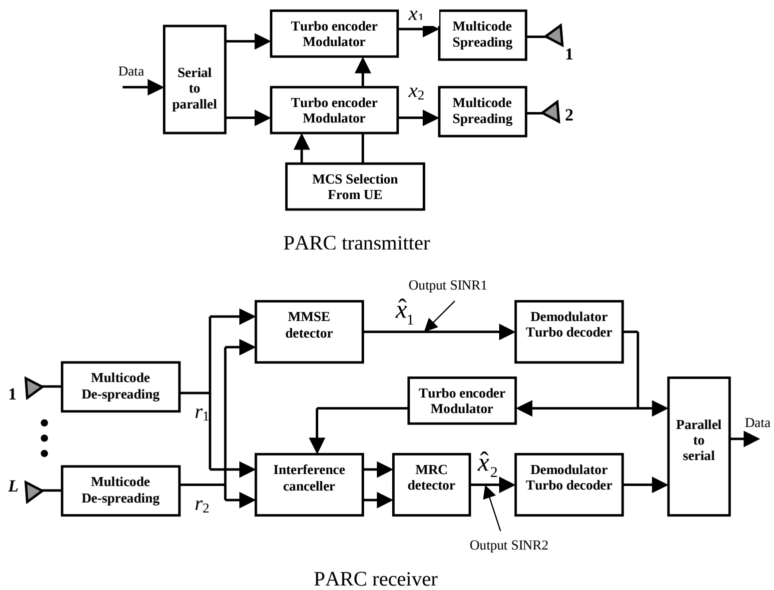

Fig. 2. Diagram of PARC system

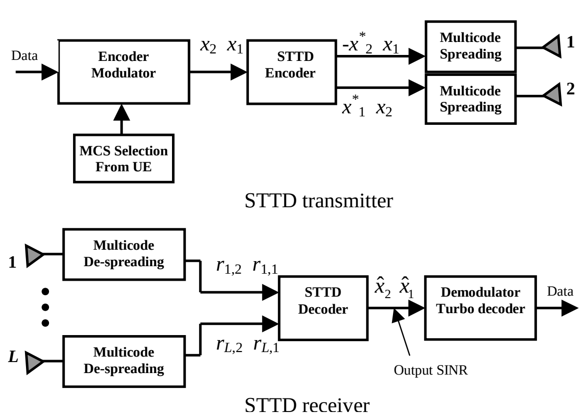

Fig. 1. Diagram of STTD system

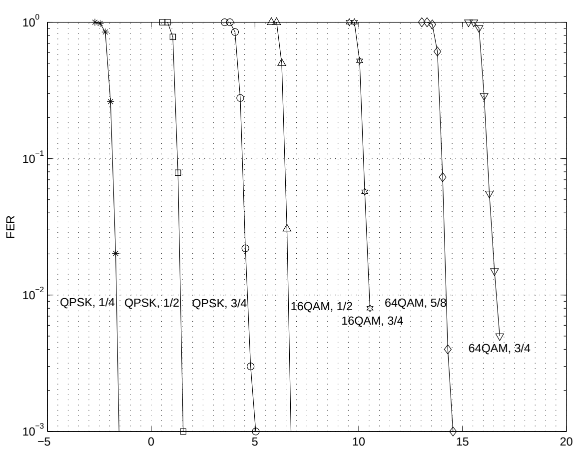

Fig. 3. FER versus SINR for each MCS

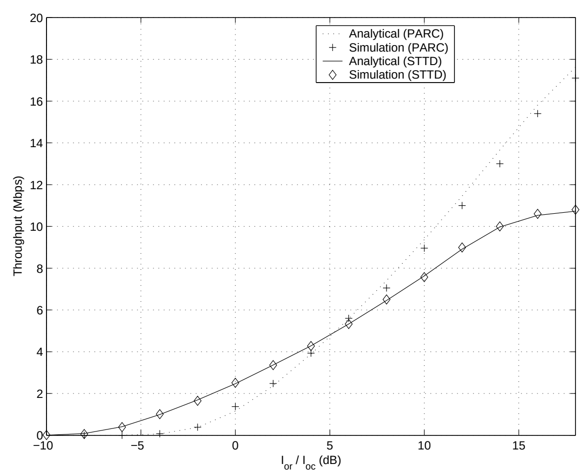

Fig. 4. Average throughput versus $I_{\mathrm{or}}/I_{\mathrm{oc}}$ for $L = 2$ receive antennas.

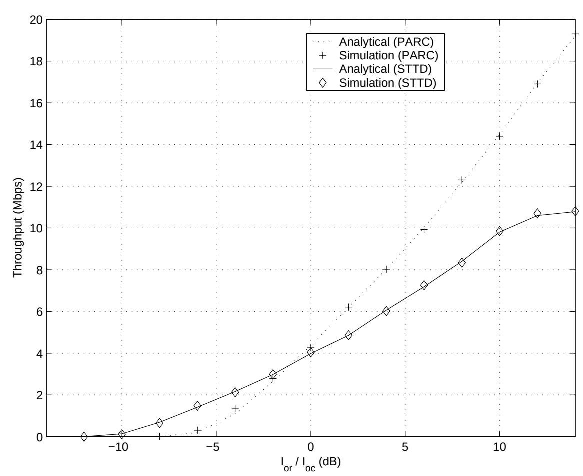

Fig. 5. Average throughput versus $I_{\mathrm{or}}/I_{\mathrm{oc}}$ for $L = 4$ receive antennas.