Performance of Turbo Coded OFDM Wireless Link for SISO, SIMO, MISO and MIMO System

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***Abstract*— This paper compares the performance of a Turbo coded OFDM wireless link for SISO, SIMO, MISO and MIMO system with uncoded OFDM wireless link for SISO, SIMO, MISO and MIMO system in the in the presence of rayleigh fading. Turbo encoder encodes the input information bits and sends to QPSK or 16 QAM or 64 QAM modulator. Modulated symbols are mapped by STBC. Outputs of STBC are split into n streams which are further modulated by OFDM and simultaneously transmitted using n transmit antennas. It is observed that the turbo coded SISO-OFDM system provides 21 dB coding gain at 10^{-4}, turbo coded SIMO-OFDM system provides 20 and 13 db coding gain for 2 and 4 receive antennas respectively at a BER of 10^{-6} , turbo coded MISO-OFDM system provides 17 and 12 dB coding gain for 2 and 4 transmit antennas respectively at a BER of 10^{-6} and turbo coded MIMO-OFDM system provides 11 to 13 dB coding gain for different combination of transmit and receive antennas at BER 10^{-6} compare to uncoded SISO-OFDM, SIMO-OFDM, MISO-OFDM and MIMO-OFDM system.**

***Index Terms*— Turbo Code, Space Time Block Code, OFDM, SISO, SIMO, MISO, MIMO.**

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) has been adopted in most of the important wireless communication systems such as Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB) [1], Wireless Local Area Network (WLAN) [2], Wireless Metropolitan Area Network (WMAN) [3] and Multi Band –OFDM Ultra Wide Band (MB–OFDM UWB) [4-6]. Moreover, this technique is also employed in important wired applications such as Asymmetric Digital Subscriber Line (ADSL) or Power Line Communication (PLC). And one of the techniques which are proposed for future generation wireless communication system is OFDM because it transmits data over extremely hostile channel at a comparable low complexity with high data rates [7-9].

OFDM divided the radio signal into multiple smaller sub-signals that are transmitted simultaneously on different frequencies, i.e. subcarriers. Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) are used to divide the frequency at transmitter and receiver respectively which are well suited for Field Programmable Gate Array (FPGA). With careful selection of subcarrier spacing and overall bandwidth, the channel frequency response for each subcarrier can be modeled with a single complex value. This allows a much easier implementation than that required for processing multi-tap time domain channel responses.

The combination of OFDM and single-input single-output (SISO) is referred to as SISO-OFDM. The combination of OFDM and single-input multiple-output (SIMO) is referred to as SIMO-OFDM. The combination of OFDM and multiple-input single-output (MISO) is referred to as MISO-OFDM. And the combination of OFDM and multiple-input multiple-output (MIMO) is referred to as MIMO-OFDM.

An orthogonal space time block coding schemes for two transmit antennas was first reported by Alamouti with code rate one [10]. Tarokh proposed a space time block coding (STBC) scheme for more than two transmit antennas with the rate less than one [11]. STBC have benefits of the spatial diversity provided by multiple antennas and temporal diversity provided by time varying signal. If we concatenate STBC with OFDM, we will obtain high-rate packet transmission system suitable for high throughput application. However, only STBC can't satisfy the reliability requirement in future mobile system, so STBC should be concatenated with channel coding to provide more coding gains. Forward Error correction (FEC) coding schemes are used as channel coding in most of the digital communication systems. Turbo Codes (TC) are a class of high-performance FEC codes which were the first practical codes to closely approach the

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channel for the SISO system capacity[12-14] which are specified as FEC schemes for most of the wireless systems.

A combination of the STBC and the TC referred to as the space time turbo coding has been widely studied with and without OFDM [15-34]. Much attention has been paid to improve the link performance of SISO and MIMO system. We published few papers from our previous research on combination of STBC and TC for SISO, SIMO, MISO and MIMO without OFDM [35-37]. This paper investigate the performance of SISO, SIMO, MISO and MIMO system for OFDM system with concatenation of STBC and TC for different number transmit and receive antennas with the concept of Alamouti's two transmit antennas with code rate one and Tarokh's four transmit antennas with code rate1/2.

The rest of the paper is organized as follows. In section II, we present the system model with encoding and decoding techniques and channel characteristics. The simulation results are presented in section III, and section VI contains the conclusions.

II. System Model

We consider a system where a transmitter and a receiver are equipped with n and m antennas respectively as shown in Fig. 1 and Fig. 2 (for SISO-OFDM and SIMO-OFDM system n=1 and SISO-OFDM and MISO-OFDM system m=1). At the transmitter, the information source generates random information data bits. The information bits are then encoded by TC encoder, the output bits of TC encoder are passed to the QPSK or 16 QAM or 64 QAM modulator and the modulated symbols are mapped using STBC. These mapped data are fed into an Inverse Fast Fourier Transform (IFFT) circuit to generate an OFDM signal. This OFDM signal is fed into a cyclic prefix insertion circuit to reduce ISI. The receiver performs the reverse process after cyclic prefixes are removed from incoming packets.

A. Encoding

At first the information are encoded by a binary turbo encoder. The turbo encoder consists of two relatively simple recursive systematic convolutional (RSC) encoders, concatenated in parallel via a pseudorandom (turbo) interleave [12-14]. The information bits are encoded by both RSC encoders. The first RSC encoder operates on the input bits in their original order, while the second RSC encoder operates on the input bits as permuted by the Turbo interleaver. If the input symbol is of length 1 and output symbol size is R, then the encoder is of code rate r_c=1/R. The interleave size and structure of turbo code affect the code error performance considerably; no attempt was made to optimize their design of turbo code. Fig. 3 shows the block diagram of a turbo encoder of rate 1/3. In the diagram b_k^s is the systematic bits, and b_k^{p1} , and b_k^{p2} are the parity check bits. The QPSK or 16 QAM or 64 QAM modulator modulates the turbo encoded bits. STBC encoder encodes the modulated symbols according to number of transmit antennas as shown in Table I and Table II. To understand the encoding of STBC, consider Alamouti's code [10]. The STBC encoder splits the data into number of orthogonal streams according to system. Each stream is fed to the IFFT modulator. Suppose modulator is 64 points long and out of 64 points, 48 bits are used for data. So, the data stream with 48 points creates a block as shown in Fig. 4. Four pilot signals are attached with 48 points for carrier phase locking. To make an OFDM symbol of 64 subcarriers, these 52 subcarriers are padded with zeros. These 64 subcarriers can be considered as 64 symbols. Then, it is converted from parallel to serial using multiplexer and finally append the CP of 16 points before transmitting. In this manner packets of 80 symbols are transmitted from each antenna.

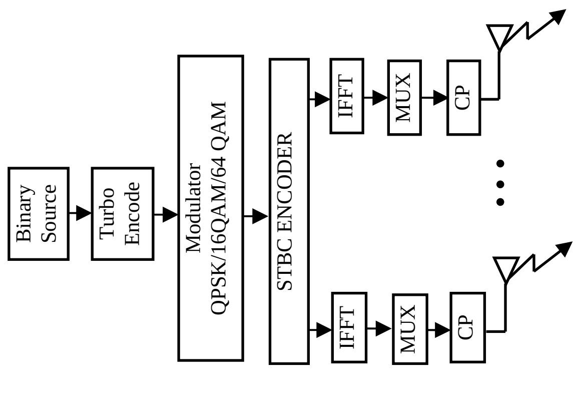

Fig. 1. Block diagram of transmitter

B. Channel

In this paper a wireless OFDM based spatial multiplexing system in broadband fading environments is considered where the channel is unknown at the transmitter and perfectly known at the receiver. Each antenna transmits statistically independent symbols from different antennas and different tones. These symbols will choose a delay path across the channel depending on their frequency. It is assumed that the environment is ideally a

TABLE I:
The encoding and transmission sequence for two

	Antenna-I	Antenna-II
Time slot-I	x_1	x_2
Time slot-II	$-x_2^*$	x_1^*

TABLE II
The encoding and transmission sequence for four

Antenna-I	Antenna-II	Antenna-III	Antenna-IV
x_1	x_2	x_3	x_4
$-x_2$	x_1	$-x_4$	x_3
$-x_3$	x_4	x_1	$-x_2$
$-x_4$	$-x_3$	x_2	x_1
x_1^*	x_2^*	x_3^*	x_4^*
$-x_2^*$	x_1^*	$-x_4^*$	x_3^*
$-x_3^*$	x_4^*	x_1^*	$-x_2^*$
$-x_4^*$	$-x_3^*$	x_2^*	x_1^*

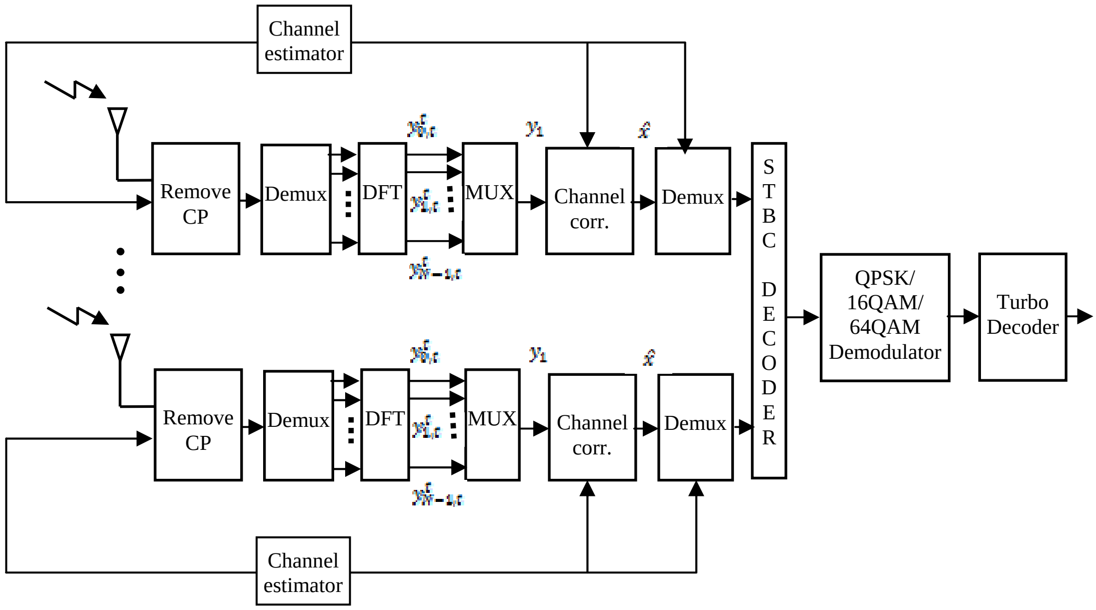

Fig. 2 Block diagram of receiver

rich scattering environment for space time coding and paths are mutually independent because of orthogonality between the data streams. In this analysis, the number of delay paths across the channel is denoted by L where each path being considered a scattered cluster and each of the paths emanating from within the same scattered cluster experiencing the same delay. Let $s[n]$ be the $M_T \times 1$ transmitted signal vector and $r[n]$ the $M_R \times 1$ received signal vector. Then,

$$r[n] = \sum_{l=0}^{L-1} H_l s[n-l] \quad (1)$$

where $M_R \times M_T$ the complex valued random matrix H_l represents the l th tap of the discrete-time MIMO fading channel impulse response. The channel model (1) is based on the assumption that there are L resolvable paths, where $L = [B\tau]$ with B and τ denoting the signal bandwidth and delay spread, respectively. The

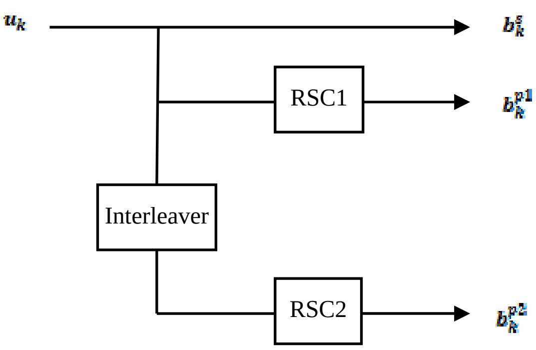

Fig. 3. Structure of Turbo Encoder

individual H_l , are (possibly correlated) zero mean circularly symmetric complex Gaussian (ZMCSCG). Different scattered clusters are uncorrelated, that is,

$$\in [vec\{H_l\} vec^H \{H_{l'}\}] = 0_{M_R M_T} \; for l \neq l' \quad (2)$$

where $\in$ denotes the expectation operator and superscript H stands for conjugate transposition and where

$$vec\{H_l\} = [h_{l,0}^T \; h_{l,1}^T \ldots h_{l,M_T-1}^T]^T \quad (3)$$

with $h_{l,k}$ being column vectors of the matrix H_l and $0_{M_R M_T}$ denoting the all zero matrix of size $M_R M_T \times M_R M_T$. Each scattered cluster has a mean angle of arrival at the Base Transceiver Station (BTS) denotes as $\bar{\theta}_l$, a cluster angle spread δ_l (proportional to the scattering radius of the cluster), and a path gain σ_l^2 (derived from the power delay profile of the channel).

It is considered that both the BTS and subscriber unit (SU) having uniform linear array (ULA) with identical antenna elements. It is possible to extend out results to nonuniform arrays. The relative antenna spacing is denoted as $\Delta = d/\lambda$ where d is the absolute antenna spacing and $\lambda = c/f_c$ is the wavelength of a

Tx1	x_1	$-x_2^*$	x_3	$-x_4^*$	$\cdots$	x_{47}	$-x_{48}^*$
Tx2	x_2	x_1^*	x_4	x_3^*	$\cdots$	x_{48}	x_{47}^*

One block

Fig. 4 Space Time Block Coding over Subcarriers

narrowband signal with center frequency f_c .

It is assumed that $h_{l,k}(l = 0,1,..., L-1;\ k = 0,1,....., M_T - 1)$ have zero mean (i.e., pure Rayleigh fading) and that the $M_R \times M_R$ correlation matrix $R_l = \in \{h_{l,k}\ h_{l,k}^H\}$ is independent of k or, equivalently, the fading statistics are the same for all transmit antennas. It is assigned that $p_l(s\Delta,\ \overline{\theta}_l,\ \delta_l) = \in \{h_{l,k}^r\ (h_{l,k}^{(r+s)})^*\}$ for $l = 0,1,...,\ L-1;\ k = 0,\ 1,...\ , M_T - 1$ where fading correlation between two BTS antenna elements spaced $s\Delta$ wavelengths apart. The correlation matrix R_l , can then be written as

$$[R_l]_{m,n} = \sigma_l^2 \rho_l((n-m)\Delta, \overline{\theta}_l, \delta_l) \quad (4)$$

The correlation matrixes already take into account the power delay profile of the channel and factor the $M_R \times M_R$ correlation matrix R_l according to $R_l = R_l^{1/2} R_l^{1/2}$, where $R_l^{1/2}$ is of size $M_R \times M_R$, the $M_R \times M_T$ matrix H_l can be written as

$$H_l = R_l^{1/2} H_{w,l}, l = 0,1,.......L-1 \quad (5)$$

where, $H_{w,l}$ is an uncorrelated matrix of size $M_R \times M_T$ with independent identically distributed (i.i.d) $CN(0,1)$ entries. We have essentially decomposed the l th tap of the stochastic MIMO channel impulse response into the product of a deterministic matrix $R_l^{1/2}$, taking into account the spatial fading correlation at the BTS and a stochastic matrix of i.i.d complex Gaussian random variables $H_{w,l}$.

It is also assumed that the angle of arrival for the l th $(l = 0,1,..., L-1)$ path cluster at the BTS is Gaussian distributed around the mean angle of arrival θ_l , [i.e., the actual angle of arrival is given by $\theta_l = \overline{\theta}_l + \hat{\theta}_l$, with $\hat{\theta}_l \sim N(0, \sigma_{\theta_l}^2)]$. The variance $\sigma_{\theta_l}^2$ is proportional to the angular spread δ_l and, hence, the scattering radius of the l th path cluster. For small angular spread the correlation function can be approximated as [20].

$$\rho_l(s\Delta, \overline{\theta}_l, \delta_l) \approx e^{-j2\pi s\Delta\cos(\overline{\theta}_l)} e^{-\frac{1}{2}(2\pi s\Delta\sin(\overline{\theta})\sigma_{\theta l})^2} \quad (6)$$

This approximation is accurate for small angular spread, but it does indicate a trend for large angular spreads, such as uncorrelated spatial fading. Note that if $\sigma_{\theta l} = 0$, the correlation matrix R_l collapses to a rank-1 matrix and can be written $R_l = \sigma_l^2 a(\overline{\theta}_l) a^H(\overline{\theta}_l)$ with the array response vector of the ULA given by

$$a(\theta) = [1\ \ e^{j2\pi\Delta\cos(\theta)}\ \dots\ e^{j2\pi(M_R-1)\Delta\cos(\theta)}]^T \quad (7)$$

C. Decoding

At the receiver, the each received signals are passed through OFDM demodulators for further decoding. The transmitted data can be shown as frequency vectors $s_k = [s_k^0\ \ s_k^1\ \dots\ \ s_k^{M_T-1}]^T$ with s_k^i denoting the data symbol transmitted from the i th antenna on the k th tone and defining $H(e^{j2\pi\theta}) = \sum_{l=0}^{L-1} H_l e^{-j2\pi l\theta} (0 \le \theta \le 1)$, it can be shown that

$$\hat{s}_k = H(e^{j2\pi\frac{k}{N}}) s_k + n_k \quad (8)$$

where $\hat{s}_k$ is the received data vector for the k th tone, N is the total number of OFDM tones, and n_k is additive white Gaussian noise satisfying

$$\in \{n_k n_l^H\} = \sigma_n^2 I_{M_R} \delta[k-l] \quad (9)$$

where I_{M_R} is the identity matrix of size M_R . It is observed from (9) that equalization requires the inversion of a constant matrix for each tone $k = 0,1,..., N-1.$ we stack the vector $\hat{s}_k$, s_k and n_k according to [14]

$$\hat{s} = [\hat{s}_0^T\ \ \hat{s}_1^T\ \dots\ \hat{s}_{N-1}^T]^T, s = [\ s_0^T\ \ s_1^T\ \dots\ s_{N-1}^T]^T, n = [\ n_0^T\ \ n_1^T\ \dots\ n_{N-1}^T]^T$$

Where $\hat{s}_k$ and n are $M_R N \times 1$ vectors and s is an $M_R N \times 1$ vector. We note that based on (8) we can infer that the noise vector n is white, that is,

$$\in \{nn^H\} = \sigma_n^2 I_{M_R N}$$

H is now a block-diagonal matrix of size $NM_R \times NM_T$, that is, $H = diag\left\{ H\left(e^{j2\pi\frac{k}{N}} \right) \right\}_{k=0}^{N-1}$

We now rewrite (8) as [9],

$$\hat{s} = Hs + n \quad (10)$$

these symbols are decoded using STBC decoder [4, 5] and demodulated by QPSK or 16QAM or 64QAM demodulator and send to turbo decoder to get the output. The turbo decoding is performed by a suboptimal iterative algorithm. The decoder consists of two identical concatenated decoders of the component codes separated by the same interleaver as shown in Fig. 5. The component decoders are based on a maximum a posteriori (MAP) algorithm or a soft output Viterbi algorithm (SOVA) generating a weighted soft estimate of the input sequence. However researchers used the MAP decoder to decode the Turbo code [6-8]. If data $u = i$ is transmitted from a set of M different signal and turbo decoder receives signal M, then the a posteriori probability (APP) of a decision on $u = i$ given by:

$$P(u=i\mid y)=\frac{p(y\mid u=i)P(u=i)}{p(y)},i=1,...,M \tag{11}$$

and

$$p(y)=\sum_{i=1}^{M}p(y\mid u=i)P(u=i) \tag{12}$$

where

$P(u=i\mid y)$ is the APP, $P(y\mid u=i)$ is the probability density function (pdf) of the received signal y given that signal set is transmitted (a propri probability), and p(y) is the pdf of the received signal. P(y) is a scaling factor for each specific observation. It can be shown using Bayes' decision rule that the optimum decision that minimizes the probability of error in detection of the signal is the decision on maximum a posteriori probability (MAP) which may be expressed as

$$u=i \text{ iff } P(u=i\mid y)>P(u=k\mid y),$$
$$\forall k=0,...,M,k\neq i \tag{13}$$

From (11), the APP's in (13) can be replaced by the following equivalent expressions canceling common term, p(y) from both sides:

$$u=i \text{ iff } p(y\mid u=i)P(u=i\mid y)>$$
$$p(y\mid u=k)P(u=k),\ \forall k=\{0,...,M\},k\neq i \tag{14}$$

Let the binary data, o and 1, be represent by -1 and +1 respectively. Then the equation (13) and (14) can be written as:

$$P(u=+1\mid y)\ \underset{H_2}{\overset{H_1}{\gtrless}}\ P(u=-1\mid y) \tag{15}$$

and

$$p(y\mid u=+1)P(u=+1\mid y)\ \underset{H_2}{\overset{H_1}{\gtrless}}\ p(y\mid u=-1)P(u=-1\mid y) \tag{16}$$

which means that one should decide in favor of hypothesis $H_1, u=+1$, if the left hand side of equation (16) is greater than the right hand side. Otherwise one should choose hypothesis $H_2, u=-1$. Equation (15) and (16) can be written in a ratio format to give the likelihood ratio test:

$$\frac{P(u=+1\mid y)}{P(u=-1\mid y)} \qquad 1 \tag{17}$$

and

$$\frac{p(y\mid u=+1)P(u=+1)}{p(y\mid u=-1)P(u=-1\mid y)}\ \underset{H_2}{\overset{H_1}{\gtrless}}\ 1 \tag{18}$$

By taking the logarithm of the likelihood ratio, the posteriori log likelihood ratio is obtained as

$$L(u\mid y)=\log\left(\frac{P(u=+1\mid y)}{P(u=-1\mid y)}\right) \tag{19}$$

The MAP decoding rule can now be translated to

$$\hat{u}=sign\left[L(u\mid y)\right] \tag{20}$$

where $\hat{u}$ is the detected signal.

III. Simulation Results

In this section, computer simulation is carried out to show the BER performance of the proposed system. The results are evaluated for several combinations of T_x and R_x antennas with and without Turbo coding with the parameters shown in Table III. In simulation, turbo codes are not used for the uncoded system, on the other hand turbo codes are used for the coded system.

We present the BERs to compare the performance of coded SISO-OFDM system with uncoded SISO-OFDM system in Fig. 6. It is observed that the coded SISO-OFDM system provides 21 dB coding gain compared to uncoded SISO-OFDM at 10^{-4}.

Fig. 7 shows the performance of SIMO-OFDM system. Coded SIMO-OFDM system (1 T_x and 2 R_x) provides 20 dB coding gain over uncoded SIMO-OFDM system with same diversity and Coded SIMO-OFDM system(1 T_x and

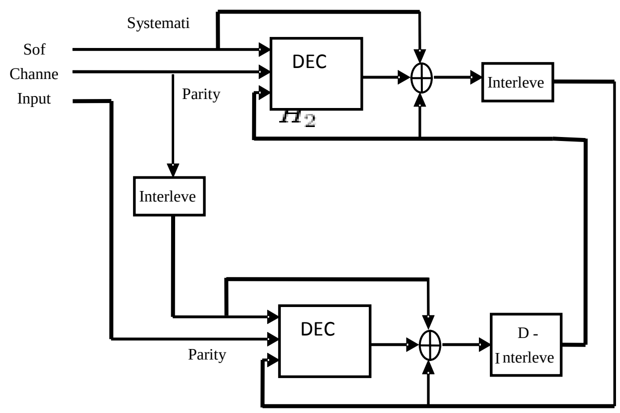

Fig. 5. Block diagram of turbo decoder

TABLE III:
SIMULATION PARAMETERS FOR SIMULATION OF TURBO CODED OFDM-SISO, OFDM-SIMO, OFDM-MISO AND OFDM-MIMO SYSTEM

Parameters	Values
Channel Coding	Turbo
Turbo Coding Rate	1/3
Number of iterations	2
Modulation	QPSK
Space- time Coding	G2 and G4
Guard interval	800 ns (16 samples)
OFDM symbol duration	64(size of FFT)+16(guard band)=80
Number of subcarrier	64
Channel model	Rayleigh
Bandwidth	20 MHz
Delay time	200 ns(Maximum)
channel estimation method	LSE

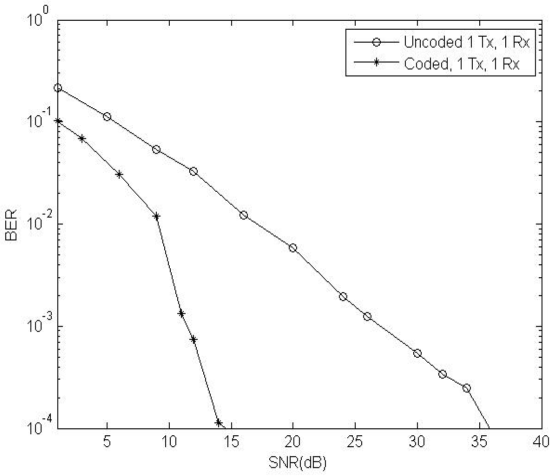

Fig. 6 BER performance comparison of coded SISO-OFDM and uncoded SISO-OFDM system

4 R_x) provides 13 dB coding gain over uncoded SIMO-OFDM system with same diversity at a BER of 10^{-6} . And there is around 7 dB gain for increasing R_x antenna from 2 to 4 of coded SIMO-OFDM system

Fig. 8 shows the performance of MISO-OFDM system. Coded MISO-OFDM system (2 T_x and 1 R_x) provides 17 dB coding gain over uncoded MISO-OFDM system with same diversity and Coded MISO-OFDM system (4 T_x and 1 R_x) provides 12 dB coding gain over uncoded MISO-OFDM system with same diversity at BER of 10^{-6}. And there is around 6 dB gain for increasing T_x antenna from 2 to 4 of coded MISO-OFDM system.

Fig. 9 shows the performance of MIMO-OFDM system with 2 T_x and 2 or 4 R_x. Coded MIMO-OFDM system (2 T_x and 2 R_x) provides 13 dB coding gain compared to uncoded MIMO-OFDM system with same diversity and Coded MIMO-OFDM system (2 T_x and 4 R_x) provides 12 dB coding gain over uncoded MIMO-OFDM system with same diversity at BER of $10^{-6.}$ And

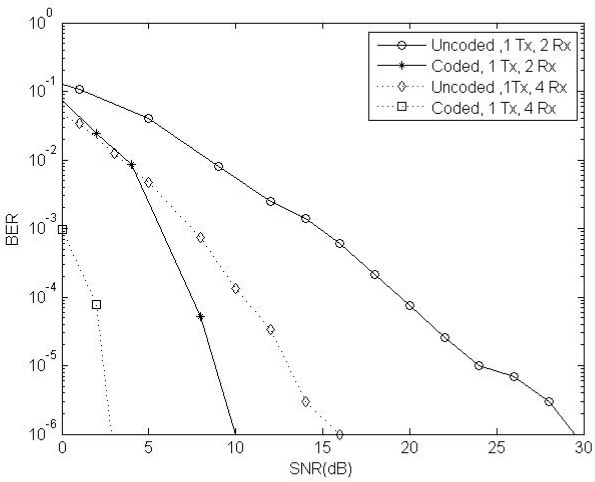

Fig. 7 BER performance comparison of coded SIMO-OFDM and uncoded SIMO-OFDM system

there is around 6 dB gain for increasing R_x antenna from 2 to 4 of coded MISO-OFDM system.

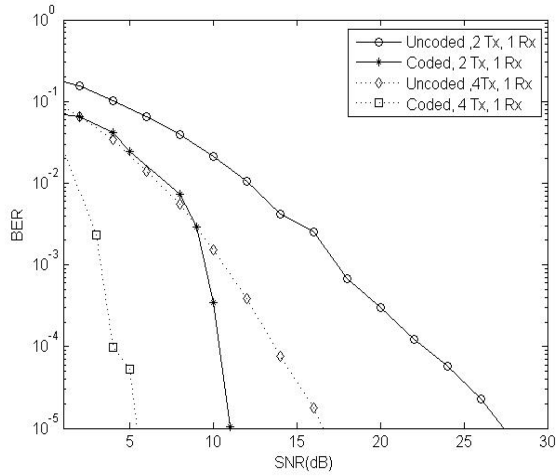

Fig. 8 BER performance comparison of coded MISO-OFDM and uncoded MISO-OFDM system

Fig. 10 shows the performance of MIMO-OFDM system with 4 T_x and 2 or 4 R_x. Coded MIMO-OFDM system (4 T_x and 2 R_x) provides 11 dB coding gain compared to uncoded MIMO-OFDM system with same diversity and Coded MIMO-OFDM system (4 T_x and 4 R_x) provides 13 dB coding gain compared to uncoded MIMO-OFDM system with same diversity at BER of 10^{-6}. And there is around 1 dB gain for increasing R_x antenna from 2 to 4 of coded MISO-OFDM system.

IV. Conclusion

From the simulation results, researchers observe that coded SISO-OFDM, SIMO-OFDM, MISO-OFDM and MIMO-OFDM systems make a significant difference over uncoded SISO-OFDM, SIMO-OFDM, MISO-OFDM and MIMO-OFDM systems and coded MIMO-OFDM systems have best performance. And coded MIMO-OFDM system with 2 T_x and 4R_x or with 4 T_x and

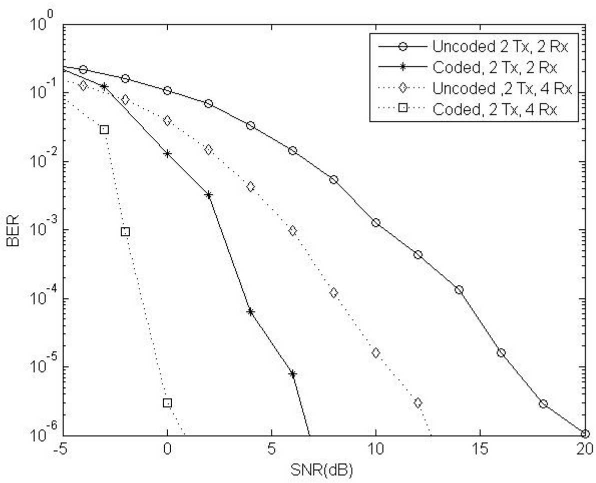

Fig. 9 BER performance comparision of coded MIMO-OFDM system (2T_x & 2/4 R_x) and uncoded MIMO-OFDM system with same diveristy.

2R_x or with 4 T_x and 4R_x has same performance.

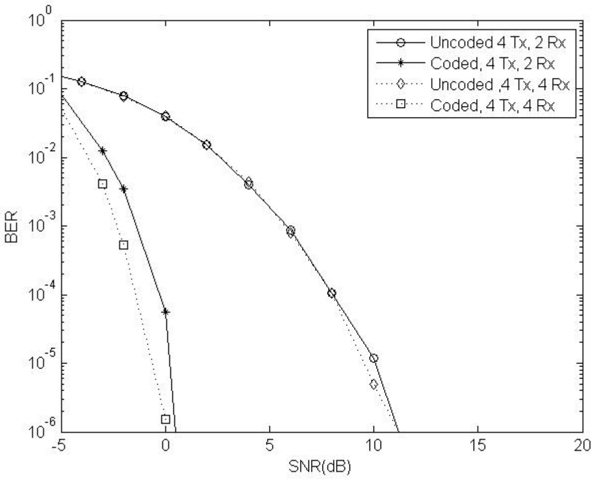

Fig. 10 BER performance comparision of coded MIMO-OFDM system ($4T_x$ & 2/4 R_x) and uncoded MIMO-OFDM system with same diveristy

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