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DESIGN OF SPACE TIME TRELLIS CODED OFDM

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ABSTRACT

Space Time Trellis Code (STTC) is a technique that can be used to improve the performance of the Orthogonal Frequency Division Multiplexing (OFDM) system over wireless channels by providing both coding gain and diversity gain. STTC is combined from two codes, Trellis Code Modulation (TCM) as an inner code and Space Time Block Code (STBC) as an outer code. TCM which combines the choice of a modulation scheme with that of a convolutional code provides the coding gain, and the other code provides the diversity gain. Simulation is done over flat fading and frequency selective Rayleigh fading channel for Eight Phase Shift Keying (8-PSK) TCM. It found that the best results are obtained for the case of two transmitters and three receivers which have a gain of about 18dB over that without STBC.

KEY WORD

Orthogonal Frequency Division Multiplexing, Space Time Block Code, Trellis Coded Modulation.

الخلاصة

نظام الترميز الشعيري الزماني المكاني (STTC) هو تقنيه يمكن استخدامها لتحسين فعالية الاتصالات اللاسلكية خلال قنوات اللاسلكية بتزويد النظام بكل من ربح الترميز و ربح التنوع. STTC يتركب من نظامين ترميزيين، التضمين ألترميزي الشعيري (TCM) كترميز داخلي و الترميز المكاني الزماني (STBC) كترميز خارجي. التضمين ألترميزي الشعيري (TCM) والذي يتم الحصول عليه بجمع عمليتي التضمين (Modulation) و الترميز الشعيري (Convolutional code) يزود النظام بربح الترميز و الترميز الآخر يزود النظام بربح التنوع. استخدمت المحاكاة عبر قناة استواء اخفاتي وقناة اختيار اخفاتي نوع (Rayleigh) ل TCM (8-PSK). وجدت أفضل النتائج في حا ة استخدام جهازي إرسال و ثلاثة أجهزة استلام (2TX-3RX) والتي تحتوي على ١٨ديسيبل.

INTRODUCTION

In most situations, the wireless channel suffers attenuation due to destructive addition of multipaths in the propagation media and to interference from other users. The channel statistic is significantly often Rayleigh which makes it difficult for the receiver to reliably determine the transmitted signal unless some less attenuated replica of the signal is provided to the receiver. This technique is called diversity, there are several kinds of diversity temporal, spatial, and frequency diversities [N. Balaban, 1991]. In recently years, transmitter diversity has been introduced by Alamouti [S. M. Alamouti, 1999] to combat fading in wireless environments and improve the performance of the wireless system without significantly increasing the size or complexity of the receiver. Space-Time Code (STC) techniques have been proposed for transmitter diversity and then employed in the OFDM system to further reduce fading and obtain the better signal quality from the diversity gain [D. Agrawal, 1998]. Space Time Block Coded OFDM presented in [M. Uysal, 2001] can only exploit space diversity. The Space Time Trellis Coded OFDM is considered to exploit both space and time diversity. In this paper, we focus on the improved performance of the OFDM system using transmit diversity with Space Time Trellis Code (STTC). STTC is a combined system from Space Time Block Code (STBC) and Trellis Coded Modulation (TCM). The STBC provides the diversity gain to the system and the TCM provides the coding gain. The diversity gain is increased by increasing the number of antennas at the receiver. TCM combines a multilevel modulation scheme with a convolutional code over band-limited channels, while the receiver, instead of performing demodulation and decoding in two separate steps, combines the two operations into one. The basic principles of TCM were published in 1982 [G. Ungerboeck, 1982], and some further developments are documented [R. Calderbank, 1984]. The performance comparisons of the bit error probability for conventional OFDM, STTC OFDM have been presented. As the simulation results, the STTC OFDM provide the much improved performance over conventional OFDM. And the best performance was found in the case of the two transmit antennas and three received antennas.

- DESIGN OF STTC CODED OFDM

OFDM System Model

OFDM is a multicarrier transmission technique, which divides the available spectrum into many carriers, each one being modulated by a low rate data stream. Fig. 1 shows the block diagram of a simplex point-to-point transmission system using OFDM system. The two main principles incorporated are: The Inverse Fast Fourier Transform (IFFT) and the Fast Fourier Transform (FFT) are used for, respectively, modulating and demodulating the data constellations on the orthogonal sub-carriers [Eric Lawrey, 1997].

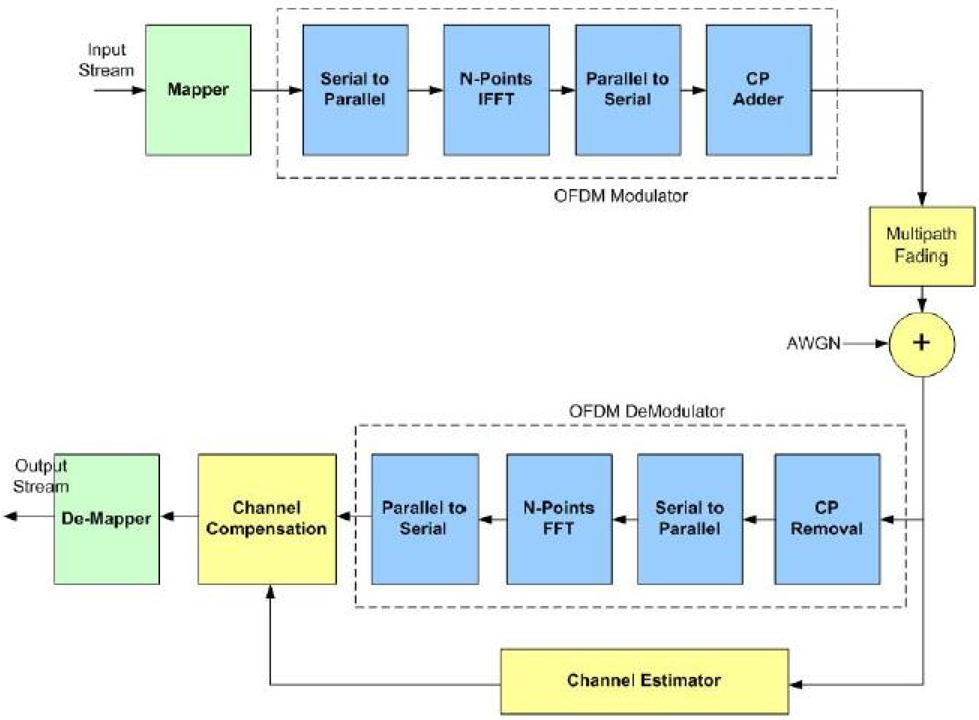

Fig. 1: Block diagram of OFDM system

Note that at the input of the IFFT, N data constellation points are present, where N is the number of FFT points. These constellations can be taken according to any Phase Shift Keying (PSK) or Quadrature Amplitude Mmodulation (QAM) signaling set (symbol mapping). The N output samples of the IFFT – being in time-domain – form the baseband signal carrying the data symbols on a set of N orthogonal sub-carriers.

In a real system, however, not all of these N possible sub-carriers can be used for data. Usually, N is taken as an integer power of two, enabling the application of the highly efficient IFFT, FFT algorithms for modulation and demodulation which provide the orthogonality to the system. The second key principle is the introduction of a cyclic prefix as a Guard Interval (GI), whose length should exceed the maximum excess delay of the multipath propagation channel. Due to the cyclic prefix, the transmitted signal becomes “periodic”, and the effect of the time-dispersive multipath channel becomes equivalent to a cyclic convolution, discarding the guard interval at the receiver. Due to the properties of the cyclic convolution, the effect of the multipath channel is limited to a point-wise multiplication of the transmitted data constellations by the channel transfer function, the Fourier transform of the channel impulse response, i.e., the sub-carriers remain orthogonal [K. Witrisal, 2002].

The Design of 8-PSK Trellis Coded Modulation

The concept of set partitioning is of central significance for TCM schemes. Fig. 2 shows this concept for Eight Phase Shift Keying (8-PSK) signal constellation.

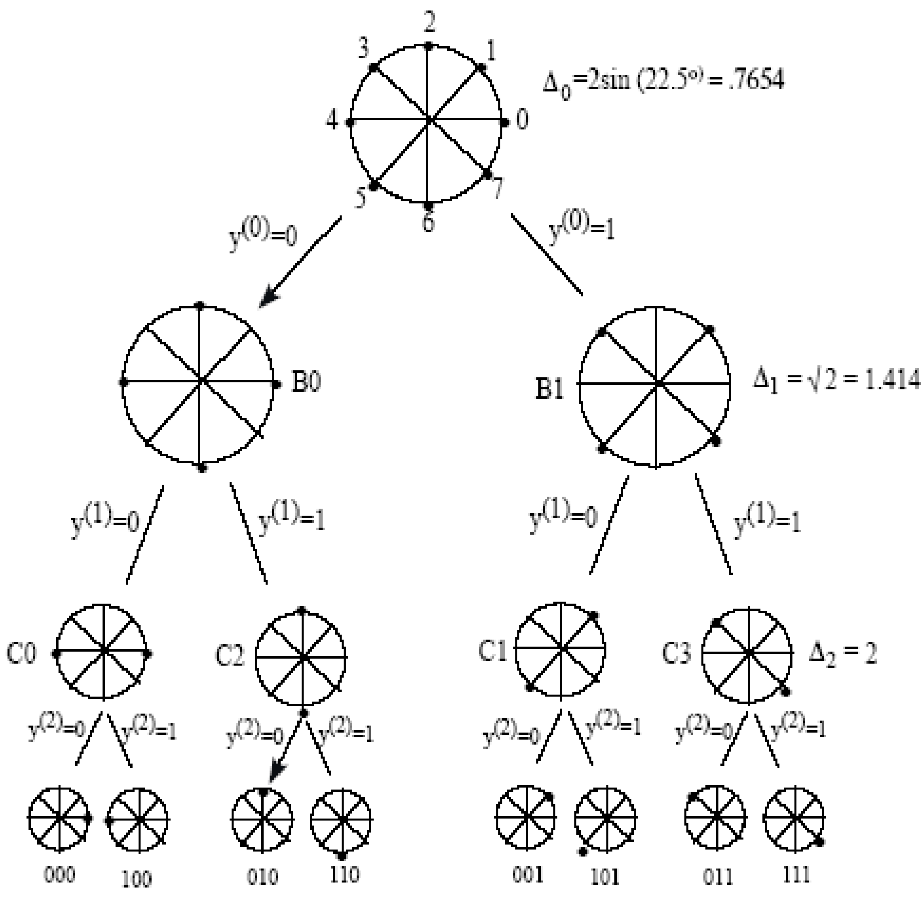

Fig. 2: Set Partitioning for 8-PSK Modulation

Set partitioning divides the signal set successively into smaller sets with maximally increasing smallest intra-set distances [Yipeng Tang, 2001]. There are a total of four partitions counting the first un partitioned set. At the top most level, the Minimum Euclidean Distance (MED) between the signals is:

$$\Delta_0 = 2\sqrt{Es}\ \ \mathrm{SIN}(\pi/8) = 0.7654\sqrt{Es} \qquad (1)$$

Note that the distance depends on the symbol energy E_s. We can normalize the energy to 1, then $\Delta_0 = 0.7654$ and the Minimum Square Euclidean Distance (MSED) is:

$$d_0^2 = \Delta_0^2 = 0.586 \qquad (2)$$

At the next level, where there are only four points in each of the two cosets, the MSED has increased to $d_1^2 = \Delta_1^2 = 2$, and at the last level, the MSED is 4.0.

An encoder for the 8-PSK 4-state TCM is shown in Fig. 3. A rate of 2/3 with two inputs x_2 x_1, and outputs $y_2\,y_1\,y_0$.

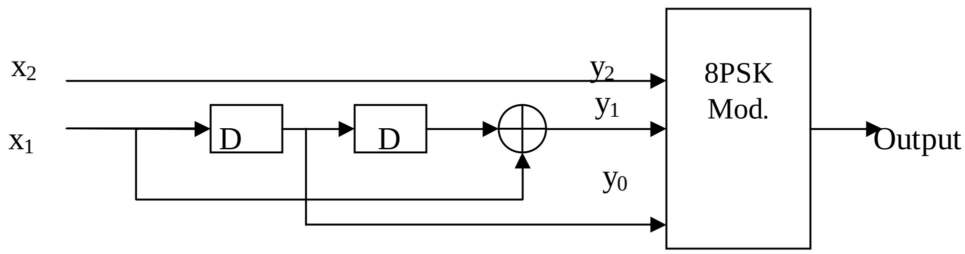

Fig. 3:8-PSK 4States TCM Encoder

This encoder involves 1/2 convolutional code, one bit x_1 in and two bits $y_1\,y_0$ out. The other bit $y_2 = x_2$ which is the most significant bit left uncoded. This encoder has four states because it contains two memories. The trellis diagram for this encoder is shown in Fig. 4.

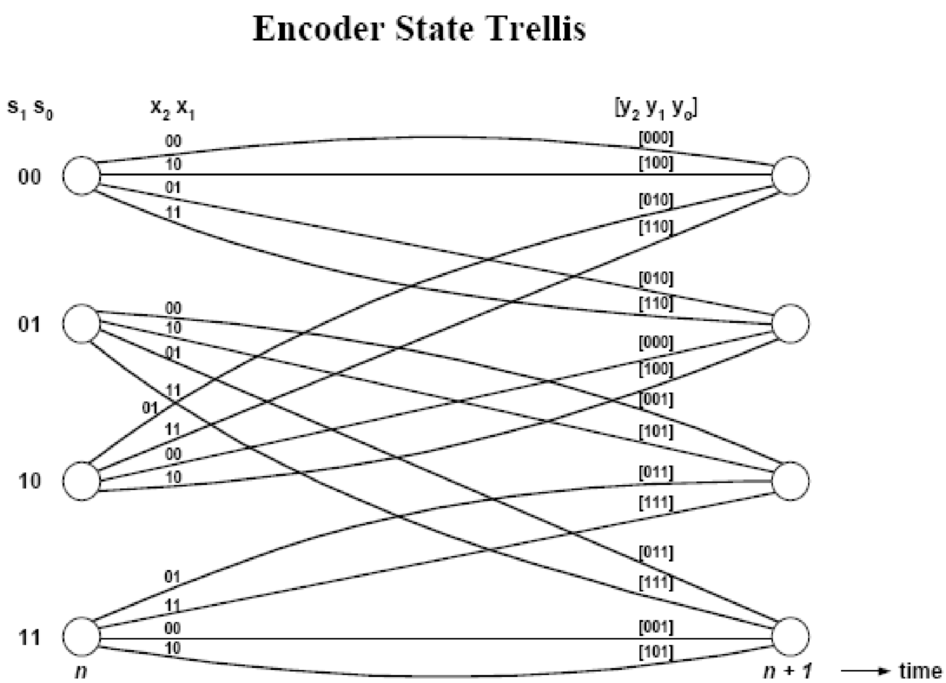

Fig. 4: Trellis Diagram of 4-States Rate 2/3 TCM Code

At each state there are two coded bits incoming as well as one uncoded bit, so each path doubles to account for the two choices for the uncoded bit.

At state (00), if coded bits are 10, then the output of the encoder is 110 if uncoded bit is 1 or 010 if it is 0. This doubling of choices is called parallel transitions.

The coding gains of TCM compared with uncoded schemes asymptotically achieved at high signal-to-noise ratios are expressed as:

$$g = 10\log_{10}\frac{d^2_{free}/E}{d^2_{\min}/E'} \tag{3}$$

where γ is the coding gain, d^2_{free} and d^2_{min} are the squared free distances of the TCM and uncoded schemes, respectively. E and E' denote the average signal energies of the TCM and uncoded systems, respectively. From the trellis in the Fig. 4, the parallel paths at t = 0, state 00. Two parallel pairs, 100 and 000 pair and the 110 and 010 pair. Each pair is 180 degree phase shift apart and this correspond to a MSED of 4.0. This is the SED at the bottom level of the partition in Fig. 2.

Now to determine the minimum distance path for this code, following from each state the path with the smallest squared distance (but not zero). This is 2.0 for the path starting at state 00. This takes us to state 2. From this state the minimum distance path is 0.586. This takes us to state 1 and from here retuning to state 0 via a path that has a squared distance of 2.0. There is no other path that can take us back to 00 state and has a smaller total distance as shown in Fig. 5.

The total MSED (d_{free}) for this code is the sum all three of these squared distances.

$$d_{free} = 2 + 0.586 + 2 = 4.586$$

Now d^2_{free} for the TCM is the smaller of the two distances d^2_{min} and d_{free} that determine the overall performance.

$$d^2_{free} = \min[d_{free}, d^2_{min}] = \min[4.586, 4.0] = 4.0 \tag{4}$$

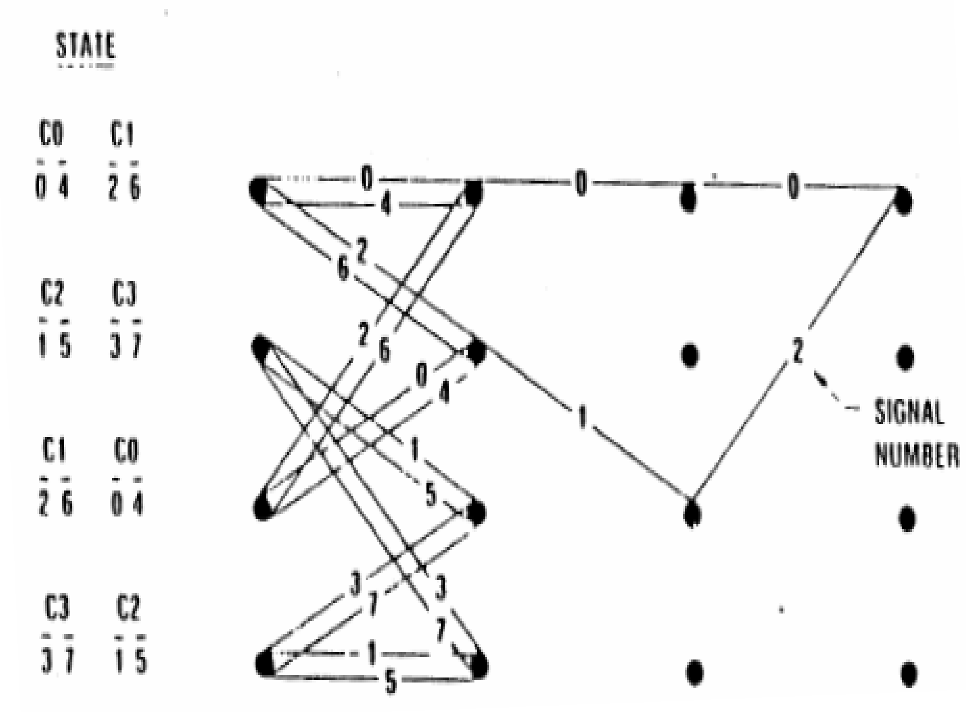

Fig. 5: Error path comparison for 8-PSK TCM

To determine the coding gain, dividing d^2_{free} by the minimum square Euclidean distance of the uncoded Quaternary Phase Shift Keying (QPSK) constellation $d^2_{min} = 2$. The coding gain from eq. (3) (assuming that both coded and uncoded signals have same energies $E = E'$) is:

$$\gamma = 10 \log [4/2] = 3\text{dB}$$

It is a remarkable result to obtain a gain of 3dB without any increase in bandwidth or symbol rate. By increasing the number of states to 8 (This is done by increasing the number of memory registers from 2 to 3), so that there are no parallel transitions in the trellis. The minimum squared distance between an error path and correct path is completely determined by the convolutional encoder as shown in Fig. 6.

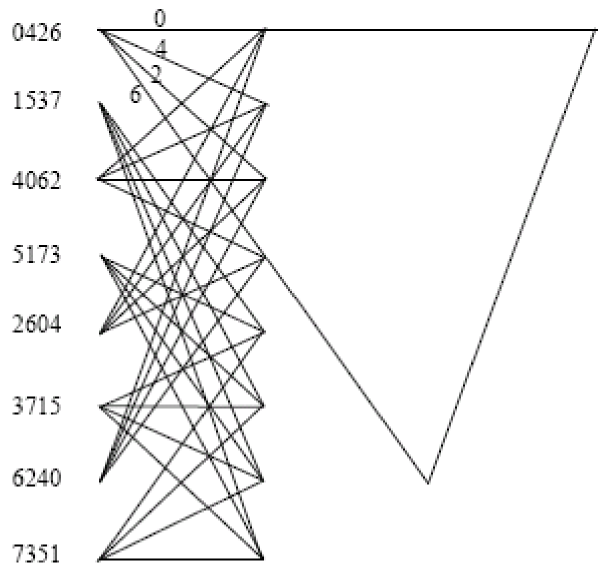

Fig. 6: Trellis of a code of a rate 1/2 with 8 states

In the figure above the left side lists the symbol numbers possible at each state. At state 0, path 6 has the smallest distance, from there going to symbol 7 and symbol 6 again. This path has the smallest SED. The sum of each of the distances is:

s_0 to $s_6 = 2.0$, s_0 to $s_7 = 0.586$, s_0 to $s_6 = 2.0$

$$d^2_{free} = 2+0.586+2=4.586$$

and now the coding gain is:

$$\gamma = 10 \log (4.586/2) = 3.7\text{dB}.$$

This is an improvement over the case of four states which had a coding gain of 3dB. More states improve this yet further.

Decoding TCM

A convenient way of describing a set of signal sequences is through a trellis. The distance properties of a TCM scheme can be studied through its trellis diagram in the same way as for convolutional codes. The optimum decoding is the search of the most likely path through the trellis once the received sequence has been observed at the channel output. Because of the noise, the path chosen may not coincide with the correct path, i.e., the path traced by the sequence of source symbols, but will occasionally diverge from it and remerge at a later time [Mei Hong, 2002].

The Viterbi algorithm, as a general technique for decoding the convolutional codes, is also used in the TCM decoder. Due to the one-to-one correspondence between signal sequences and paths traversing the trellis, maximum-likelihood (ML) decoding consists of searching for the trellis path with the minimum Euclidean distance to the received signal sequence. If a sequence of length K is transmitted, and the sequence $r_0, r_1, \ldots, r_{k-1}$ is observed at the output of the AWGN channel, then the ML receiver looks for the sequence $x_0, x_1, \ldots, x_{k-1}$ that minimizes $\sum_{i=0}^{k-1} |r_i - x_i|^2$. This can be done by using the Viterbi algorithm. The branch metrics to be used are obtained as follows. The branch in the trellis used for coding is labeled by signal x , if there are no parallel transitions, then at discrete time i the metric associated with that branch is $|r_i - x\ |^2$. If a pair of nodes is connected by parallel transitions, and the branches have labels $x', x'', \ldots\ldots$ in the set x , then in the trellis used for decoding the same pair of nodes is connected by a signal branch, whose metric is $\min_{x^i \in x} |r_i - x^i|^2$. That is, in the presence of parallel transitions the decoder first selects the signal among $x', x'', \ldots\ldots,$ with the minimum distance from r_i (this is a "demodulation" operation), then builds the metric based on the signal selected.

STBC with Two-Branch Transmit Diversity and One-Receiver

The structure is shown in Fig. 7. At a symbol period, two signals are transmitted from the two antennas simultaneously. Table 1 shows that the symbol transmitted from antenna zero is s_0 and

Table 1 : The transmit sequence for two-branch transmit diversity.

	antenna 0	antenna 1
time t	s_0	s_1
time t+T	$-s_1^*$	s_0^*

antenna one is s_1 . At next symbol period, the symbol transmitted from antenna zero is - s_1^* and antenna one is s_0^* where * is the complex conjugate operation [S. M. Alamouti, 1999].

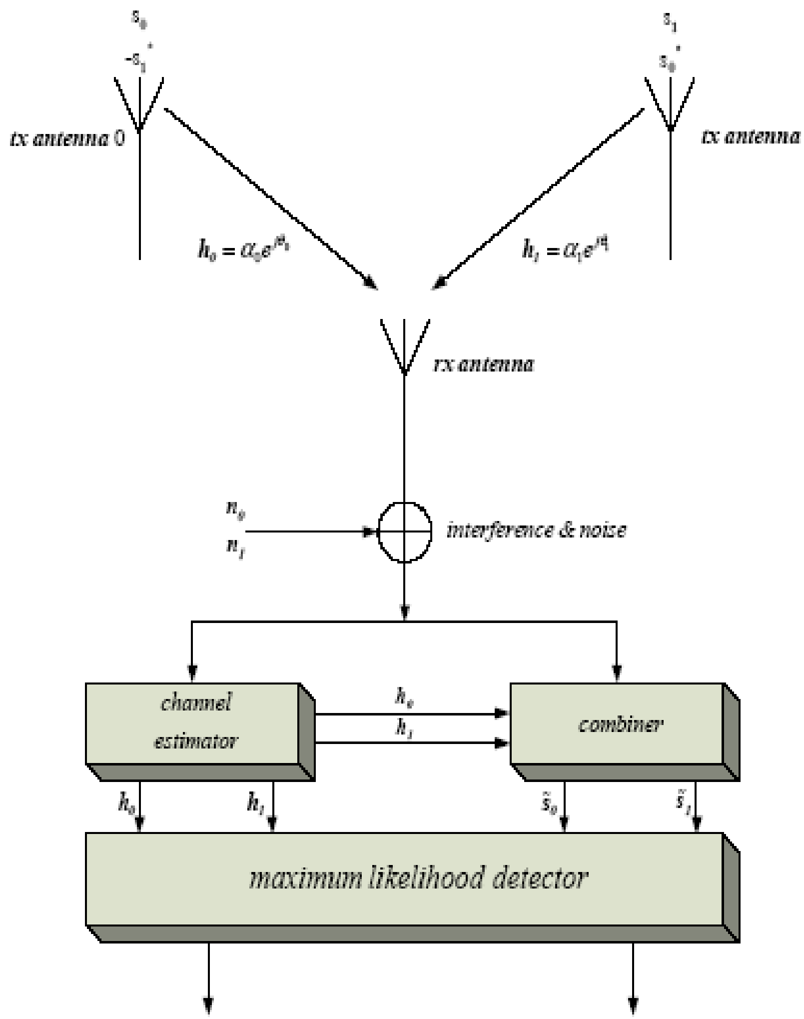

Fig. 7: A space-time block code with two-branch transmit diversity

The channel path gain at time *t* is modeled by a complex distortion $h_0(t)$ for transmit antenna zero and $h_1(t)$ for transmit antenna one. Assume the fading coefficient is constant across two consecutive symbols. It can be seen that the transmit sequence is divided into many blocks, and each block length is two symbol time units [S. M. Alamouti, 1999]**.**

These combined signals are then sent to the maximum likelihood detector and using the decision rule of MPSK to make the most possible decision to recover the original transmission signals. The space-time block coding provides us to design concatenated codes with others. It is useful to combat the interference in Rayleigh fading channel. If there were two transmit antennas and M receive antennas, then the diversity advantage is 2M.

STBC with Two-Branch Transmit Diversity and Two-Receivers

There may be applications where a higher order of diversity is needed and multiple receive antennas at the remote units are feasible. In such cases, it is possible to provide a diversity order of 2*2 with two transmit and 2 receive antennas. The sequences are listed in Table 2 and Table 3.

Table 2: The Definition of Channels Between The Transmit And Receive Antenna

	rx antenna 0	rx antenna 1
tx antenna 0	h_0	h_2
tx antenna 1	h_1	h_3

Table 3: The Notation For The Received Signals At The Two Receive Antennas

	rx antenna 0	rx antenna 1
time t	r_0	r_2
time $t+T$	r_1	r_3

Fig. 8 shows the baseband representation of the scheme with two transmit and two receive antennas. The encoding and transmission sequence of the information symbols for this configuration is identical to the case of a single receiver, shown in Table (1). Table (2) defines the channels between the transmit and receive antennas, and Table (3) defines the notation for the received signal at the two receive antennas [S. M. Alamouti, 1999].

Where

$$\begin{aligned} r_0 &= h_0 s_0 + h_1 s_1 + n_0 \\ r_1 &= -h_0 s_1^* + h_1 s_0^* + n_1 \\ r_2 &= h_2 s_0 + h_3 s_1 + n_2 \\ r_3 &= -h_2 s_1^* + h_3 s_0^* + n_3 \end{aligned} \tag{5}$$

n_o,n_1,n_2 and n_3 are complex random variables representing receiver thermal noise and interference. The combiner in Fig. 8 builds the following two signals that are sent to the maximum likelihood detector:

$$\begin{aligned} \tilde{s}_0 &= h_0^* r_0 + h_1 r_1^* + h_2^* r_2 + h_3 r_3^* \\ \tilde{s}_1 &= h_1^* r_0 - h_0 r_1^* + h_3^* r_2 - h_2 r_3^*. \end{aligned} \tag{6}$$

Substituting the appropriate equations we have

$$\tilde{s}_1 = (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2) s_1 - h_0 n_1^* + h_1^* n_0 - h_2 n_3^* + h_3^* n_2. \tag{7}$$

These combined signals are then sent to the maximum likelihood decoder which for signal $\mathbf{s_0}$ uses the decision criteria expressed in eq. (22) or eq. (23) for PSK signals. Choose $\mathbf{s_i}$ iff

$$\begin{aligned} &(\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2 - 1)|s_i|^2 + d^2(\tilde{s}_0, s_i) \\ &\qquad \le (\alpha_0^2 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2 - 1|s_k|^2 + d^2(\tilde{s}_0, s_k). \end{aligned} \tag{8}$$

Choose $\mathbf{s_i}$ iff

$$d^2(\tilde{s}_0, s_i) \le d^2(\tilde{s}_0, s_k), \qquad \forall i \neq k. \tag{9}$$

Similarly, for $\mathbf{s_1}$ using the decision rule is to choose $\mathbf{s_i}$ signal iff

$$(\alpha_0^2+\alpha_1^2+\alpha_2^2+\alpha_3^2-1)|\mathbf{s_i}|^2+d^2(\tilde{\mathbf{s}}_1,\mathbf{s_i}) \leq (\alpha_0^2+\alpha_1^2+\alpha_2^2+\alpha_3^2-1)|\mathbf{s_k}|^2+d^2(\tilde{\mathbf{s}}_1,\mathbf{s_k}) \tag{10}$$

or, for PSK signals, choose $\mathbf{s_i}$ iff

$$d^2(\tilde{\mathbf{s}}_1,\mathbf{s_i}) \leq d^2(\tilde{\mathbf{s}}_1,\mathbf{s_k}), \qquad \forall i \neq k. \tag{11}$$

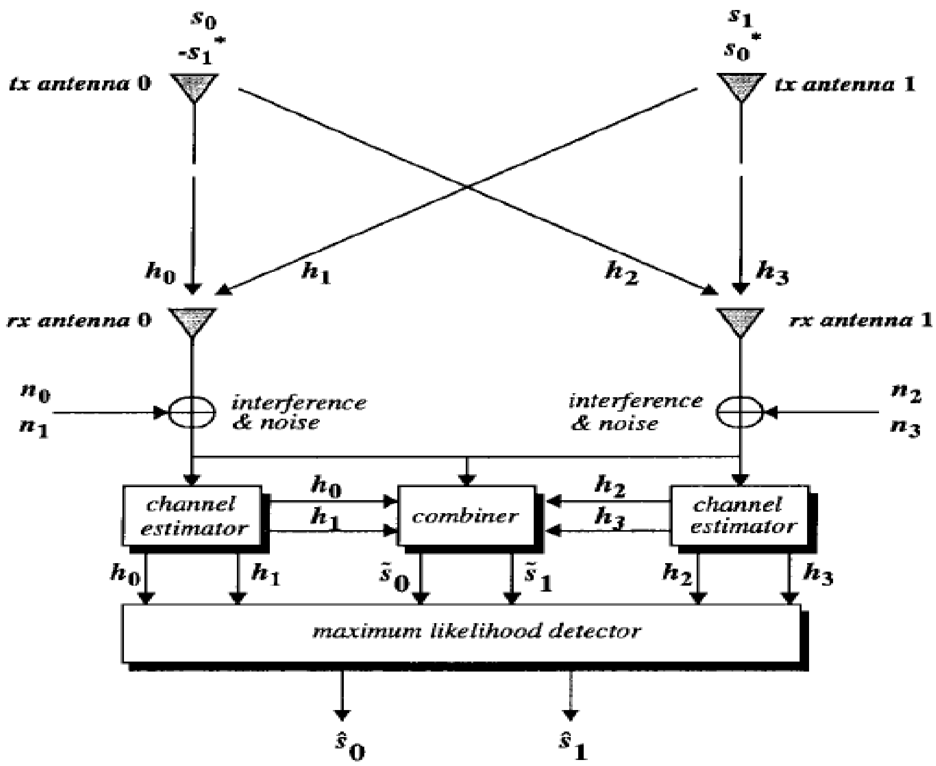

Fig. 8: two-branch transmit diversity scheme with two receivers

STBC with Two-Branch Transmit Diversity and Three-Receivers

It is possible to provide a diversity order of 2*M with two transmit and M receive antennas. It can use the combiner for each receive antenna and then simply add the combined signals from all the receive antennas. Therefore for this case of two transmitters and three receivers (2TX-3RX), it can be applied the same method used for the case of two transmitters and two receivers (2TX-2RX) mentioned above**.**

Concatenated STBC with TCM for OFDM System

Fig. 9 shows the block diagram of concatenated STBC with TCM for OFDM system. First, the TCM encoder encodes the source data. Next, the encoded data is interleaved because the Viterbi Algorithm (VA) is not effective against burst errors. Adding interleaver to distribute burst error. And then the space-time encoder encodes the data. The concatenated code is used in the OFDM system. At each time interval, the symbols are modulated and transmitted simultaneously over different transmit antennas.

At the receiver, the received data is demodulated by the OFDM demodulater, and then combined according to the combining techniques described for STBC. The soft output of the combiner is sent directly to the deinterleaver. Finally, a TCM decoder, such as the Viterbi algorithm, decodes the data.

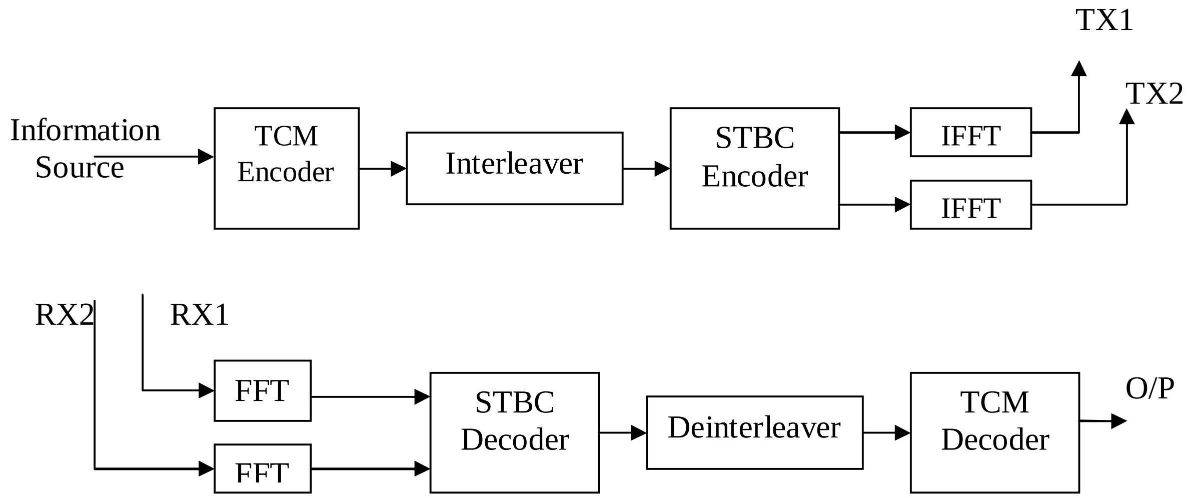

Fig. 9: Block diagram of concatenated STBC with TCM for OFDM system.

The outer code is TCM, then its decoder must use soft-decisions and hence the SBTC decoder must be soft output. Since the SBTC combats the fading by antenna diversity, the outer code (TCM) combats the AWGN to achieve additional coding gain.

- SIMULATION RESULTS

This section gives the simulation results and evaluation tests of these proposed systems, STTC coded OFDM for the cases, Two Transmitters-One Receiver (2TX-1RX), Two Transmitters-Two Receivers (2TX-2RX), and Two Transmitters-Three Receivers (2TX-3RX). The results of the systems in two types of channels, flat fading channel and frequency selective channel, will be examined and compared. The effects of several parameters of wireless channels on the two systems will be investigated. In the OFDM system the FFT transformation is considered. For the TCM, Four States (4States) and Eight States (8States) convolutional code were done. Table 4 shows the parameters of the systems that are used in the simulation. Simulations were done in MATLAB 7. Generation of 2000 packets, each one contains 128 bits.

Table 4: Simulation Parameters.

TCM	8PSK (4-STATES & 8-STATES)
Number of sub-carriers	64
Number of FFT points	64

Channel model	Flat fading + AWGN
	Frequency selective fading + AWGN

Fig. 10 and Fig. 11 illustrate the performance of STTC-OFDM system for 4States and 8States 8-PSK TCM in Flat Fading channel. It can be seen that the performance of the system increases with increasing the diversity gain and coding gain. The best case is that of 2TX-3RX.

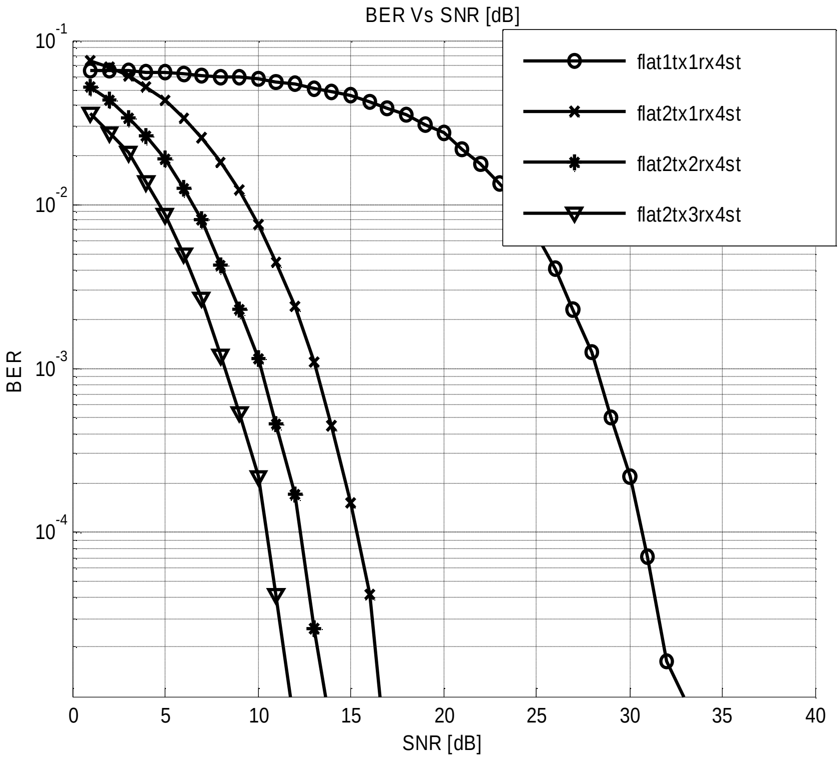

Fig. 10: BER performance of STTC-OFDM for 4-STATES 8PSK TCM in flat fading channel.

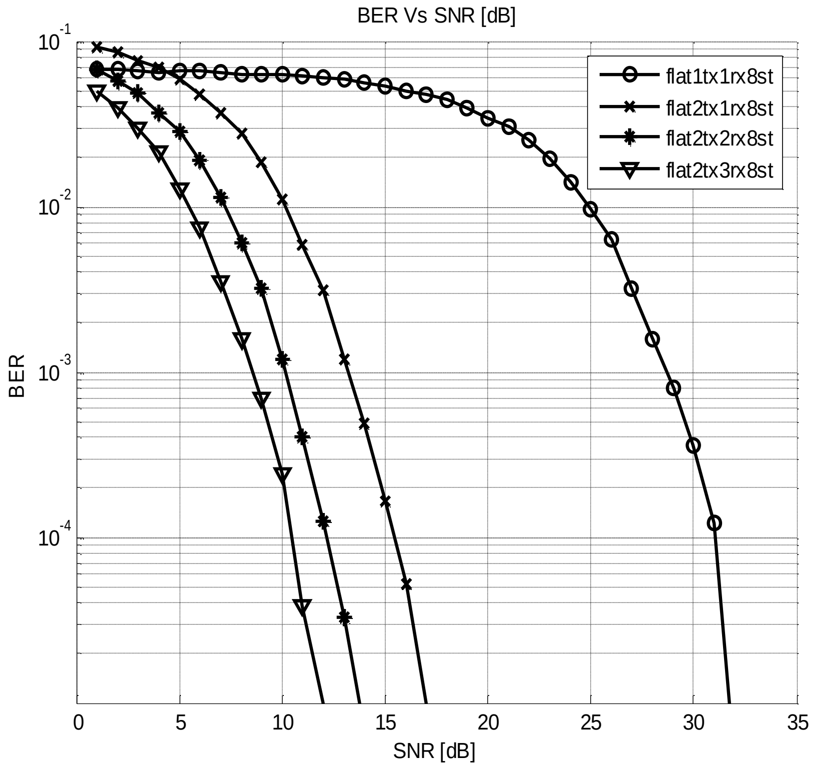

Fig. 11: BER performance of STTC-OFDM for 8-STATES 8PSK TCM in flat fading channel.

Fig. 12 and Fig. 13 illustrate the performance of STTC-OFDM system for 4States and 8States 8-PSK TCM in Frequency Selective Fading channel. It can be seen that the performance of the system increases with increasing the diversity gain and coding gain. The best case is that of 2TX-3RX.

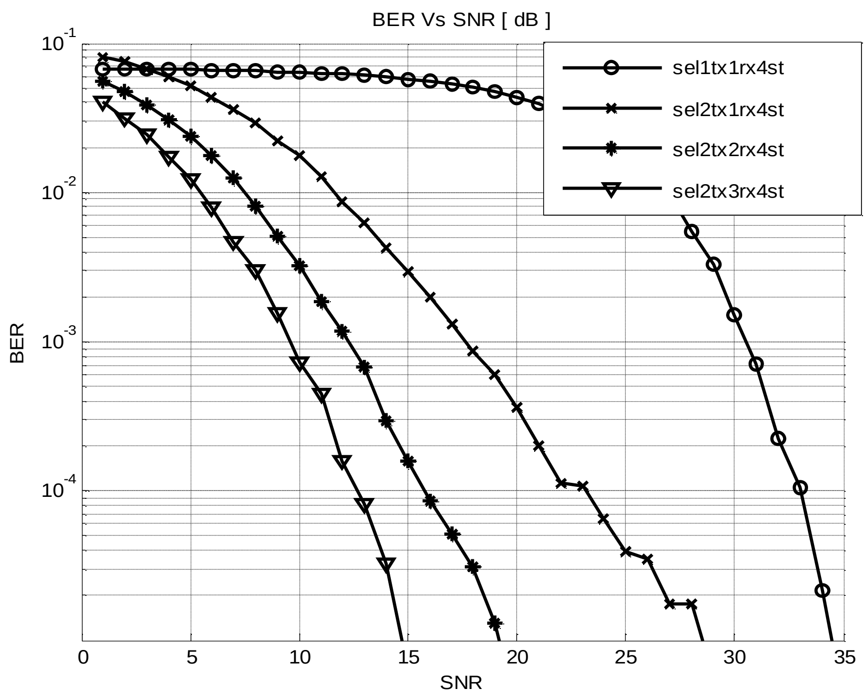

Fig. 12: BER performance of STTC-OFDM for 4-STATES 8PSK TCM in frequency selective fading channel.

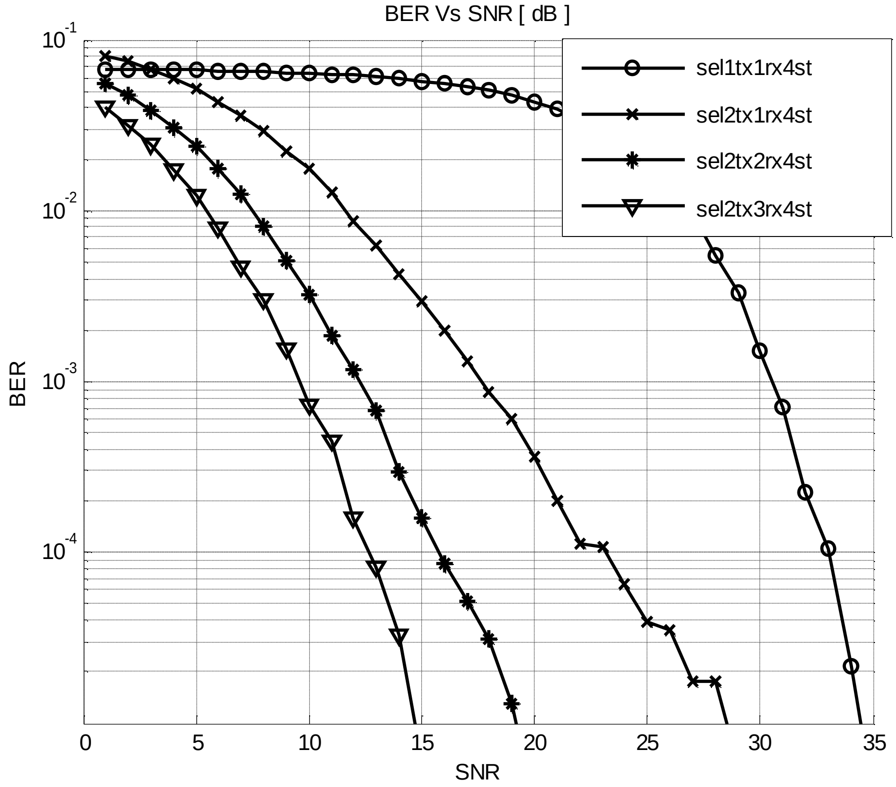

Fig. 13: BER performance of STTC-OFDM for 8-STATES 8PSK TCM in frequency selective fading channel.

- CONCLUSION

In this paper, we investigate the improved performance of the combined OFDM system using STTC based TCM schemes with two transmit antennas and multiple receive antennas, 4-States and 8-States convolutional encoder. The performance comparisons of bit error probability for the conventional OFDM, STTC OFDM have been presented. Simulation results were provided to demonstrate that significant gains can be achieved by increasing the number of receive antennas for the STBC and the number of states for the TCM with very little decoding complexity. Therefore, the STTC coded OFDM is a feasible.

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List of Abbreviations

DFT : Discrete Fourier Transform
FFT : Fast Fourier Transform
IDFT: Inverse Discrete Fourier Transform
IFFT : Inverse Fast Fourier Transform
MED : Minimum Euclidean Distance
MSED : Minimum Square Euclidean Distance
OFDM : Orthogonal Frequency Division Multiplexing
PSK : Phase Shift Keying
QPSK : Quaternary Phase Shift Keying
STBC : Space Time Block Code
STC : Space Time Code
STTC : Space Time Trellis Code
TCM : Trellis Coded Modulation