Throughput Performance of MC-CDMA HARQ using Space-Time Block Coded-Joint Transmit/Receive Diversity

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Abstract— **Hybrid automatic repeat request (HARQ) is an indispensable error control technique for wireless packet access. A combination of multi-carrier code division multiple access (MC-CDMA) and HARQ can provide a good throughput performance in a severe frequency-selective fading channel. Recently, we proposed the space-time block coded-joint transmit/receive diversity (STBC-JTRD), which allows an arbitrary number of transmit antennas while limiting the number of receive antennas to 6. In this paper, we evaluate, by computer simulation, the throughput performance of MC-CDMA HARQ using STBC-JTRD, and show that the STBC-JTRD provides a better throughput performance than the space-time block coded transmit diversity (STTD).**

Keywords-component; Frequency-selective fading channel, STBC-JTRD, STTD, HARQ, MC-CDMA.

I. INTRODUCTION

In the next generation mobile communications systems, broadband packet services will be in great demand [1]. Hybrid automatic repeat request (HARQ), which is a combination of ARQ and error correcting coding (e.g., turbo code), is an indispensable error control technique for broadband packet access [2-3]. The wireless channel is severely frequency-selective [4-5]. Multi-carrier code division multiple access (MC-CDMA) can be used to exploit the frequency-selectivity of the channel and improve the transmission performance [6-8].

Antenna diversity is a well-known technique for improving the transmission performance [4-5]. Transmit antenna diversity has been attracting much attention because the complexity problem of a mobile terminal can be alleviated [9-12]. Recently, we proposed the space-time block coded-joint transmit/receive antenna diversity (STBC-JTRD) for a frequency-nonselective fading channel [13, 14], which allows an arbitrary number of transmit antennas without sacrificing the coding rate while the coding rate of well-known space-time block coded transmit diversity (STTD) is reduced when more than 2 transmit antennas are used [10]. We also showed [15, 16] that the STBC-JTRD can be extended to the case of frequency-selective fading channel by introducing the frequency-domain pre-equalization (pre-FDE) [17, 18]. In this paper, we evaluate, by computer simulation, the throughput performance of turbo coded MC-CDMA HARQ using STBC-JTRD.

The remainder of this paper is organized as follows. Sect. II introduces the transmission system model of turbo-coded MC-CDMA HARQ using STBC-JTRD. In Sect. III, we show the computer simulation results of the throughput performance. Sect. IV offers some conclusions.

II. TRANSMISSION SYSTEM MODEL

We assume multi-code MC-CDMA signal transmission using N_c subcarriers. Figure 1 illustrates the transmitter and receiver structure for multi-code MC-CDMA HARQ with STBC-JTRD. N_t transmit antennas and N_r receive antennas are assumed. In this paper, we consider Chase combining [19] as a packet combining.

At the transmitter, after the turbo coding and puncturing, the turbo-coded bit sequence is stored in the transmitter buffer. The turbo-coded bit sequence is transformed into a data modulated symbol sequence and the symbol sequence is serial-to-parallel (S/P) converted to U symbol streams $\{d_u(n); n=\ldots-1, 0, 1, \ldots\}$, $u=0\sim U-1$. Each U stream is spread by orthogonal spreading codes $\{c_u(t); t=0\sim(SF-1)\}$, $u=0\sim(U-1)$, where SF is the spreading factor, to obtain the multi-code chip sequence, and further multiplied with a scrambling sequence $c_{scr}(t)$. A resulting multi-code block sequence to be transmitted is grouped into a sequence of blocks of J blocks. At the STBC-JTRD encoding, the J consecutive blocks are encoded into N_t parallel codewords; each codeword consisting of a sequence of Q blocks as shown in Fig. 2. Table 1 shows the number J of information blocks in a codeword, the number Q of coded blocks in a codeword, and coding rate R for N_r=1~6. After STBC-JTRD encoding, N_c-point inverse fast Fourier transform (IFFT) is applied to each block of N_t codewords to generate the time-domain coded MC-CDMA signal blocks. After inserting a cyclic prefix of N_g chips into the guard interval (GI), N_t MC-CDMA signal blocks of (N_c+N_g) samples each are transmitted from N_t transmit antennas.

At the receiver, after removing the GI from the received MC-CDMA signal blocks, the N_c-point FFT is applied to decompose each of them into the N_c subcarrier components. Then, STBC-JTRD decoding is carried. After the de-scrambling and de-spreading, the turbo decoding is carried out.

In what follows, without loss of generality, we assume the transmission of one codeword (transmission of JN_c/SF data symbols $\{d_u(n); n=0\sim(J(N_c/SF)-1), u=0\sim(U-1)\}$).

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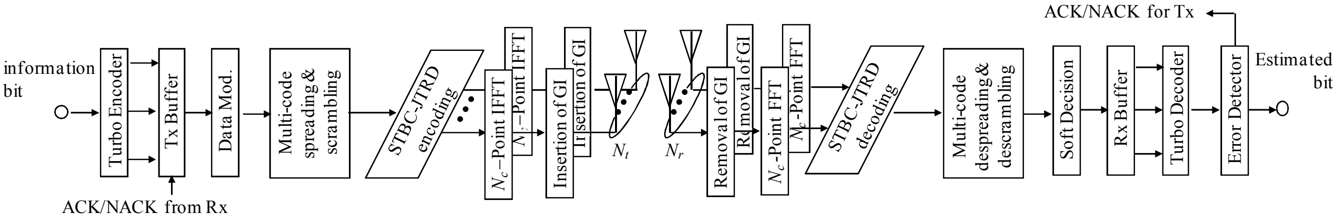


Fig. 1 Transmitter/receiver structure of multi-code MC-CDMA HARQ using STBC-JTRD.

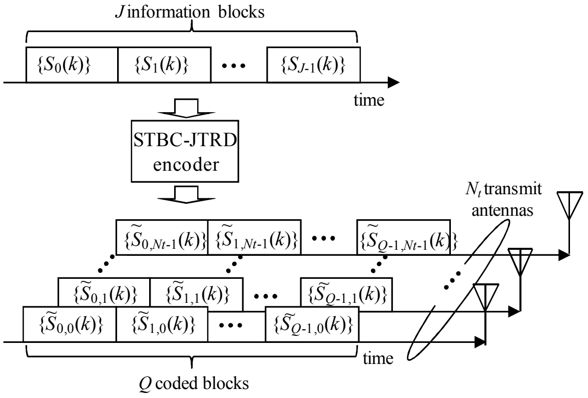


Fig. 2 STBC-JTRD encoding.

Table 1 J, Q, R for N_r=1~6

N_r	J	Q	R
1	1	1	1
2	2	2	1
3	3	4	3/4
4	3	4	3/4
5	10	15	2/3
6	20	30	2/3

A. Channel model

In this paper, we assume a sample-spaced L-path frequency-selective block fading channel. The channel impulse response $h_{m,n}^{(i)}(\tau)$ between the n-th transmit antenna and m-th receive antenna at the i-th packet transmission is expressed as

$$h_{m,n}^{(i)}(\tau)=\sum_{l=0}^{L-1} h_{m,n,l}^{(i)}\delta(\tau-l) \quad , \qquad (1)$$

where $h_{m,n,l}^{(i)}$ is the complex-valued path gain and time delay of the l-th propagation path between the n-th (n=0~(N_t−1)) transmit antenna and the m-th (m=0~(N_r−1)) receive antenna at the i-th packet transmission. The channel gain at the k-th subcarrier component is given by

$$H_{m,n}^{(i)}(k)=\sum_{l=0}^{L-1} h_{m,n,l}^{(i)} \exp\left(-j2\pi k\frac{l}{N_c}\right) \qquad (2)$$

B. STBC-JTRD encoding

At the STBC-JTRD encoding, the J consecutive blocks $\{S_j(k)$, k=0~(N_c−1)$\}$, j=0~(J−1), are encoded into N_t parallel codewords; the n-th codeword (n=0~(N_t−1)) consisting of a sequence of Q blocks $\{\tilde{S}_{q,n}^{(i)}(k)$; q=0~(Q−1)$\}$ for the i-th packet transmission. $S_j(k)$ is expressed as

$$S_j(k)=\sqrt{\frac{2P}{SF}}\sum_{u=0}^{U-1} c_{scr}(k)c_u(k \bmod SF)d_u\left(\lfloor k/SF\rfloor + jN_c/SF\right) \quad , \qquad (3)$$

where P denotes the transmit power per data symbol and $\lfloor x\rfloor$ is the largest integer smaller than or equal to x.

STBC-JTRD encoding for N_r=1~6 number of receive antennas was shown in [16, 20]. Below, the encoding algorithms are presented for the case of N_r=2 and 4 only. When N_r=2 (4), the J=2 (3) information symbol blocks are encoded into N_t codewords, each consisting of Q=2 (4) consecutive blocks as [16]

$$\begin{pmatrix}\tilde{\mathbf{S}}_0^{(i)}(k)\\ \tilde{\mathbf{S}}_1^{(i)}(k)\end{pmatrix}=C_2^{(i)}\begin{pmatrix}S_0(k)\mathbf{W}_0^{(i)*}(k)+S_1(k)\mathbf{W}_1^{(i)*}(k)\\ S_0^*(k)\mathbf{W}_1^{(i)*}(k)-S_1^*(k)\mathbf{W}_0^{(i)*}(k)\end{pmatrix} \quad \text{for } N_r=2 \qquad (4a)$$

$$\begin{pmatrix}\tilde{\mathbf{S}}_0^{(i)}(k)\\ \tilde{\mathbf{S}}_1^{(i)}(k)\\ \tilde{\mathbf{S}}_2^{(i)}(k)\\ \tilde{\mathbf{S}}_3^{(i)}(k)\end{pmatrix}=C_4^{(i)}\begin{pmatrix}S_0(k)\mathbf{W}_0^{(i)*}(k)+S_1(k)\mathbf{W}_1^{(i)*}(k)+S_2(k)\mathbf{W}_2^{(i)*}(k)\\ S_0^*(k)\mathbf{W}_1^{(i)*}(k)-S_1^*(k)\mathbf{W}_0^{(i)*}(k)+S_2(k)\mathbf{W}_3^{(i)*}(k)\\ S_0^*(k)\mathbf{W}_2^{(i)*}(k)-S_1(k)\mathbf{W}_3^{(i)*}(k)-S_2^*(k)\mathbf{W}_0^{(i)*}(k)\\ S_0(k)\mathbf{W}_3^{(i)*}(k)+S_1^*(k)\mathbf{W}_2^{(i)*}(k)-S_2^*(k)\mathbf{W}_1^{(i)*}(k)\end{pmatrix} \quad \text{for } N_r=4, \qquad (4b)$$

where $\tilde{\mathbf{S}}_q^{(i)}(k)=[\tilde{S}_{q,0}^{(i)}(k),\tilde{S}_{q,1}^{(i)}(k),\ldots,\tilde{S}_{q,N_t-1}^{(i)}(k)]^{\mathrm{T}}$, q=0~(Q−1). $\mathbf{W}_m^{(i)}(k)=[W_{m,0}^{(i)}(k),W_{m,1}^{(i)}(k),\ldots,W_{m,N_t-1}^{(i)}(k)]^{\mathrm{T}}$ is the MMSE pre-FDE weight vector (m=0~N_r−1), which is given by [16]

$$\mathbf{W}_m^{(i)}(k)=\frac{\mathbf{H}_m^{(i)}(k)}{\frac{1}{N_r}\sum_{m=0}^{N_r-1}\|\mathbf{H}_m^{(i)}(k)\|^2+\left(\frac{U}{SF}\frac{E_s}{N_0}\right)^{-1}}, \qquad (5)$$

where $\mathbf{H}_m^{(i)}(k)=[H_{m,0}^{(i)}(k),H_{m,1}^{(i)}(k),\ldots,H_{m,N_t-1}^{(i)}(k)]^{\mathrm{T}}$ and E_s=PN_cT_c (T_c is the FFT/IFFT sampling period). N_0 is the single-sided power spectrum density of the additive white Gaussian noise (AWGN) process at the receiver. For performing MMSE pre-FDE, the channel gain and the noise power of the receiver are required at the transmitter. $C_{N_r}^{(i)}$ is the power normalization factor , which is given by

$$C_{N_r}^{(i)} = \left(N_c / \sum_{m=0}^{N_r-1}\sum_{k=0}^{N_c-1} \| \mathbf{W}_m^{(i)}(k) \|^2 \right)^{1/2} \quad . \qquad (6)$$

In STBC-JTRD, when more than 2 receive antennas are used, the coding rate is reduced (see Table 1). After the STBC-JTRD encoding, by applying the N_c-point IFFT, a sequence of the time-domain multi-code MC-CDMA signal blocks is generated. After the insertion of GI, each signal blocks is transmitted from each transmit antennas.

C. STBC-JTRD decoding

At the receiver, after the removal of GI, N_c-point FFT is applied to decompose the received signal block into the N_c subcarrier components. The q-th received signal vector $\mathbf{R}_q^{(i)}(k) = [R_{q,0}^{(i)}(k), R_{q,1}^{(i)}(k), ..., R_{q,N_r-1}^{(i)}(k)]^{\mathrm{T}}$, where $R_{q,m}^{(i)}(k)$ is the k-th subcarrier component of the q-th received signal block on the m-th receive antenna at the i-th packet transmission, is expressed as

$$\mathbf{R}_q^{(i)}(k) = \mathbf{H}^{(i)}k)\widetilde{\mathbf{S}}_q^{(i)}(k) + \mathbf{\Pi}_q^{(i)}(k) \quad , \qquad (7)$$

where $\mathbf{H}^{(i)}(k) = [\mathbf{H}_{i,0}^{(i)}(k), \mathbf{H}_{i,1}^{(i)}(k), ..., \mathbf{H}_{i,N_r-1}^{(i)}(k)]^{\mathrm{T}}$. $\mathbf{\Pi}_q^{(i)}(k) = [\Pi_{q,0}^{(i)}(k), \Pi_{q,1}^{(i)}(k), ..., \Pi_{q,N_r-1}^{(i)}(k)]^{\mathrm{T}}$ is the noise vector, where $\Pi_{q,m}^{(i)}(k)$ is the AWGN with a zero mean and a variance $2N_0/T_c$. STBC-JTRD decoding is carried out on $\{ R_{q,m}^{(i)}(k)$;q=0~(Q−1), m=0~(N_r−1)} as follows [16]:

$$\begin{pmatrix} \hat{S}_0^{(i)}(k) \\ \hat{S}_1^{(i)}(k) \end{pmatrix} = \begin{pmatrix} R_{0,0}^{(i)}(k) + \{R_{1,1}^{(i)}(k)\}^* \\ R_{0,1}^{(i)}(k) - \{R_{1,0}^{(i)}(k)\}^* \end{pmatrix} \qquad \text{for } N_r\text{=2 (8a)}$$

$$\begin{pmatrix} \hat{S}_0^{(i)}(k) \\ \hat{S}_1^{(i)}(k) \\ \hat{S}_2^{(i)}(k) \end{pmatrix} = \begin{pmatrix} R_{0,0}^{(i)}(k) + \{R_{1,1}^{(i)}(k)\}^* + \{R_{2,2}^{(i)}(k)\}^* + R_{3,3}^{(i)}(k) \\ R_{0,1}^{(i)}(k) - \{R_{1,0}^{(i)}(k)\}^* - R_{2,3}^{(i)}(k) + \{R_{3,2}^{(i)}(k)\}^* \\ R_{0,2}^{(i)}(k) + R_{1,3}^{(i)}(k) - \{R_{2,0}^{(i)}(k)\}^* - \{R_{3,1}^{(i)}(k)\}^* \end{pmatrix}$$

$$\text{for } N_r\text{=4.} \qquad (8b)$$

Finally, despreading is performed to get the decision variable $\hat{d}_u(n)$ for the n-th data symbol $d_u(n)$ as

$$\hat{d}_u(n + jN_c / SF) = \frac{1}{SF} \sum_{t=nSF}^{(n+1)SF-1} \hat{S}_j^{(i)}(k) c_{scr}^*(k) c_u^*(k \bmod SF)$$
$$, n = 0 \sim (N_c / SF - 1), \; j = 0 \sim J - 1 \quad . \qquad (9)$$

Turbo decoding is carried out using a sequence of the soft decision variable. In this paper, the ideal error detection is assumed. If no error is detected after the turbo decoding, a acknowledgement (ACK) signal is transmitted to the transmitter. Otherwise, a negative ACK (NACK) signal is transmitted to the transmitter to request the retransmission of the same packet.

III. COMPUTER SIMULATION

The simulation conditions are summarized in Table 2. We assume N_c=256, N_g=32, and a sample-spaced L=16-path frequency-selective block Rayleigh fading channel with uniform power delay profile (i.e., the ensemble average of E[| $h_{m,n,l}^{(i)}$ |^2]=1/L for all i, m, n, l). The ideal channel estimation for frequency-domain STBC-JTRD encoding is assumed. For the turbo coding, we use an original coding rate R_c=1/3 turbo encoder having two (13, 15) recursive systematic component encoders, which are concatenated with S-random internal interleaver followed by puncturer, is used. For comparison, we also evaluate, by computer simulation, the throughput performance of conventional STTD with MMSE-FDE reception jointly used with maximal-ratio-combining (MRC) receive antenna diversity combining [21]. Table 3 compares the STBC-JTRD and STTD.

Table 2 Simulation conditions

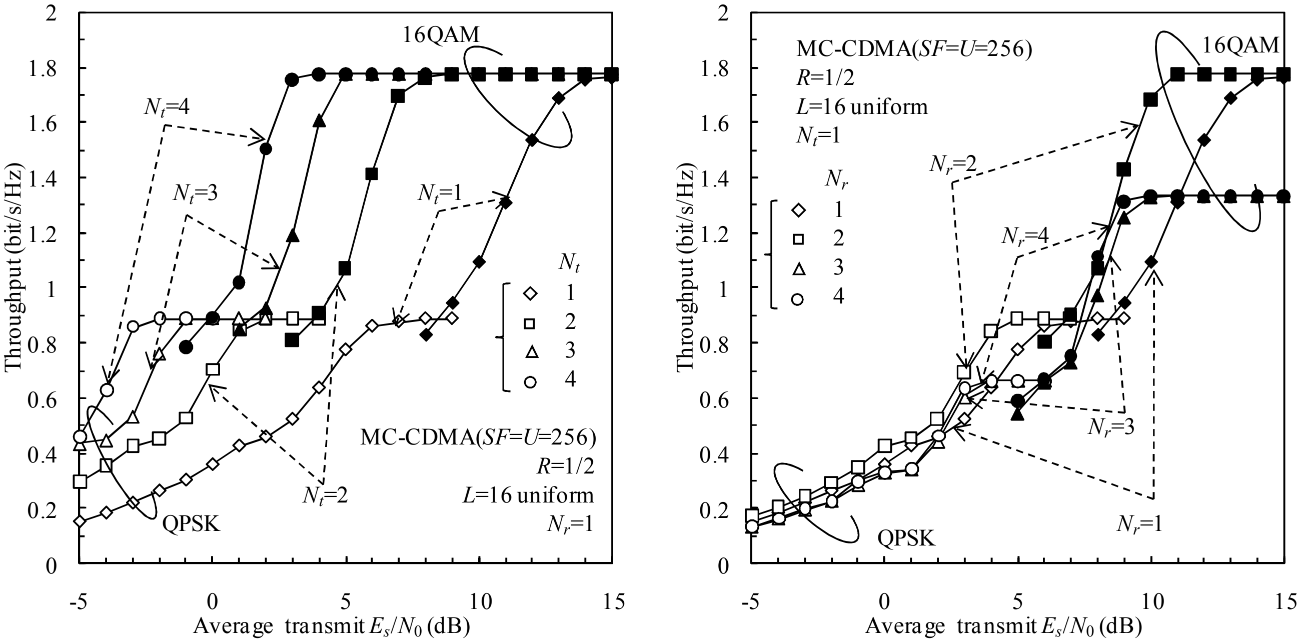
Data modulation		QPSK, 16QAM
MC-CDMA	No. of subcarriers	N_c=256
	Spreading factor	SF=256
	No. of Code multiplexing order	U=256
	No. transmit antennas	N_t=1, 2, 3, 4
Channel coding	No. of info. bits	1536
	Encoder	(13, 15) RSC
	Coding rate	R_c=1/2
	Channel inter-leaver	Block
	Packet combining	Chase combining
	Decoder	Log MAP with 8 iterations
Channel model	Fading type	Block Rayleigh
	No. of paths	L=16
	Power delay profile	Uniform
	Time delay	τ_l=l, l=0~L−1
	Doppler frequency	f_D=0
Receiver	No. receive antennas	N_r=1, 2, 3, 4
Channel estimation		Ideal

Table 3 Comparison STBC-JTRD and STTD

Diversity scheme	No. of transmit antennas, N_t	No. of receive antennas, N_r	CSI required at	Coding rate, R
STBC -JTRD	Arbitrary	1, 2	Transmitter side	1
		3, 4		3/4
STTD	1,2	Arbitrary	Receiver side	1
	3,4			3/4

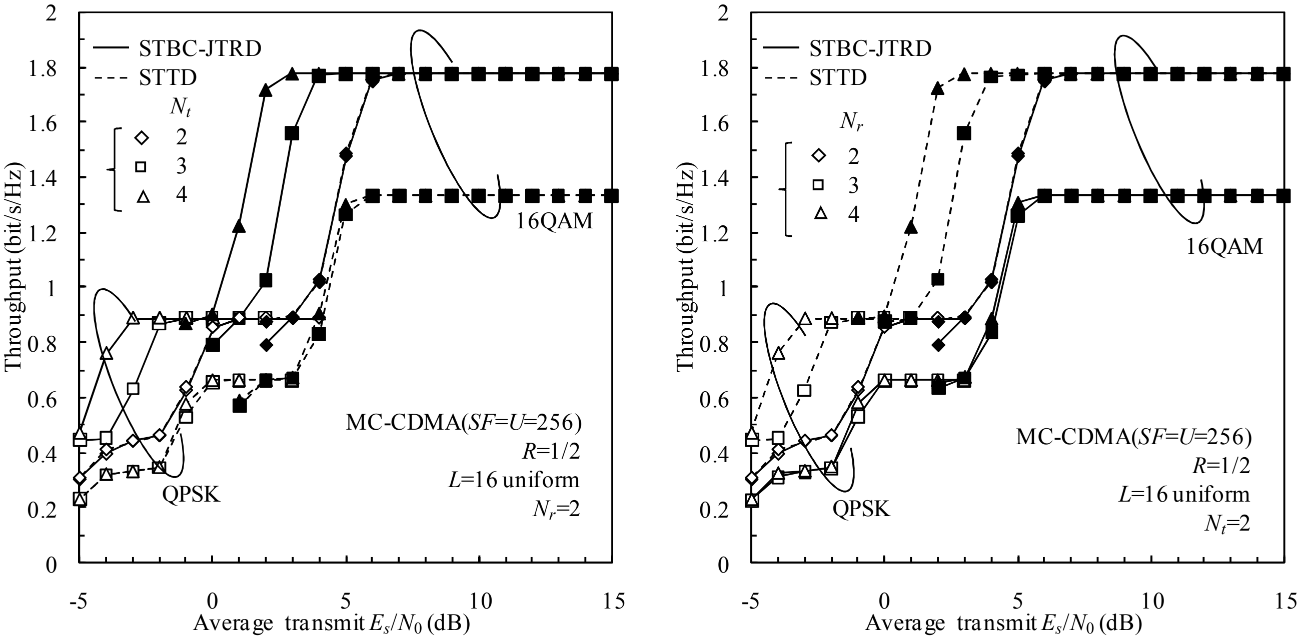
A. Throughput performance

Figure 3(a) shows the throughput performance achievable by STBC-JTRD for N_r=1 as a function of the average transmit E_s/N_0 with N_t as a parameter. It is seen that the throughput performance can be improved as the number N_t of transmit antennas increases since larger transmit antenna diversity gain is obtained. The required E_s/N_0 for the peak throughput performance is reduced by 10 (12) dB as N_t increases from 1 to 4 in the case of QPSK (16QAM) data modulation. Figure



(a) Effect of transmit diversity gain (N_r=1) (b) Effect of receive diversity gain (N_t=1)

Fig. 3 Throughput performance of STBC-JTRD.



(a) Effect of transmit diversity gain (N_r=2) (b) Effect of receive diversity gain (N_t=2)

Fig. 4 Comparison between STBC-JTRD and STTD.

3(b) shows the throughput performance of STBC-JTRD for N_t=1 with N_r as a parameter. While the throughput performance can be improved as N_r increases from 1 to 2, the performance improvement is smaller than by increasing N_t. This is because that the received signal-to-noise power ratio (SNR) after the STBC-JTRD decoding is reduced by a factor of $1/N_r$ [14]. It should be noted that the throughput when more than 2 receive antennas are used is smaller than when 2 receive antennas are used since the coding rate R of STBC-JTRD becomes less than 3/4 when more than 2 receive antennas are used.

B. *Comparison between STBC-JTRD and STTD*

Figure 4(a) compares the throughput performances of STBC-JTRD and STTD with N_t as a parameter for N_r=2. It is seen from Fig. 4(a) that the throughput performance of STBC-JTRD is superior to that of STTD when N_t>2. This is because the received SNR is reduced by a factor of $1/N_t$ for STTD while it is reduced by a factor of $1/N_r$ for STBC-JTRD. And, the coding rate R of STTD becomes less than 3/4 when more than 2 transmit antennas are used. On the other hand, in the STBC-JTRD, the coding rate R is kept 1 even if more than 2 transmit antennas are used.

On the other hand, when the number N_r of receive antennas increases, STTD can provide better throughput performances than STBC-JTRD since the coding rate of STBC-JTRD. This can be seen from Fig. 4(b). The reason for STTD throughput is higher than STBC-JTRD is that the coding rate of STBC-JTRD becomes less than 3/4 when N_r>2 while the coding rate of STTD is kept to 1.

It can be understood from Figs. 3 and 4 that STBC-JTRD is suitable for the downlink signal transmission since the number of antennas at a mobile terminal is limited due to space limitation while a relatively large number of antennas can be implemented at a base station. On the other hand, STTD is suitable for the uplink signal transmission since most of receive antennas can be implemented at the base station side.

IV. CONCLUSION

In this paper, we evaluated the throughput performance of turbo coded MC-CDMA HARQ using STBC-JTRD and compared with STTD. STBC-JTRD is suitable for the downlink (base-to-mobile) applications. By using the STBC-JTRD for the downlink transmission and the STTD for the uplink transmission, an arbitrary number of antennas can be implemented at the base station without the coding rate reduction, and a large antenna diversity gain obtained without increasing the complexity of mobile terminal.

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