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Performance Analysis of Hybrid Concatenated Space – Time Coding and Spatial Multiplexing over Rayleigh Flat Fading Channel

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Abstract

Spatial Multiplexing is a better choice for high data rate systems operating at relatively high SNR while Space-Time coding is more appropriate for transmitting at relatively low rates and low SNRs. In this paper, we propose and analyse a class of codes which is a concatenation of Space-Time Trellis code and Space-Time Block code combined with Spatial Multiplexing. The Hybrid concatenation scheme gives an improved coding gain as well as diversity gain, compared to a simple Space-time code with multiple antennas, where as the Spatial Multiplexing gives the higher possible through put.

Keywords: Space-time trellis codes, Space-time block codes, Concatenated space-time codes, Spatial Multiplexing, Multiple antennas and Diversity

Introduction

The explosion in mobile telephone, Internet and Multimedia services, coupled with a limited radio spectrum has necessitated the demand for increased channel capacity in wireless communication [1]. The performance of wireless systems is limited by multipath fading and interference from other users [2]. It has been shown in [3], that an increase in channel capacity can be obtained by exploiting the use of multiple transmit and receive antennas. Foschini and Gans showed that the channel capacity limits grow approximately linear with the number of antennas, assuming ideal propagation conditions.

Transmit antenna diversity becomes more attractive in applications such as broadcasting or forward link transmission in wireless cellular systems. To exploit this type of diversity and approach Foschini's capacity bound, many diversity schemes such as space-time trellis codes and space-time block codes have been proposed. Space-time trellis codes [5] – [10], proposed by Tarokh et al, employ multiple transmit and receive antenna and are capable of providing both spatial diversity gain and coding gain. Space-time block code [11]-[13] is a simple transmit diversity scheme proposed by Alamouti with further generalisation to include any number of transmit antennas, by Tarokh et al.

The main objective of space-time codes is to achieve the maximum possible diversity. Space time codes provide a diversity gain equal to the product of the number of transmit and receive antennas NM. When the number of transmit and receive antennas are the same, there is a capacity growth atleast linear as the number of antennas. By concatenating space-time codes [14]-[18] with other coding schemes, it is possible to further improve their code performance. STBC is a popular choice to concatenate with convolutional codes (CC), turbo and trellis-coded modulations (TTCM), to name a few. In fact, there is a trade-off between these two gains from multiple antennas [19], [20]. In this paper, a system concatenating STBC and STTC with combined spatial multiplexing over Rayleigh fading channel is proposed and analysed.

The outline of this paper is as follows. Sections 2 gives our system model. Section 3 gives the system description. Section 4 describes the performance analysis of the proposed model. In Section 5, we conclude our discourse.

System Model

Consider a hybrid concatenated space-time coded system with N transmit and M receive antennas which is shown in Fig. 1. The information data is first encoded by the STTC encoder, and then fed into the space-time block encoders connected in parallel. At each time slot, the output symbols are modulated and transmitted simultaneously each from a different transmit antenna. At the receiver end, the space-time block decoder, followed by Viterbi decoder can be used to decode the received signals. The proposed system model is shown in Figure 1.

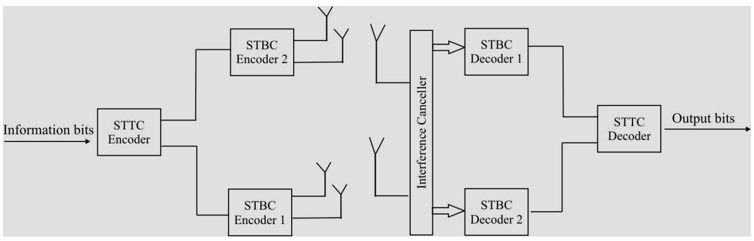

Figure 1 : Block diagram of Hybrid concatenated Space-time coded system, N=4 and M=2

System Description

The channel fading parameter between the i^{th} transmitter and the j^{th} receiver is given as h_{ji}. The received signal vector over two symbol periods can be expressed as

$$Y = H_{eff}\, S + n \tag{i}$$

where $H_{eff} = [h_1\ h_2\ h_3\ h_4]$

$$= \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{12}^* & -h_{11}^* & h_{14}^* & -h_{13}^* \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{22}^* & -h_{21}^* & h_{24}^* & -h_{23}^* \end{bmatrix}$$

In the above equation (i), $S \in C^{4x1}$ is the complex transmitted vector, $Y \in C^{4x1}$ is the complex received vector, $n \in C^{4x1}$ zero mean complex AWGN vector with $E\left[nn^H\right] = \sigma^2 I$ and $H_{eff} \in C^{4x4}$ is the complex channel matrix characterizing frequency-flat channel, with two receive antennas and two STBCs (each equipped with two antennas).

$$\begin{pmatrix} y_1(t) \\ y_1^*(t+1) \\ \hline y_2(t) \\ y_2^*(t+1) \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{12}^* & -h_{11}^* & h_{14}^* & -h_{13}^* \\ \hline h_{21} & h_{22} & h_{23} & h_{24} \\ h_{22}^* & -h_{21}^* & h_{24}^* & -h_{23}^* \end{pmatrix} \begin{pmatrix} s_1^1 \\ s_2^1 \\ \hline s_1^2 \\ s_2^2 \end{pmatrix} + \begin{pmatrix} n_1(t) \\ n_1^*(t+1) \\ \hline n_2(t) \\ n_2^*(t+1) \end{pmatrix}$$

$y_1(t)$, $y_1^*(t+1)$ represent the received signals at the first receive antenna at time t and t+1 respectively.

$y_2(t)$, $y_2^*(t+1)$ represent the received signals at the second receive antenna at time t and t+1 respectively.

s_1^1, s_2^1 represent the transmitted symbols for the first and second antennas of the first STBC encoder.

s_1^2, s_2^2 represent the transmitted symbols from the first and second antennas of the second STBC encoder.

Then, the maximum likelihood decoding for S requires the minimization of the following metric:

$$m\left(s/y\right) = \left\|y - H_{eff}\ S\right\|^2$$

where ||.|| denotes the Euclidean norm. Thus, for

M_c – QAM or M - QPSK, the ML estimate of

$\hat{s} = \left\{\hat{s}_1^1,\ \hat{s}_2^1, \hat{s}_1^2, \hat{s}_2^2\right\}$ is obtained as

$$\hat{s} = \arg\min_{S \in Q^4} \left\|y - H_{eff}\ S\right\|^2 \tag{ii}$$

where Q is the signal constellation of size M_c.

Although ML detection attains the optimal performance, it suffers huge decoding complexity which increases exponentially with the constellation size; since the number of candidate search in (ii) equals M_c^4.

In more compact form,

$$\left(\frac{Y_1}{Y_2}\right)=\left(\begin{array}{c|c}\frac{H_{11}}{H_{21}} & \frac{H_{12}}{H_{22}}\end{array}\right)\left(\frac{S_1}{S_2}\right)+\left(\frac{N_1}{N_2}\right)$$

where Y_i is the processed signal from the i^{th} receive antenna and N_i is the corresponding noise vector. Moreover, S_i consists of the two subvectors representing the symbols transmitted from the i^{th} user's first and second transmit antennas at time t, i.e.,

$$Y_i=\begin{pmatrix} y_i(t) \\ y_i*(t+1)\end{pmatrix}, S_i=\begin{pmatrix} s_1^i(t) \\ s_2^i(t)\end{pmatrix}, N_i=\begin{pmatrix} n_1^i(t) \\ n_2^i*(t+1)\end{pmatrix}$$

and each H_{ij} is the Alamouli – like overall frequency domain channel matrix from the i^{th} user transmit antennas to the j^{th} receive antenna.

The two STBCs are decoupled as follows

$$\begin{bmatrix} I_2 & -H_{12}H_{22}^{-1} \\ -H_{21}H_{11}^{-1} & I_2 \end{bmatrix}\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}=\begin{bmatrix} \Sigma & 0 \\ 0 & \Delta \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \end{bmatrix}+\begin{bmatrix} N_1 \\ N_2 \end{bmatrix}$$

where $\Sigma=H_{11}-H_{12}H_{22}^{-1}H_{21}; \Delta=-H_{21}H_{11}^{-1}H_{12}+H_{22}$

Equating L.H.S and R.H.S., we get the combined signals $\tilde{s}_1^1, \tilde{s}_2^1$, $\tilde{s}_1^2$ and $\tilde{s}_2^2$ which are then sent to the maximum likelihood decoder.

The decoupling of STBCs ensures that the interference caused by STBC1 to STBC2 and vice-versa is cancelled and the input to the STBC decoder 1 is the output symbols from STBC encoder 1 and the input to the STBC decoder 2 is the output symbols from STBC encoder 2.

Thus the proposed model gets decomposed to models similar to that of Alamouti's two branch transmit diversity with two receivers, as follows.

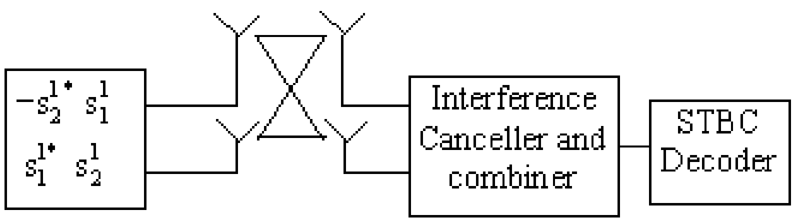

Figure 2 : The link between STBC Encoder 1 and STBC decoder 1

Table II : The Definition of channels between the STBC Encoder 1, and STBC Decoder 1

	rx antenna 1	rx antenna 2
tx antenna 1	h_{11}	h_{21}
tx antenna 2	h_{12}	h_{22}

Table III : The notation for the received signals at the two receive antennas corresponding to Figure 2

	rx antenna 1	rx antenna 2
time t	$y_1(t)$	$y_2(t)$
time t+T	$y_1^*(t+T)$	$y_2^*(t+T)$

$$\left.\begin{aligned} y_1(t) &= h_{11}s_1^1 + h_{12}s_2^1 + n_1^1(t) \\ y_1^*(t+T) &= -h_{11}s_2^{1*} + h_{12}s_1^{1*} + n_1^{1*}(t+T) \\ y_2(t) &= h_{21}s_1^1 + h_{22}s_2^1 + n_2^1(t) \\ y_2^*(t+T) &= -h_{21}s_2^{1*} + h_{22}s_1^{1*} + n_2^{1*}(t+T) \end{aligned}\right\} \quad (A)$$

$$\left.\begin{aligned} h_{11} &= \alpha_{11}e^{j\theta_{11}}; h_{21} = \alpha_{21}e^{j\theta_{21}} \\ h_{12} &= \alpha_{12}e^{j\theta_{12}}; h_{22} = \alpha_{22}e^{j\theta_{22}} \end{aligned}\right\} \quad (B)$$

From (A)

$$\left.\begin{aligned} \tilde{s}_1^1 &= h_{11}^* y_1(t) + h_{12}y_1^*(t+T) + h_{21}^* y_2(t) + h_{22}y_2^*(t+T) \\ \tilde{s}_2^1 &= h_{12}^* y_1(t) - h_{11}y_1^*(t+T) + h_{22}^* y_2(t) - h_{21}y_2^*(t+T) \end{aligned}\right\} (C)$$

Substituting (A) and (B) in (C),

$$\tilde{s}_1^1 = \left(\alpha_{11}^2 + \alpha_{12}^2 + \alpha_{21}^2 + \alpha_{22}^2\right)s_1^1 + h_{11}^* n_1^1(t) + h_{12}n_1^{1*}(t+T)$$
$$+h_{21}^* n_2^1(t) + h_{22}n_2^{1*}(t+T)$$

Similarly,

$$\tilde{s}_2^1 = \left(\alpha_{12}^2 + \alpha_{11}^2 + \alpha_{22}^2 + \alpha_{21}^2\right)s_2^1 + h_{12}^* n_1^1(t) - h_{11}n_1^{1*}(t+T)$$
$$+h_{22}^* n_2^1(t) - h_{21}n_2^{1*}(t+T)$$

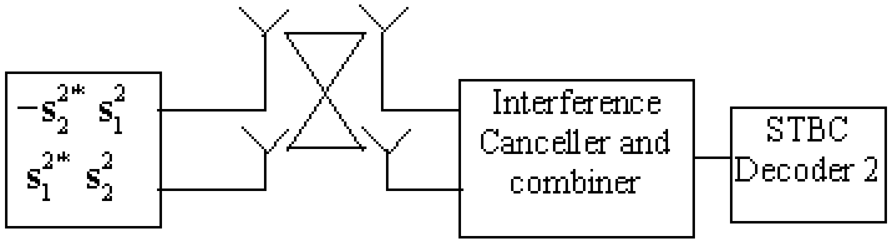

Figure 3 : The link between STBC Encoder 2 and STBC decoder 2

Table IV : The Definition of channels between the STBC Encoder 2 and STBC Decoder 2

	rx antenna 1	rx antenna 2
tx antenna 3	h_{13}	h_{23}
tx antenna 4	h_{14}	h_{24}

Table V : The Notation for the received signals at the two receive antennas corresponding to Figure 3

	rx antenna 1	rx antenna 2
time t	$y_1(t)$	$y_2(t)$
time t+T	$y_1*(t+T)$	$y_2(t+T)$

$$\left.\begin{aligned} y_1(t) &= h_{13}\, s_1^2 + h_{14}\, s_2^2 + n_1^2(t) \\ y_1(t+T) &= -h_{13}\, s_2^2 + h_{14}\, s_1^{2*} + n_1^{2*}(t+T) \\ y_2(t) &= h_{23}\, s_1^2 + h_{24}\, s_2^2 + n_2^2(t) \\ y_2(t+T) &= -h_{23}\, s_2^{2*} + h_{24}\, s_1^{2*} + n_2^{2*}(t+T) \end{aligned}\right\} \quad \text{(D)}$$

$$\left.\begin{aligned} h_{13} = \alpha_{13} e^{j\theta_{13}}; h_{23} = \alpha_{23} e^{j\theta_{23}} \\ h_{14} = \alpha_{14} e^{j\theta_{14}}; h_{24} = \alpha_{24} e^{j\theta_{24}} \end{aligned}\right\} \quad \text{(E)}$$

From (D)

$$\left.\begin{aligned} \tilde{s}_1^2 &= h_{13}^* y_1(t) + h_{14} y_1^*(t+T) + h_{23}^* y_2(t) + h_{24} y_2^*(t+T) \\ \tilde{s}_2^2 &= h_{14}^* y_1(t) - h_{13} y_1^*(t+T) + h_{24}^* y_2(t) - h_{23} y_2^*(t+T) \end{aligned}\right\} \quad \text{(F)}$$

Substituting (D) and (E) in (F)

$$\begin{aligned} \tilde{s}_1^2 = &\left(\alpha_{13}{}^2 + \alpha_{14}{}^2 + \alpha_{23}{}^2 + \alpha_{24}{}^2\right) s_1^2 + h_{13}^* n_1^2(t) + h_{14} n_1^{2*}(t+T) \\ &+ h_{23}^* n_2^2(t) + h_{24} n_2^{2*}(t+T) \end{aligned}$$

Similarly,

$$\begin{aligned} \tilde{s}_2^2 = &\left(\alpha_{14}{}^2 + \alpha_{13}{}^2 + \alpha_{24}{}^2 + \alpha_{23}{}^2\right) s_2^2 + h_{14}^* n_1^2(t) - h_{13} n_1^{2*}(t+T) \\ &+ h_{24}^* n_2^2(t) - h_{23} n_2^{2*}(t+T) \end{aligned}$$

Thus, after interference suppression, each group is decoded separately similar to that of an orthogonal STBC. The decoded signals from both the STBC decoders are fed to the STTC decoder along with the channel state information. The channel $h_{i,j}$ between the transmit antenna i and receive antenna j is estimated after turning off all the transmit antennas except antenna i and send a pilot signal to antenna j using antenna i. Further the Viterbi algorithm for ML decoding of STTC is explained as follows:

If a branch of the trellis transmits symbols s_1 and s_2 from antennas 1 and 2 respectively, the corresponding branch metric is given by

$$\sum_{m=1}^{M} | r_{t,m} - \alpha_{1,m} s_1 - \alpha_{2,m} s_2 |^2$$

where $r_{t,m}$ represents the received signal at time slots t = 1,2,…,T+Q and Q represents the memory of the convolutional code representing the state machine. $\alpha_{i,j}$ represents the magnitude of the path gain between the i^{th} transmit antenna and j^{th} receive antenna.

Then the path metric of a valid path is the sum of the branch metrics for the branches that form the path. The most likely path is the one which has the minimum path gain. The ML decoder finds the set of constellations symbols that construct a valid path and solves the following minimization problem:

$$\min_{c_{1,1},c_{1,2}c_{2,1}c_{2,2}\ldots c_{T+Q,1}c_{T+Q,2}} \sum_{t=1}^{T+Q}\sum_{m=1}^{M} | r_{t,m} - \alpha_{1,m}c_{t,1} - \alpha_{2,m}c_{t,2} |^2$$

where $c_{1,1}$ represents the space-time trellis coded symbols, T+Q represents the frame length of the transmitted symbols.

The simulation results for the proposed model have appeared in [4].

Performance analysis

Let the transmitted codeword matrix

$$C = \begin{bmatrix} s_1^1 & -s_2^{1*} \\ s_2^1 & s_1^{1*} \\ s_1^2 & -s_2^{2*} \\ s_2^2 & s_1^{2*} \end{bmatrix}$$

The estimated codeword matrix is

$$E = \begin{bmatrix} e_1^1 & -e_2^{1*} \\ e_2^1 & e_1^{1*} \\ e_1^2 & -e_2^{2*} \\ e_2^2 & e_1^{2*} \end{bmatrix}$$

The Difference Matrix is

$$D(c,e) = \begin{bmatrix} e_1^1 - s_1^1 & -e_2^{1*} + s_2^{1*} \\ e_2^1 - s_2^1 & e_1^{1*} - s_1^{1*} \\ e_1^2 - s_1^2 & -e_2^{2*} + s_2^{2*} \\ e_2^2 - s_2^2 & e_1^2 - s_1^{2*} \end{bmatrix}$$

The channel matrix is

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \end{bmatrix}$$

The product of the codeword difference matrix and the channel matrix is

$$Y = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \end{bmatrix} \begin{bmatrix} e_1^1 - s_1^1 & -e_2^{1*} + s_2^{1*} \\ e_2^1 - s_2^1 & e_1^{1*} - s_1^{1*} \\ e_1^2 - s_1^2 & -e_2^{2*} + s_2^{2*} \\ e_2^2 - s_2^2 & e_1^{2*} - s_1^{2*} \end{bmatrix}$$

In general,

$$Y_i = \begin{bmatrix} U & V \\ W & X \end{bmatrix}$$

where

$$U = \left(e_i^1 - s_i^1\right) h_{11} + \left(e_{i+1}^1 - s_{i+1}^1\right) h_{12} + \left(e_i^2 - s_i^2\right) h_{13} + \left(e_{i+1}^2 - s_{i+1}^2\right) h_{14}$$
$$V = \left(e_{i+1}^{1\ *} + s_{i+1}^{1\ *}\right) h_{11} + \left(e_i^{1*} - s_i^{1*}\right) h_{12} + \left(-e_{i+1}^{2\ *} + s_{i+1}^{2\ *}\right) h_{13} + \left(e_i^{2*} - s_i^{2*}\right) h_{14}$$
$$W = \left(e_i^1 - s_i^1\right) h_{21} + \left(e_{i+1}^1 - s_{i+1}^1\right) h_{22} + \left(e_i^2 - s_i^2\right) h_{23} + \left(e_{i+1}^2 - s_{i+1}^2\right) h_{24}$$

$$X = \left(-e_{i+1}^{1\ *} + s_{i+1}^{1\ *}\right) h_{21} + \left(e_i^{1*} - s_i^{1*}\right) h_{22} + \left(-e_{i+1}^{2\ *} + s_{i+1}^{2\ *}\right) h_{23} + \left(e_i^{2*} - s_i^{2*}\right) h_{24}$$

After interference suppression, the pair wise error probabilities for the two groups are given by

$$P\left(C \to E / h_{11}, h_{12}, h_{21}, h_{22}\right) = P\begin{bmatrix} m\left(Y, E; h_{11}, h_{12}, h_{21}, h_{22}\right) \\ \geq m\left(Y, C; h_{11}, h_{12}, h_{21}, h_{22}\right) \end{bmatrix}$$

and

$$P\left(C \to E / h_{13}, h_{14}, h_{23}, h_{24}\right) = P\begin{bmatrix} m\left(Y, E; h_{13}, h_{14}, h_{23}, h_{24}\right) \\ \geq m\left(Y, C; h_{13}, h_{14}, h_{23}, h_{24}\right) \end{bmatrix}$$

By Chernoff's bound,

$$P\left(C \to E / h_{11}, h_{12}, h_{21}, h_{22}\right)$$

$$\leq \exp\left\{ \sum_{i=1,3,\ldots 2L-1} \left[\left| \left(e_i^1 - s_i^1\right) h_{11} + \left(e_{i+1}^1 - s_{i+1}^1\right) h_{12} \right|^2 \right.\right.$$

$$+ \left| \left(s_{i+1}^{1*} - e_{i+1}^{1*}\right) h_{11} + \left(e_i^{1*} - s_i^{1*}\right) h_{12} \right|^2$$

$$+ \left| \left(e_i^1 - s_i^1\right) h_{21} + \left(e_{i+1}^1 - s_{i+1}^{1*}\right) h_{22} \right|^2$$

$$\left.\left. + \left| \left(s_{i+1}^{1*} - e_{i+1}^{1*}\right) h_{21} + \left(e_i^{1*} - s_i^{1*}\right) h_{22} \right|^2 \right] \right\} \frac{-E_s}{4N_o}$$

$$\leq \exp\left\{ \sum_{i=1,2,3,\ldots}^{2L} \left[\left| \left(e_i^1 - s_i^1\right) \right|^2 \left(\left|h_{11}\right|^2 + \left|h_{12}\right|^2 + \left|h_{21}\right|^2 + \left|h_{22}\right|^2 \right) \right] \right.$$

$$+\sum_{i=1,2,3,\ldots}^{2L}\left[\left|\left(e_{i+1}^{1}-s_{i+1}^{1}\right)\right|^{2}\left(\left|h_{11}\right|^{2}+\left|h_{12}\right|^{2}+\left|h_{21}\right|^{2}+\left|h_{22}\right|^{2}\right)\right]$$

and

$$P\left(C\rightarrow E/h_{13},h_{14},h_{23},h_{24}\right)$$

$$\leq \exp\left\{\sum_{i=1,3,\ldots 2L-1}\left[\left|\left(e_{i}^{2}-s_{i}^{2}\right)h_{13}+\left(e_{i+1}^{2}-s_{i+1}^{2}\right)h_{14}\right|^{2}\right.\right.$$

$$+\left|\left(s_{i+1}^{2*}-e_{1+1}^{2*}\right)h_{13}+\left(e_{i}^{2*}-s_{i}^{2*}\right)h_{14}\right|^{2}$$

$$+\left|\left(e_{i}^{2*}-s_{i}^{2*}\right)h_{23}+\left(e_{i+1}^{2}-s_{i+1}^{2}\right)h_{24}\right|^{2}$$

$$\left.\left.+\left|\left(s_{i+1}^{2*}-e_{i+1}^{2*}\right)h_{23}+\left(e_{i}^{2*}-s_{i}^{2*}\right)h_{24}\right|^{2}\right]\right\}\frac{-E_{s}}{4N_{o}}$$

$$\leq \exp\left\{\sum_{i=1,2,3\ldots}^{2L}\left[\left|\left(e_{i}^{2}-s_{i}^{2}\right)\right|^{2}\left(\left|h_{13}\right|^{2}+\left|h_{14}\right|^{2}+\left|h_{23}\right|^{2}+\left|h_{24}\right|^{2}\right)\right]\right.$$

$$\left.+\sum_{i=1,2,3,\ldots}^{2L}\left[\left|\left(e_{i+1}^{2}-s_{i+1}^{2}\right)\right|^{2}\left(\left|h_{13}\right|^{2}+\left|h_{14}\right|^{2}+\left|h_{23}\right|^{2}+\left|h_{24}\right|^{2}\right)\right]\right\}\frac{-E_{s}}{4N_{o}}$$

Assuming that the absolute values of h_{ji} are Rayleigh distributed (with average power of one) and are independent, using the law of total probability, we have:

$$P\left(C\rightarrow E\right)\leq \int_0^\infty\int_0^\infty\int_0^\infty\int_0^\infty\left[P\left(C\rightarrow E/h_{11},h_{12},h_{21},h_{22}\right)\right.$$

$$\left.16\left|h_{11}\right|\left|h_{12}\right|\left|h_{21}\right|\left|h_{22}\right|\;e^{-}\left(\left|h_{11}\right|^{2}+\left|h_{12}\right|^{2}+\left|h_{21}\right|^{2}+\left|h_{22}\right|^{2}\right)\right]$$

$$d\left|h_{11}\right|d\left|h_{12}\right|d\left|h_{21}\right|d\left|h_{22}\right|$$

$$+\int_0^\infty\int_0^\infty\int_0^\infty\int_0^\infty\left[P\left(C\rightarrow E/h_{13},h_{14},h_{23},h_{24}\right)\right.$$

$$16\left|h_{13}\right|\left|h_{14}\right|\left|h_{23}\right|\left|h_{24}\right|$$

$$\left.e^{-}\left(\left|h_{13}\right|^{2}+\left|h_{14}\right|^{2}+\left|h_{23}\right|^{2}+\left|h_{24}\right|^{2}\right)\right]$$

$$d\left|h_{13}\right|d\left|h_{14}\right|d\left|h_{23}\right|d\left|h_{24}\right|$$

$$\leq \int_0^\infty\int_0^\infty\int_0^\infty\int_0^\infty \exp\left[\left\{\sum_{i=1}^{2L}\left|\left(e_i^1 - s_i^1\right)\right|^2 \left[\left|h_{11}\right|^2 + \left|h_{12}\right|^2 + \left|h_{21}\right|^2 + \left|h_{22}\right|^2\right]\right\}\frac{-E_s}{4N_o}\right.$$
$$\left. - \left[\left|h_{11}\right|^2 + \left|h_{12}\right|^2 + \left|h_{21}\right|^2 + \left|h_{22}\right|^2\right]\right] 16\left|h_{11}\right|\left|h_{12}\right|\left|h_{21}\right|\left|h_{22}\right|$$
$$d\left|h_{11}\right| d\left|h_{12}\right| d\left|h_{21}\right| d\left|h_{22}\right|$$

$$+ \int_0^\infty\int_0^\infty\int_0^\infty\int_0^\infty \exp\left[\left\{\sum_{i=1}^{2L}\left|\left(e_i^2 - s_i^2\right)\right|^2 \left[\left|h_{13}\right|^2 + \left|h_{14}\right|^2 + \left|h_{23}\right|^2 + \left|h_{24}\right|^2\right]\right\}\frac{-E_s}{4N_o}\right.$$
$$\left. - \left[\left|h_{13}\right|^2 + \left|h_{14}\right|^2 + \left|h_{23}\right|^2 + \left|h_{24}\right|^2\right]\right] 16\left|h_{13}\right|\left|h_{14}\right|\left|h_{23}\right|\left|h_{24}\right|$$
$$d\left|h_{13}\right| d\left|h_{14}\right| d\left|h_{23}\right| d\left|h_{24}\right|$$

$$= \int_0^\infty\int_0^\infty\int_0^\infty\int_0^\infty e^{-\left[1 + \frac{E_s}{4N_o}\sum_{i=1}^{2L}\left|\left(e_i^1 - s_i^1\right)\right|^2 \left[\left|h_{11}\right|^2 + \left|h_{12}\right|^2 + \left|h_{21}\right|^2 + \left|h_{22}\right|^2\right]\right]}$$
$$16\left|h_{11}\right|\left|h_{12}\right|\left|h_{21}\right|\left|h_{22}\right| \; d\left|h_{11}\right| d\left|h_{12}\right| d\left|h_{21}\right| d\left|h_{22}\right|$$

$$+ \int_0^\infty\int_0^\infty\int_0^\infty\int_0^\infty e^{-\left[1 + \frac{E_s}{4N_o}\sum_{i=1}^{2L}\left|\left(e_i^2 - s_i^2\right)\right|^2 \left[\left|h_{13}\right|^2 + \left|h_{14}\right|^2 + \left|h_{23}\right|^2 + \left|h_{24}\right|^2\right]\right]}$$
$$16\left|h_{13}\right|\left|h_{14}\right|\left|h_{23}\right|\left|h_{24}\right| \; d\left|h_{13}\right| d\left|h_{14}\right| d\left|h_{23}\right| d\left|h_{24}\right|$$

$$= \frac{1}{\left[1 + \frac{E_s}{4N_0}\sum_{i=1}^{2L}\left|e_i^1 - s_i^1\right|^2\right]^4} + \frac{1}{\left[1 + \frac{E_s}{4N_0}\sum_{i=1}^{2L}\left|e_i^2 - s_i^2\right|^2\right]^4}$$

$$\Rightarrow P\left(C \to E\right) \leq \left[\frac{1}{d_{free}^2\left(\frac{E_s}{4N_0}\right)}\right]^4 + \left[\frac{1}{d_{free}^2\left(\frac{E_s}{4N_0}\right)}\right]^4$$

$$P\left(C \to E\right) \leq 2\left[\frac{1}{d_{free}^2\left(\frac{E_s}{4N_0}\right)}\right]^4$$

Conclusion

We have presented a new performance bound for the scheme combining Hybrid concatenated space-time coding and spatial multiplexing, on slow Rayleigh fading channels for a large product (>3) of the number of transmit and receive antennas. We have also shown that the combined concatenated scheme provides a diversity order of 4 and additional coding gain of 2, an added advantage compared to Alamouti’s STBC which aims at increasing the diversity order.

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