Iterative Joint and Interference Nulling/ Cancellation

Decoding Algorithms for Multi-Group Space Time Trellis Coded Systems

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Abstract: **In this paper, we will propose and evaluate the performance of several decoding algorithms for multi-group space time trellis coded (MGSTTC) systems. By considering a single user who transmits simultaneously through K parallel space time trellis encoders, the system can provide high spectral efficiencies; transmit diversity advantages and coding gains. The system is analogous to synchronous multi-users each is transmitting a space time trellis code. The transmitter will divide the information stream and transmits from each encoder (called a group) simultaneously resulting in an increase in the transmitted data rates. The receiver will apply some multi-user detection (MUD) algorithms to detect and decode each group. The paper will focus on joint detection and interference nulling/ cancellation algorithms.**

Key Words: Multi-Group STTCs, high data rate MIMO architecture, Multi-user detection.

I. INTRODUCTION

New emerging high data rate wireless applications demand modems that can support their needs. Information theorists have shown that multiple input multiple output channels (MIMO) can dramatically increase the capacity of wireless communication systems [1,3]. Also, MIMO channels can provide both transmit and receive antenna diversity. To deploy and take advantage of the MIMO channels, Foschini in 96 proposed the Bell Labs Layered Space Time (BLAST) architecture [2]. It showed a huge increase in spectral efficiencies compared to single input single output (SISO) systems. However, one of its drawbacks is that the number of receive antennas must be at least equal to the number of transmit antennas. That may limit the design of the receiving end, such as a mobile unit. Also, BLAST has poor power efficiency and it doesn't provide any transmit diversity.

Another approach that doesn't have the above disadvantages is the Space Time Trellis Coding (STTC) proposed by [5]. These codes integrate the design of coding/ modulation and transmit diversity to fully utilize the MIMO channel without any bandwidth expansions. Its mean drawback is that its complexity increases exponentially with number of transmit antennas. In order to reduce the complexity of the STTC, Tarokh in 98 used the principal ratio combining which was a nontrivial extension of the maximum ratio combining for multiple transmit antennas [6]. He showed that the complexity of the STT decoder can be reduced by almost a factor of M (number of receive antennas). However, the complexity still increases exponentially with the number of transmit antennas. A reduced complexity structure was proposed by [4] to support high data rate applications. It was a generalized version of BLAST and it was called multilayered space-time architecture. This architecture is the first multi-group space time trellis coded (MGSTTC) system appeared in the literature. The encoder was divided into K parallel STT encoders each transmits through N_i antennas. The decoder used a signal processing technique called serial group interference suppression.

In this paper, we will concentrate on developing reduced complexity decoding algorithms for the MGSTTC systems. This is a high data rate architecture that solves the exponential complexity problem of STTCs while still provides transmit diversity and coding gains. Furthermore, the developed algorithms are based on MUD techniques and could be easily adapted to synchronous multi-user STTC systems.

The multi-group decoders developed in this work can be classified under two categories. The first is based on joint detection/ decoding. We started our analysis by building the optimum joint space time trellis decoder (OJSTTD) using the super trellis principle. This decoder has a huge complexity but it can be built for a small number of groups. The optimum receiver complexity could be reduced by dividing the detection/ decoding process into two stages: a joint detector followed by a STTD for each group. Based on that, we proposed two suboptimum reduced complexity joint receivers. The first one uses a maximum likelihood (ML) hard detector while the other uses an iterative maximum a posteriori (MAP) detector followed by a MAP STTD for each group. The algorithm is called suboptimum MAP-detection/ MAP-decoding. Although the complexity per group is exponential for the detection stage, it is linear for the decoding stage. The above decoders are quite complex and they can only be practically used for a small number of groups, which is a good assumption for MGSTTC systems.

The other multi-group receivers covered in this paper are based on group interference suppression (nulling)/ cancellation. They achieve linear complexity per group but they have poor BER performance compared to the joint detection. Two interference cancellation algorithms are evaluated. The first one was proposed by [4] and we will call it serial group interference nulling/ cancellation (SGINC). This technique serially decodes each group and it has two mean drawbacks: error propagation and unequal diversity advantages for each group. In order to overcome these disadvantages, we proposed a new algorithm called parallel group interference nulling/ cancellation (PGINC). This algorithm will greatly improve the performance of the SGINC because the parallel structure will guarantee a full receive diversity for each group and the iterative structure will reduce the error propagation.

Section II will describe the multi-group system. Joint detection algorithms will be described in section III and interference nulling/ cancellation methods will be covered in section IV. Simulation results are presented in section V.

II. SYSTEM DESCRIPTION

A. *Encoder*

The encoder is divided into K parallel Groups $\{G_i : i = 1, 2, ..., K\}$. Each group is a Space Time Trellis Encoder (STTE) with N_i transmit antennas. The total number of transmit antennas is N. The input stream is divided into K Blocks $\{B_i$: $i=1, 2, \ldots, K\}$. Each G_i encodes B_i bits into the STTC (C_i) which will be transmitted simultaneously through N_i antennas. All groups operate simultaneously and the transmission is synchronous. Fig. 1 describes the system architecture. The N_i transmitted symbols from G_i at time t are represented by the column vector $\bar{X}_i^t = (x_1^t, x_2^t, \ldots, x_{N_i}^t)'$. The encoder's transmitted symbols at each instant of time can be written as:

$$\mathbf{X}^t = \left[\bar{X}_1^t \quad \cdots \quad \bar{X}_K^t \right]^T \tag{1}$$

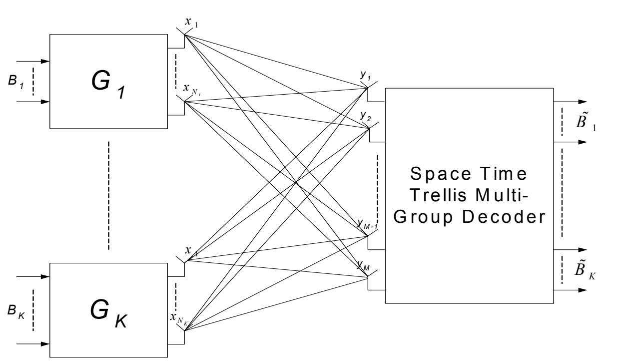

Figure 1: Block Diagram Of the Multi-Group Space Time Trellis Coding architecture

B. *Discrete Channel Model*

The channel is a multiple-input multiple-output (MIMO) channel. There are $M \times N$ paths arriving at the receiver, where M is the number of receive antennas. To evaluate the optimum performance, we assumed fully independent paths. Each path is a quasi-static fading channel for which the fading coefficient is constant over one frame and independent from one frame to another. Each coefficient is a complex Gaussian random variable with mean zero and variance 0.5 per dimension. It has a Rayleigh distributed envelope and a uniformly distributed phase. Let α_{mn} denotes the path gain from antenna n to antenna m where $n=1 \ldots N$ and $m=1 \ldots M$, the channel coefficient matrix can be written as:

$$\mathbf{H} = \begin{bmatrix} \alpha_{11} & \cdots & \alpha_{1N_1} & \alpha_{1(N_1+1)} & \cdots & \alpha_{1N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_{M1} & \cdots & \alpha_{MN_1} & \alpha_{M(N_1+1)} & \cdots & \alpha_{MN} \end{bmatrix}_{M \times N} \tag{2}$$

$$\mathbf{H} = \left[\bar{H}_1 \quad \bar{H}_2 \quad \cdots \quad \bar{H}_K \right]_{M \times N} \tag{3}$$

where $\left[\bar{H}_i\right]_{M \times N_i}$ represents the channel coefficient matrix for the MIMO channel from group G_i to the receiver.

At each receive antenna m, an independent complex Gaussian random variable (η_m) is added to the received signal (y_m). This noise has a mean zero and variance $N_0/2$ per dimension. The received vector at time $t=1,2,\ldots,L$ is:

$$\mathbf{Y}^t = \mathbf{H}\mathbf{X}^t + \boldsymbol{\eta}^t \tag{4}$$

where L is the length of the frame transmitted from each antenna and

$$\mathbf{Y}^t_{M \times 1} = \left[y_1 \quad \cdots \quad y_M \right]' \quad \text{and} \quad \boldsymbol{\eta}^t_{M \times 1} = \left[\eta_1^t \quad \cdots \quad \eta_M^t \right]'$$

III. JOINT DETECTION

Two joint detection algorithms will be used to jointly decode the groups. They are the optimum and suboptimum MAP-MAP joint decoders. These joint receivers will provide a diversity order of ($N_i \times M$)

A. *Optimum Joint Space Time Trellis Decoder (OJSTTD)*

The OJSTTD uses a super trellis to jointly decode the encoders. The first apparent drawback is the huge complexity associated with this approach. However, we will implement it to be used as a reference for the other proposed decoder. For S-states STTC, the super trellis will have S^K states. Each state will have $2^{\sum_{i=1}^{K} B_i}$ transitions and each transition corresponds to N symbols. Although the transmitter will transmit through N antennas, the MGSTTC can't have a rank greater than the rank of each group. Assume that the decoder knows the channel coefficient matrix; it will select the maximum likelihood sequence $\tilde{\mathbf{Q}}$ that minimizes the following cumulative decision metric:

$$\sum_{t=1}^{L} \left\| \mathbf{Y}^t - \mathbf{H}\mathbf{Q}^t \right\|^2 \qquad (5)$$

where $\tilde{\mathbf{Q}} = \left(\mathbf{Q}^1, \mathbf{Q}^2, \cdots, \mathbf{Q}^L\right)$ is the sequence of concatenated vectors transmitted from all groups

and $\mathbf{Q}^t = (\bar{q}_1^t, \bar{q}_2^t, \ldots, \bar{q}_K^t)'$ is a concatenated vector of the transmitted vectors from all groups at time t.

and $\bar{q}_i^t = (q_1^t, q_2^t, \ldots, q_{N_i}^t)'$ is the vector of transmitted symbols from G_i

B. Suboptimum Joint Space Time Trellis Decoder (SJSTTD)

The OJSTTD suffers from the exponential increase in complexity with an increase in number of groups. To overcome this drawback, we propose to divide the receiver into two parts: a joint detector followed by a STT decoder for each group. Thus, the second part of the receiver will have a linear complexity while the first part will still have exponential complexity per group. However, the overall complexity will be much less than the OJSTTD. This method will be implemented with two algorithms: Hard and soft decoding.

The hard decoding uses a hard maximum likelihood (ML) detector at the first stage after which the hard decisions are fed to K parallel STTDs. The soft decoding approach uses a soft in/soft out (SISO) detector for the first stage followed by K parallel SISO STTDs. Furthermore, the two stages will share the soft information iteratively similar to the turbo decoding principle. The SISO detector and STTD are based on the maximum a posteriori (MAP) probability algorithms. The block diagram of the iterative MAP-MAP Joint decoder is shown in Fig. 2.

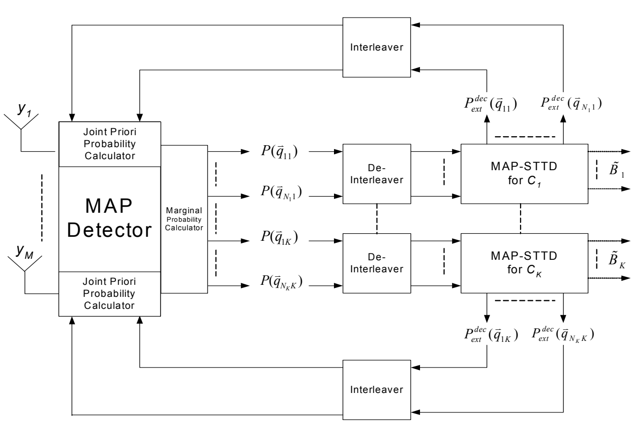

Figure 2: Suboptimum iterative MAP-MAP Space Time Trellis Group Decoder

IV. GROUP INTERFERENCE NULLING/ CANCELLATION

A more practical approach for implementing the multi-group decoder is to use interference nulling/ cancellation techniques. The decoder combines interference nulling and cancellation. It uses basic linear algebra principles to null out all other groups when decoding C_i. After the nulling operation, the algorithm can proceed in two ways. The first is to decode C_i then its contribution to the received vector is cancelled. The nulling/ cancellation process will be serially repeated until all groups are decoded. This method was proposed by Tarokh [4] and we will call it serial group interference nulling/ cancellation (SGINC). It reduces the complexity of the joint STT group decoding with some loss in performance. This performance degradation has not been evaluated in literature but we will do that in this paper via simulation. In this method, ordering is very important. In order to get the best performance, the decoder should cancel the strongest group first. A detailed study of this and on the optimal power allocation was presented in [7]. SGINC has two drawbacks. The first is that decoding errors propagate from one group to another. The second is that the diversity advantage is not equal for all groups. The earlier decoded groups have less receive antenna diversity than the later and that will affect the overall performance.

To overcome these drawbacks, we proposed a new method based on iterative parallel processing. The algorithm will is called parallel group interference nulling/ cancellation (PGINC). The error propagation can be reduced by the iterative structure and each group will have full receive antenna diversity by using the parallel structure.

V. PERFORMANCE EVALUATION VIA SIMULATION

A. Joint Detection

To test the optimum performance of the proposed group decoders, we will assume fully independent Rayleigh fading MIMO channel. Each path is a quasi-static Rayleigh fading channel which has a constant fading coefficient over the whole frame and it is independent from one frame to another. Each coefficient is a complex Gaussian random variable with mean zero and variance 0.5 per dimension. It has a Rayleigh distributed envelope and a uniformly distributed phase. For this study, the STTC used is an 8states QPSK STTC designed by Tarokh in 98 [5] for quasistatic Raleigh fading channels. It can transmit 2b/s/Hz.

At this simulation, two QPSK STT encoders will be used. Each one can transmit 2 b/s/Hz simultaneously through two antennas. Thus, the spectral efficiency of this system is 4 b/s/Hz and the total number of transmit antennas is $N=4$. The rank and the transmit diversity advantage of the resultant STTC is 2. At the receiver, two receive antennas will be used ($M=2$). The number of receive antennas in the joint detection receivers are not restricted which is an advantage over the interference cancellation receivers. Furthermore, perfect channel state information is assumed.

Fig. 3 shows the BER performance verses the signal to noise ratio (E_s / N_0) per receive antenna of the 4×2 two-group STTC system. The first plot evaluates the performance of the Optimum JSTTD compared to the uncoded 16QAM. It shows the huge diversity and coding gain achieved by the OJSTTD without any bandwidth expansions. This gain is about 19 dB at BER=1E-3. The second plot illustrates the poor performance of the Hard Suboptimum JSTTD. This performance degradation is a result of using hard detection at the first stage which throws away valuable information needed by the STTD. Thus, a soft in/soft out detector is needed at the first stage. The BER performance of the suboptimum MAP-MAP joint decoder is also shown in Fig. 3. Without any iterations, this soft suboptimum decoder outperforms the hard one by 6dB at BER=1E-3. After the first iteration, the performance improves a lot. With higher number of iterations, diminishing returns are observed. After three iterations, the difference between the optimum and the suboptimum MAP-MAP STTD is around 1.75 dB at BER=1E-3.

One problem with the proposed suboptimum MAP-MAP JSTTD is that the complexity of the MAP-Detection stage is exponential per group. It can only be practically used for a small number of groups.

B. Group interference nulling/ cancellation

To evaluate the performance of the group interference cancellation receivers, we used the same QPSK STTC used in the previous section. Also, 4 b/s/Hz are transmitted using two QPSK STT encoders each transmits through two antennas. However, the number of receive antennas must be grater than or equal to 3. Thus, in this section, the MIMO channel will be 4×4 quasi-static Rayleigh fading channels. The 4×4 paths are independent and perfect channel state estimation is assumed.

Fig. 4 shows the performance of the SGINC receiver verses the SNR per receive antenna. The first code (C_1) benefits from a diversity order of 2×2. On the other hand, the second code (C_2) should take advantage of 2×4 diversity order after serially canceling the contribution of the first code from the received vector. However, due to error propagation, this diversity order is not achieved as can be seen from Fig. 4. By comparing the slope of the plot of the second group with the perfect cancellation plot, we can see the huge degradation in performance due to propagating errors. The performance gain of the second group is better than the first by 2dB. However, the overall performance of the 4 b/s/Hz system using the SGINC receiver lies between the performances of the two STTCs.

In order to reduce the effect of error propagation and improve the overall system performance, we proposed the PGINC receiver. The performance of this iterative parallel receiver is shown in Fig. 5. At the first stage, the receiver performs nulling operation simultaneously for all groups. Then the interference free output is passed to two STTDs. At this stage, each group has a 2×2 diversity order and the 4b/s/Hz system performance is similar to the performance of the first code with SGINC. However, after performing parallel cancellation (after one iteration), the diversity order for each group increased to 2×4 and the overall system performance gained 2dB. More iteration reduces the effect of error propagation. However, after three iterations, diminishing returns are observed. Also, error propagation still affects the performance of the system and it is clear from looking at the performance of the system with perfect cancellation.

In order to estimate the loss in performance due to the reduced complexity, we re-simulated the optimum JSTTD and the suboptimum MAP-MAP JSTTD over 4×4 MIMO quasi-static Rayleigh fading channels. The result is shown in Fig. 6. Compared to the optimum JSTTD, the PGINC receiver lost 4.5dB and SGINC lost 6.6dB. This lost in performance is compromised by the linear complexity per group provided by these receivers.

VI. SUMMARY AND CONCLUSION

Two classes of STT group decoders were presented in this paper. The first used joint decoding while the second implemented more practical receivers based on group interference nulling/ cancellation. These multi-group STT coded systems transmit high data rates with diversity advantages and coding gains without any bandwidth expansions. The joint decoders were the optimum JSTTD and the suboptimum MAP-MAP JSTTD. The later used iterative processing between the MAP-detection stage and the MAP-STT decoding stage. The other class consists of the SGINC and the PGINC receivers. Both receivers were implemented in an iterative architecture but the difference is that the SGINC algorithm iterates in order to decode each code serially. On the other hand, the PGINC decodes all codes at the same time and it iterates to improve the performance of the system. These receivers are less complex than the joint receiver. However, the later performs much better. Table 1 compares between these receivers in term of complexity per group, performance, diversity advantage and number of receive antennas required by the receiver.

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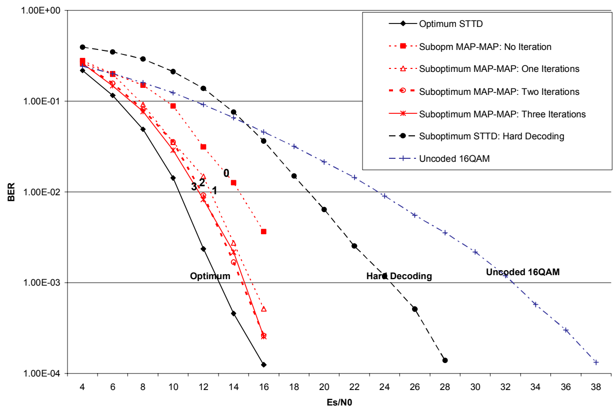

Figure 3: Performance of the 4b/s/Hz STT coded two-group system using the Suboptimum MAP-MAP Joint STTDs over 4×2 MIMO quasi-static Rayleigh fading channels**.**

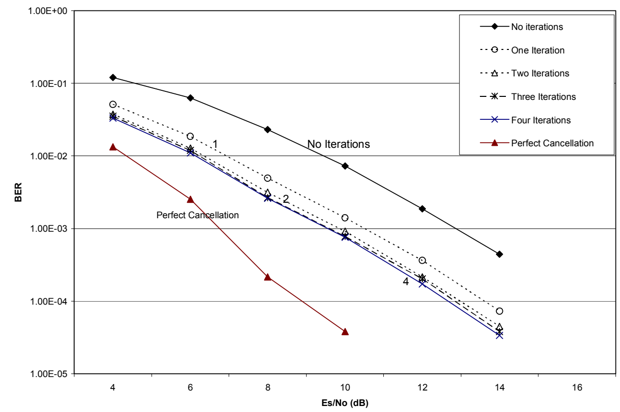

Figure 5: Performance of the 4b/s/Hz STT coded two-group system using the PGINC receiver. The channel is a 4x4 MIMO quasi-static Rayleigh fading channel.

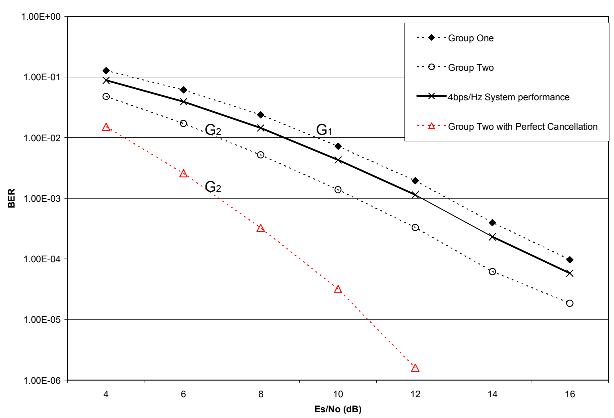

Figure 4: Performance of the 4b/s/Hz STT coded two-group system using the SGINC receiver. The channel is a 4x4 MIMO quasi-static Rayleigh fading channel.

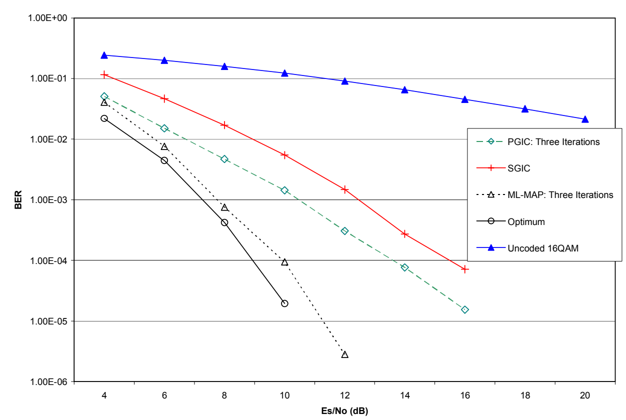

Figure 6: Performance comparison of the 4b/s/Hz STT coded two-group receivers. The channel is a 4x4 MIMO quasi-static Rayleigh fading channel

TABLE 1 Comparison between the multi-group STT decoders

	Optimum Decoder	Suboptimum MAP-MAP Decoder	SGINC Decoder	PGINC Decoder
Complexity per group	Exponential	The first stage is exponential and the second stage is linear	Linear	Linear
Performance	Optimum	Close to the optimal performance. [1]	Far from the optimal performance[1]	Much better than the SGIC and moderate difference from the optimal performance.[1]
Diversity Advantage	$N_i \times M$	$N_i \times M$	For G_i : $N_i \times (N_1 + \cdots + N_i + M - N)$	For G_i : $N_i \times M$
Number of receive Antennas (M)	$M \geq 1$	$M \geq 1$	If G_i is decoded first $M \geq N - N_i + 1$	$M \geq N - \max(N_i) + 1$

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[1] See the simulation results