

Research Article

Joint Decoding of Concatenated VLEC and STTC System

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We consider the decoding of wireless communication systems with both source coding in the application layer and channel coding in the physical layer for high-performance transmission over fading channels. Variable length error correcting codes (VLECs) and space time trellis codes (STTCs) are used to provide bandwidth efficient data compression as well as coding and diversity gains. At the receiver, an iterative joint source and space time decoding scheme are developed to utilize redundancy in both STTC and VLEC to improve overall decoding performance. Issues such as the inseparable systematic information in the symbol level, the asymmetric trellis structure of VLEC, and information exchange between bit and symbol domains have been considered in the maximum a posteriori probability (MAP) decoding algorithm. Simulation results indicate that the developed joint decoding scheme achieves a significant decoding gain over the separate decoding in fading channels, whether or not the channel information is perfectly known at the receiver. Furthermore, how rate allocation between STTC and VLEC affects the performance of the joint source and space-time decoder is investigated. Different systems with a fixed overall information rate are studied. It is shown that for a system with more redundancy dedicated to the source code and a higher order modulation of STTC, the joint decoding yields better performance, though with increased complexity.

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1. INTRODUCTION

Providing multimedia service has become an attractive application in wireless communication systems. Due to bandwidth limitation and harsh wireless channel conditions, reliable source transmission over wireless channel remains a challenging problem. Space time code and variable length source code are two key enabling techniques in the physical and application layers, respectively.

Tarokh introduced space time trellis codes (STTCs) [1] in multiple-input multiple-output (MIMO) systems, which obtain bandwidth efficiency four times higher than that of diversity systems without space time coding. While these STTCs are designed to achieve the maximum diversity in space dimension, the coding gain in time dimension, on the other hand, still may be improved.

Variable length error correcting codes (VLECs) [2] are a family of error correcting codes used in source coding. VLEC maps source symbols to codewords of variable length according to the source statistics. Compared to Huffman code aiming for high-compression efficiency, VLEC has inherent redundancy and some error resilient capability. However, VLEC is still sensitive to channel errors and

one single bit error may cause continuous source symbol partition errors due to the well-known synchronization problem.

Shannon's classical separation theory states that we can optimize the system by designing optimal source code and channel code separately. However, this theorem holds only for infinite size of packets. Therefore, with delay and computation resource constraint, joint optimization of source and channel coding or decoding often yields better performance in realistic systems. Joint source channel decoding (JSCD) basically focuses on using the redundancy in the source coded stream to improve the overall decoding performance. Constraint JSCD (C-JSCD) is discussed in [3, 4], in which the output from channel decoder is modeled as an output from binary symmetric channel (BSC) and the source decoder exploits the statistical character of BSC as a constraint in the maximum a posteriori probability (MAP) algorithm. Integrated JSCD (I-JSCD), proposed in [5, 6], merges the trellises of source code and channel code into one integrated trellis and carries out MAP decoding based on the combined trellis. The drawback of I-JSCD is that the decoding complexity dramatically increases with the number of states in the combined trellis. Recently, iterative JSCD

[7, 8] adopts iterative decoding structure and information exchange between source decoder and channel decoder. It has attracted increasing attention because of its relatively low decoding complexity.

Joint decoding schemes with space time components have also been considered recently. A mega concatenation system of multiple-level code, trellis-coded modulation (TCM), and STTC is proposed in [9] to provide unequal error protection for MPEG4 streams. Variable length space time-coded modulation (VL-STCM) is proposed in [10, 11] by concatenating VLC and BLAST in MIMO systems. Iterative detection structure is proposed in [12] for a concatenated system with reversible variable length code (RVLC), TCM, and diagonal block space time trellis code (DBSTTC). In this paper, we consider another type of systems where recursive STTCs (Rec-STTCs) with full transmit diversity gain and some coding gain are concatenated with source VLECs. For this type of systems, we design an iterative decoding scheme to fully utilize the redundancy in both source code and space time code. Modification of MAP decoding algorithms and information exchange between symbol and bit domains from the two component decoders are addressed. This iterative decoding is evaluated in both quasi static and rapid fading channels when either perfect channel information is available or the channel estimation errors exist. The results show significant decoding gain over noniterative decoding in the tested cases. Furthermore, we study the rate allocation issue dealing with how to allocate the redundancy between STTC and VLEC for better decoding performance under the overall bandwidth and transmission power constraint. We find that with increased decoding complexity, the joint decoding system performance can be improved by introducing more redundancy into source code while using a higher-order modulation in STTC.

The rest of paper is organized as follows. The concatenation structure of VLEC and STTC is described in Section 2. Joint source and space time decoding algorithm is discussed in Section 3 in detail. Performance in case of perfect channel estimation is provided in Section 4. Performance in presence of channel estimation errors is presented in Section 5. The rate allocation issue is then investigated in Section 6. Finally, conclusions are drawn in Section 7.

2. SYSTEM WITH VLEC AND STTC

The encoder block diagram is depicted in Figure 1. We assume a_i , $i = 0, 1, \dots, K - 1$ is one packet of digital source symbols, drawn from a finite alphabet set $0, 1, \dots, N - 1$. K is the packet length, N is the source alphabet size. The VLEC encoder maps each source symbol to a variable length codeword at a code rate $R_{\text{VLEC}} = H/\bar{l}$. \bar{l} is the average VLEC codeword length. H is the entropy of the source. The generated bit sequence is b_j , $j = 0, 1, \dots, L - 1$. A bit interleaver is inserted before the use of STTC for time diversity. In this paper, we use a random interleaver.

Consider 2^p -ary modulation is used, the bit stream is grouped every p bits and converted to symbol stream c_t , $t = 0, 1, \dots, \lceil L/p \rceil - 1$ as the input to STTC encoder. The output from STTC is N_T modulated symbol sequences

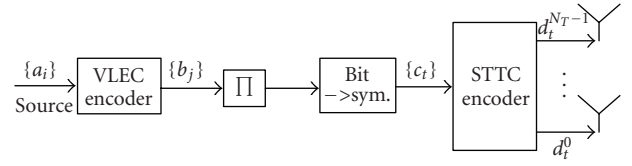


FIGURE 1: Serial concatenation of VLEC and STTC.

TABLE 1: Examples of VLEC [8].

Symbol	Probability	Huffman	C1	C2
0	0.33	00	00	11
1	0.3	11	11	001
2	0.18	10	101	0100
3	0.1	010	010	0101100
4	0.09	011	0110	0001010
$E[l]$	$H = 2.14$	2.19	2.46	3.61
d_f		1	2	3

d_t^i , $i = 0, \dots, N_T - 1$; $t = 0, 1, \dots, M - 1$ ($M = \lceil L/p \rceil$), which are sent to radio channel through N_T transmit antennas. The overall effective information rate is pH/\bar{l} bit/s/Hz.

Suppose there are N_R antennas at the receiver; at time t , the signal on the j th receive antenna is

$$r_t^j = \sum_{i=0}^{N_T-1} \sqrt{E_s} f_t^{i,j} d_t^i + \eta_t^j, \quad (1)$$

where $i = 0, \dots, N_T - 1$; $j = 0, \dots, N_R - 1$; E_s is the average power of the transmitted signal; $f_t^{i,j}$ is the path gain between the i th transmit antenna and the j th receive antenna at time t . We consider two fading cases: quasi static fading channel (also referred as block fading) in which the path gain keeps constant over one packet and rapid fading channel in which the path gain changes from one symbol to the other. η_t^j is the additive complex white Gaussian noise on the j th receive antenna at time t with zero mean and variance of $N_0/2$ per dimension.

2.1. Variable length error correcting code

In [2], Buttigieg introduced variable length error correcting code (VLEC). It is similar to block error correcting code in that each source symbol is mapped to a codeword, but with different length. The more frequent symbols are assigned with shorter codewords. The codewords are designed so that a minimum free distance is guaranteed. With a larger free distance, VLEC has stronger error resilience capability. However, in the mean time, more redundancy is introduced and the average length per symbol increases, which reduces the overall effective information rate. Table 1 gives the examples of Huffman code and two VLECs of a same source with different free distances from [8].

Since a bit-based trellis representation was proposed for VLEC [13], the MAP decoding algorithm can also be adopted for bit-level VLEC decoding. Figure 2 gives the tree structure and the bit-level trellis representation of VLEC C1. Each

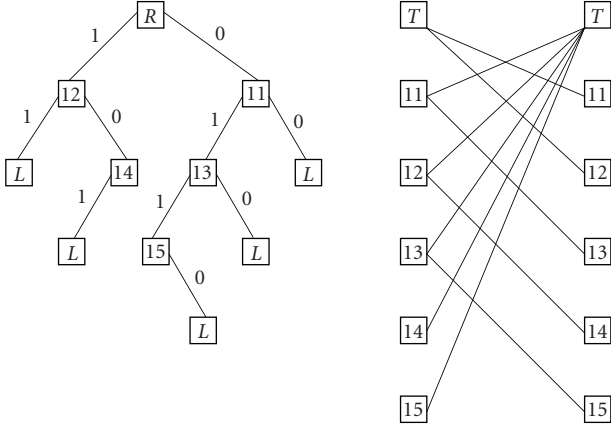


FIGURE 2: Example of VLEC tree structure and bit-level trellis [7].

interior node on the VLEC coding tree is represented by “ I_t ”. The root node and the leaf nodes can be classified as terminal nodes and denoted by the “ T ” states in the trellis. The branches in the trellis describe the state transitions at any bit instance along the source coded sequence.

2.2. Recursive space time trellis code

The recursive nature of component encoders is critical to the excellent decoding performance of turbo codes. General rules for designing parallel and serial concatenated convolutional codes have been presented in [14, 15]. In both cases, recursive convolutional code is required.

In [16], Tujkovic proposed recursive space time trellis code (Rec-STTC) with full diversity gain for parallel concatenated space time code. Figure 3 gives the example of Rec-STTCs in [16] for two transmit antennas. The upper part is a 4-state, QPSK modulated Rec-STTC (ST1) with bandwidth efficiency 2 bit/s/Hz and the lower part is an 8-state, 8PSK modulated Rec-STTC (ST2) with bandwidth efficiency 3 bit/s/Hz. Each line represents a transition from the current state to the next state. The numbers on the left and right sides of the dashes are the corresponding input symbols and two output symbols, respectively.

3. JOINT VLEC AND SPACE TIME DECODER

Consider the above serial concatenated source and space time coding system. Conventionally, the separate decoding stops after one round of STTC decoding followed by VLEC decoding. In this paper, we utilize both redundancy in VLEC and error correcting ability of STTC in time dimension to facilitate each other's decoding through an iterative process, and hence to improve the overall decoding performance.

Figure 4 illustrates the iterative joint source and space time decoding structure. Assume that the packet has been synchronized and the side information of the packet length in bit after VLEC encoder is known at the receiver. Soft-input soft-output MAP algorithm [17] is used in both VLEC and STTC decoders.

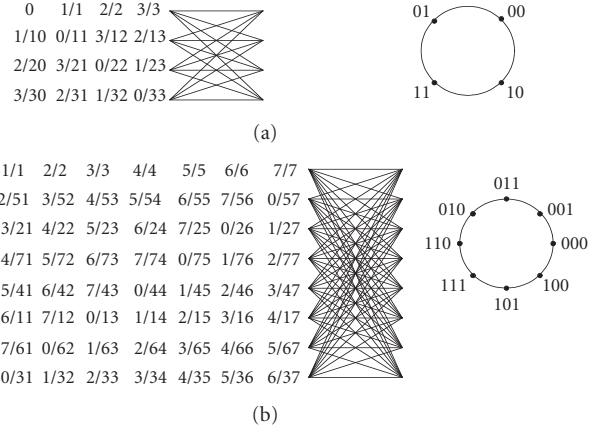


FIGURE 3: Trellis graphs of QPSK and 8PSK recursive STTCs.

3.1. MAP in symbol and bit domains

The MAP decoder takes the received sequences as soft inputs and a priori probability sequences and outputs an optimal estimate of each symbol (or bit) in the sense of maximizing its a posteriori probability. The a posteriori probability is calculated through the coding constraints represented distinctly by trellis.

Given the received streams,

$$\mathbf{r} = \begin{bmatrix} r_0^0, & \dots, & r_t^0, & \dots \\ \vdots & \ddots & \vdots & \\ r_0^{N_R-1}, & \dots, & r_t^{N_R-1}, & \dots \end{bmatrix}, \quad (2)$$

and assume perfect channel information $\mathbf{f} = [f_t^{i,j}]$, $i = 0, \dots, N_T - 1$, $j = 0, \dots, N_R - 1$, known at the receiver, at each time index t , then the space time decoder generates symbol domain log-likelihood values for all symbols in the signal constellation $Q = q$, $q = 0, \dots, 2^p - 1$ as follows:

$$L(\hat{c}_t = q | \mathbf{r}) = \ln \sum_{(s',s) \Rightarrow q} \alpha_{t-1}(s') \gamma_t(s', s) \beta_t(s), \quad (3)$$

where (s', s) represents the state transition from time $t - 1$ to time t on the STTC trellis,

$$\gamma_t(s', s) = P(\mathbf{r}_t | (s', s)) P(s | s'). \quad (4)$$

$\mathbf{r}_t = r_t^j$, $j = 0, \dots, N_R - 1$ is the array of received signal on the N_R receive antennas at index t . The first part on the right-hand side of (4) involves channel information given by

$$\ln P(\mathbf{r}_t | (s', s)) = -C \sum_{j=0}^{N_R-1} \left| r_t^j - \sum_{i=0}^{N_T-1} f_t^{i,j} d_t^i \right|^2, \quad (5)$$

where d_t^i , $i = 0, \dots, N_T - 1$ are the transmitted signals associated with transition branch (s', s) at time t . C is a constant that depends on the channel condition at time t and is the same for all possible transition branches. $P(s | s')$ is a

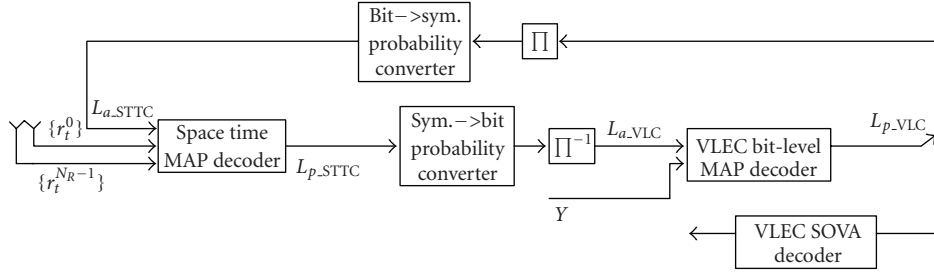


FIGURE 4: Joint source space time decoder.

priori information and equal to $P(q : (s', s) \leftrightarrow q)$. Without any a priori information, every symbol in constellation is considered as generated with equal possibility and $P(s|s')$ is set to $1/2^p$.

$\alpha_t(s)$ is the probability that the state at time t is s and the received signal sequences up to time t are $\mathbf{r}_{k < t+1}$, It can be calculated by a forward pass as

$$\alpha_t(s) = \sum_{s'} \gamma_t(s', s) \alpha_{t-1}(s'). \quad (6)$$

$\beta_{t-1}(s')$ is the probability that the state at time $t-1$ is s' and the received data sequences after time $t-1$ are $\mathbf{r}_{k > t-1}$, and can be calculated by a backward pass as

$$\beta_{t-1}(s') = \sum_s \beta_t(s) \gamma_t(s', s). \quad (7)$$

The initial values $\alpha_0(0) = \beta_{N_s}(0) = 0$ (N_s is the packet length in modulated symbol), assuming tail symbols are added to force the encoder registers back to the zero state.

It needs to be pointed out that $L(\hat{c}_t = q | \mathbf{r})$ in (3) is a log-likelihood value but not the log-likelihood ratio in the conventional MAP decoding. This is because multiple candidate symbols exist in the STTC constellation. Besides, the systematic and parity information can no longer be separated in (5), because the two output symbols in any trellis transition are sent through two transmit antennas simultaneously. Received signal on any receive antenna is an additive effect of two symbols and the noise. Equation (3) can be rewritten as

$$L(\hat{c}_t = q | \mathbf{r}) = L_{a,STTC} + L_{e,STTC}, \quad (8)$$

where

$$L_{a,STTC} = \ln P(\hat{c}_t = q),$$

$$L_{e,STTC} = \ln \sum_{(s', s) \rightarrow q} \alpha_{t-1}(s') P(\mathbf{r}_t | (s', s)) \beta_t(s). \quad (9)$$

As a result, each symbol domain log-likelihood value comprises only two parts: extrinsic information and a priori information. The extrinsic information of STTC will be sent to the VLEC decoder as a priori information.

The bit-indexed soft input sequence Y to VLEC decoder is the extrinsic information from the channel decoder in the

first iteration. VLEC MAP decoder calculates bit domain log-likelihood ratio for each coded bit u_k as

$$L(\hat{u}_k | Y) = \ln \frac{P(\hat{u}_k = 1 | Y)}{P(\hat{u}_k = 0 | Y)} \quad (10)$$

$$= \ln \frac{\sum_{(s', s) \Rightarrow \hat{u}_k = 1} \alpha_{k-1}(s') \gamma_k(s', s) \beta_k(s)}{\sum_{(s', s) \Rightarrow \hat{u}_k = 0} \alpha_{k-1}(s') \gamma_k(s', s) \beta_k(s)}.$$

The forward and backward calculations of α and β are similar to STTC MAP decoding. Since this is a serially concatenated system without separable systematic information, Y will be regarded as the $L_{p,STTC}$ minus the a priori information of the STTC decoding in the first iteration and will remain the same for the use of all iterations. The a priori information of VLEC decoder ($L_{a,VLEC}$) in the following iterations will be updated with the extrinsic information from the STTC decoder. The calculation of γ can be written as

$$\gamma_k(s', s) = P(Y_k | (s', s)) P(u_k), \quad u_k \in \{1, 0\}, \quad (11)$$

where u_k is the output bit from VLEC encoder associated with transition from previous state s' to current state s at instant k along the trellis. Equation (10) can be further represented as

$$L(\hat{u}_k | Y) = L_{a,VLEC} + L_{e,VLEC}, \quad (12)$$

where

$$L_{a,VLEC} = \ln \frac{P(\hat{u}_k = 1)}{P(\hat{u}_k = 0)},$$

$$L_{e,VLEC} = \ln \frac{\sum_{(s', s) \Rightarrow \hat{u}_k = 1} \alpha_{k-1}(s') P(Y_k | (s', s)) \beta_k(s)}{\sum_{(s', s) \Rightarrow \hat{u}_k = 0} \alpha_{k-1}(s') P(Y_k | (s', s)) \beta_k(s)}. \quad (13)$$

Therefore, once the VLEC log-likelihood ratio is calculated, the extrinsic information $L_{e,VLEC}$ will be extracted and sent to the STTC decoding as the new a priori information.

3.2. Iterative information exchange

The principle of iterative decoding is to update the a priori information of each component decoder with the extrinsic information from the other component decoder back and forth. By iterative information exchange, the decoder can

make full use of the coding gain in the coding trellises of the component codes to remove channel noise in a build up way. During the first iteration, the a priori probability to Rec-STTC decoder $L_{a,STTC}$ is set to be equally distributed over every possible symbol. The log-likelihood output from space time decoder $L_{p,STTC}$ is separated into two parts: soft information (including the systematic and extrinsic information since systematic information is not separable in space time coding scheme) and a priori information, which, in later iterations, is the extrinsic information from VLEC decoder. The soft symbol information $L_{e,STTC}$ is extracted and converted to log-likelihood ratio in bit domain. After de-interleaving, it is sent to VLEC decoder as a priori information $L_{a,VLEC}$. The a posteriori probability output of VLEC decoder $L_{p,VLEC}$ consists of two parts: a priori information and extrinsic information $L_{e,VLEC}$. Only extrinsic information is interleaved and converted to the a priori information in symbol domain for Rec-STTC decoder in the next iteration. After the final iteration, Viterbi VLEC decoding is carried out on $L_{p,VLEC}$ to estimate the source symbol sequence.

The conversion between the bit domain log-likelihood ratio and the symbol domain log-likelihood value is implemented based on the mapping method and the modulation mode. Each symbol q consists of p bits $q \rightarrow w_0, w_1, \dots, w_{p-1}$, $w_i \in \{0, 1\}$. For a group of p bits $y_0 y_1 \dots y_{p-1}$, we derive the relation between $L(q)$, $q = 0, 1, \dots, 2^p - 1$ and corresponding $L(y_i)$, $i = 0, \dots, p - 1$ as follows:

$$\begin{aligned} L(y_i) &= \ln \frac{P(y_i = 1)}{P(y_i = 0)} = \ln \frac{\sum_{q:(w_i=1) \in q} P(q)}{\sum_{q:(w_i=0) \in q} P(q)} \\ &= \ln \frac{\sum_{q:(w_i=1) \in q} e^{L(q)}}{\sum_{q:(w_i=0) \in q} e^{L(q)}}, \end{aligned} \quad (14)$$

$$L(q) = \ln P(q) = \ln \prod_{i=0}^{p-1} P(w_i) = \sum_{i=0}^{p-1} \ln \frac{e^{w_i L(y_i)}}{1 + e^{L(y_i)}}, \quad (15)$$

where $i = 0, \dots, p - 1$. In (15), we use a conversion pair between LLR $L(a)$ and absolute probability $P(a = 1)$ and $P(a = 0)$ as follows:

$$P(a = 1) = \frac{e^{L(a)}}{1 + e^{L(a)}}, \quad P(a = 0) = \frac{1}{1 + e^{L(a)}}. \quad (16)$$

4. PERFORMANCE OVER FADING CHANNELS

Throughout this paper, a MIMO system with two transmit antennas and two receive antennas is used to transmit VLEC coded source stream. A symbol stream is first generated and fed to source encoder. Each symbol is drawn from a 5-ary alphabet with probability distribution shown in Table 1. Each input packet has 100 source symbols. We use the VLEC (C1, C2) schemes in Table 1 and the Rec-STTCs (ST1, ST2) with signal constellations in Figure 3. The average transmitted signal power is set to one ($E_s = 1$) and the amplitudes of QPSK and 8PSK are both equal to one ($\sqrt{E_s} = 1$). The output bit stream from VLEC

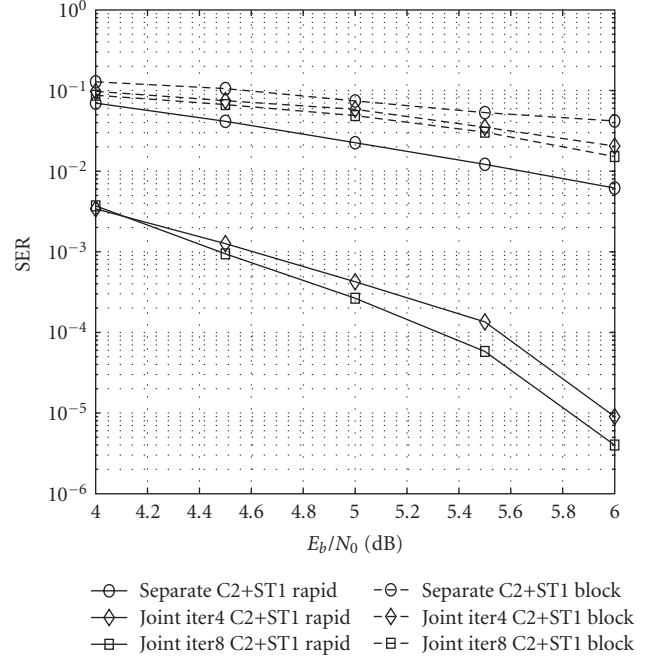


FIGURE 5: SER performance of joint source and space time decoder over Rayleigh fading channels.

encoder is padded with “0” if necessary so that its length can be divided by p . Tail symbols are added so that Rec-STTC encoder registers return to zero states. A random interleaver is used between the VLEC encoder and the Rec-STTC encoder. We adopt Rayleigh distributed channel model of both rapid fading case and quasi static fading case. Following the iterative decoding and information conversion described in the previous section, the end-to-end system performance is measured by the symbol error rate (SER) each time after VLEC SOVA decoder. SER is measured in terms of Levenshtein distance [18] which is the minimum number of insertions, deletions, and substitutions required to transform one sequence to another.

In this section, we study VLEC C2 concatenated with QPSK modulated Rec-STTC ST1. The overall effective information rate is 1.1856 bit/sec/Hz. Figure 5 shows the SER performance comparison between the joint VLEC and space time decoder and the separable space time and VLEC decoder over quasi static (i.e., block) Rayleigh fading channel and rapid Rayleigh fading channel. The joint source space time decoder achieves more than 2 dB gain over separate decoding in SER in rapid fading channel and about 0.8 dB gain in quasi static fading channel. Especially, at 6 dB in rapid fading channels, after 8th iteration, SER also drops to 10^{-3} of the SER of separate decoding.

We also observe that the concatenated VLEC and STTC system has a less performance gain in quasi static fading channel than in rapid fading channel, as shown in Figure 5. This is reasonable because the rapid fading channels, which are also called interleaved fading channels, can provide additional diversity gain, compared with the quasi static channel.

5. PERFORMANCE IN PRESENCE OF CHANNEL ESTIMATION ERRORS

In this section, we evaluate the joint source and space time decoding in more realistic scenarios. In Section 3, the decoder assumes in the first place that the channel state information (CSI) is perfectly known at the receiver. However, in real communication systems, regardless of what method is used, there are always errors in the channel estimation. How the joint source and space time decoder performs in presence of channel estimation errors is examined here.

Considering imperfect channel estimation, the actual channel fading matrix \mathbf{f} used to calculate metric in (5) becomes the estimated channel fading matrix $\hat{\mathbf{f}}$. We model each estimated channel fading coefficient $\hat{f}_t^{i,j}$ between the i th transmit antenna and the j th receive antenna at time t as a noisy version of the actual channel fading coefficient $f_t^{i,j}$,

$$\hat{f}_t^{i,j} = f_t^{i,j} + \eta_t^{i,j}, \quad (17)$$

where $\eta_t^{i,j}$ is the channel estimation error and modeled as a complex Gaussian random variable, with zero mean and variance of σ_η^2 and is independent on $f_t^{i,j}$. The correlation coefficient ρ between $f_t^{i,j}$ and $\hat{f}_t^{i,j}$ is given by

$$\rho = \frac{1}{\sqrt{1 + \sigma_\eta^2}}. \quad (18)$$

We use VLEC C1 and Rec-STTC ST1 for simulation. Other simulation parameters keep the same. Figure 6 shows the SER performance over quasi static fading channels. When channel information is accurately estimated $\rho = 1.0$, the SER decreases through iterations. There is about 0.7 dB gain at the level of 10^{-3} in SER over separate VLEC and STTC decoding. In both cases of channel estimation error ($\rho = 0.98$ case I and $\rho = 0.95$ case II), the joint RVLC and STTC decoding still achieves iterative decoding gain. After 8 iterations, the joint decoding scheme achieves a performance gain of more than 0.7 dB gain at the level of 10^{-3} in SER in case I, compared with separate decoding. In case II, a performance gain of 3.5 dB at the level of 10^{-2} in SER is achieved after 8 iterations.

The decoding performance in case I and case II over rapid fading channels in Figure 7 shows a similar result. Although channel estimation for rapid fading channels is not practical in real systems, the result provides some theoretic perspectives of the joint VLEC and STTC decoding. Similar decoding gain is observed. After 8 iterations, the joint decoding scheme achieves a performance gain of 1.5 dB in SER at the level of 10^{-3} with perfect channel estimation, a performance gain of nearly 4 dB at the level of 10^{-2} in SER in case I, and a performance gain of more than 5 dB at the level of 10^{-1} in SER in case II, compared with separate VLEC and STTC decoding.

It can be found that in both quasi static fading channel and rapid fading channel, from $\rho = 1$ to $\rho = 0.95$, the decoding gain increases. When channel estimation is less accurate, the channel information fed to space time decoder deviates more from correctness and causes more

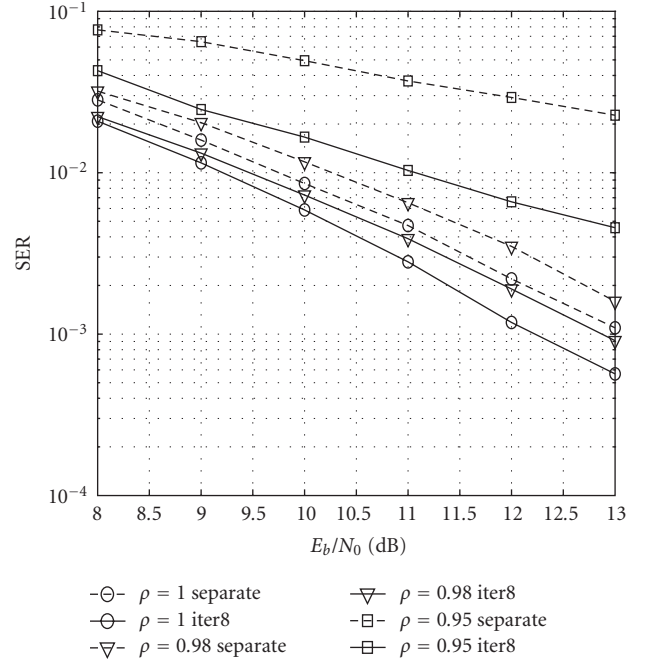


FIGURE 6: SER performance joint source and space time decoding over quasi static fading channel with channel estimation error.

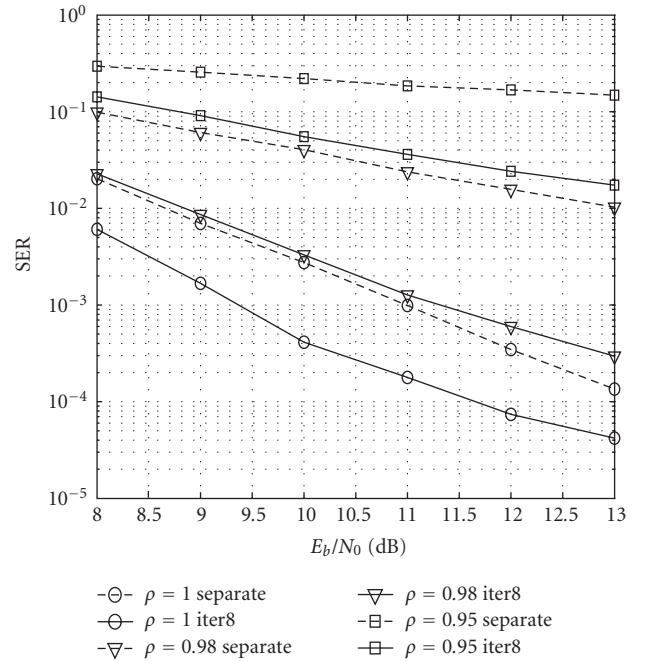


FIGURE 7: SER performance joint source and space time decoding over rapid fading channel with channel estimation error.

errors. The iterative decoder can still achieve significant improvement over the separate decoding through iterations. Therefore, the joint source space time decoder is robust to channel estimation errors to some extent. The result is also consistent with the decoder's convergence characteristic. After 6 iterations, the iterative decoding algorithm has

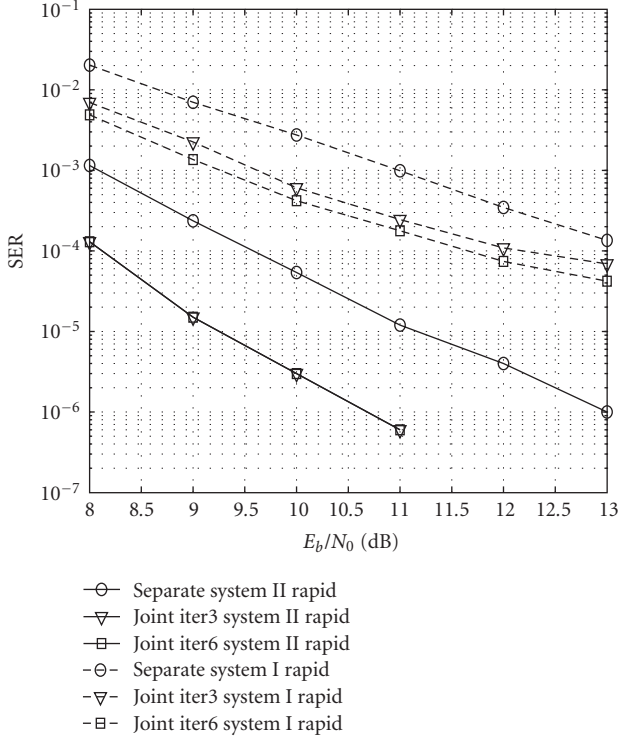


FIGURE 8: SER performance comparison between (C1+ST1) and (C2+ST2) over rapid fading channel.

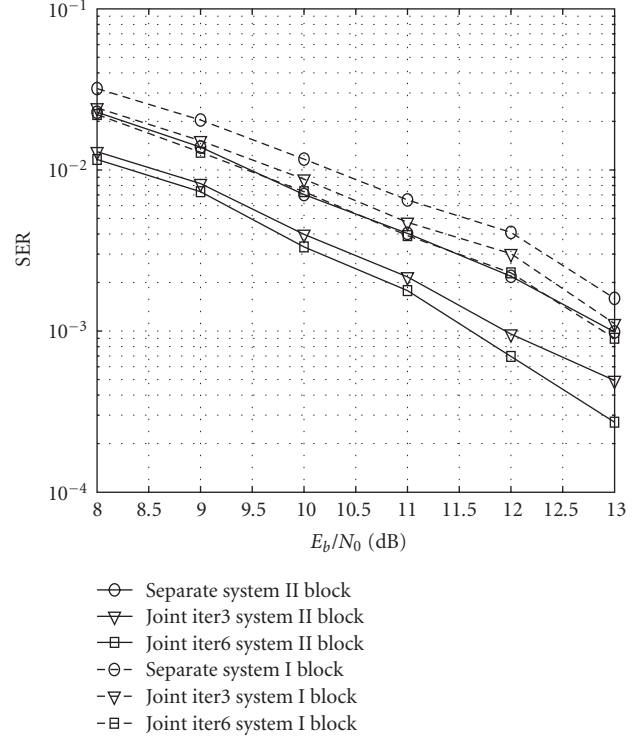


FIGURE 9: SER performance comparison between (C1+ST1) and (C2+ST2) over quasi static fading channel.

little improvement in case of $\rho = 1$ while iterative gain is still observed in case of $\rho = 0.95$. However, we also did simulations in case of $\rho \leq 0.65$ which means the channel estimation is very poor. We did not find much improvement using the iterative decoding. This is because at this situation, the estimation does not reflect correct information of the actual channel situation and the space time component decoder cannot work effectively to extract the correct information for the iterative utilization.

6. RATE ALLOCATION BETWEEN STTC AND VLEC

The frequency bandwidth resource available to a communication system is always limited, the overall effective data rate that can be transmitted from antennas is hence constrained. The power efficiency is measured by the energy required for transmitting one bit. When communicating at a rate of R with transmit power E , the power efficiency is defined as E/R . The overall effective data rate depends on both the modulation order of Rec-STTC and the average codeword length of VLEC. On one hand, for a source with given entropy H and a fixed power efficiency, the overall effective information rate is given by pH/\bar{l} . It increases with the modulation order p in Rec-STTC. However, the decoding performance decreases due to a smaller average Euclidean distance between each pair of signal points in the modulation constellation. On the other hand, VLEC with a larger average length \bar{l} helps to increase error resilience capability due to extra redundancy introduced.

However, this decoding performance is improved at the cost of data rate loss which needs to be compensated later, for example, by the increase of modulation order. As a result, one interesting question is that, given the overall effective information rate and transmit power, whether introducing more redundancy in VLEC or reducing the modulation order of Rec-STTC gives more performance improvement. This question is partially answered in the following simulation.

We study the iterative source space time decoding performance of two different concatenated systems. System I concatenates VLEC C1 with QPSK Rec-STTC ST1. System II concatenates VLEC C2 with 8PSK Rec-STTC code ST2. With the source entropy of 2.14, the average bit length for each source symbol of C1 and C2 equals to 2.46 and 3.61. The bandwidth efficiencies of QPSK and 8PSK equal to 2 bit/s/Hz and 3 bit/s/Hz. System II has a slightly higher overall effective information rate (1.7784 bit/s/Hz) than system I (1.7398 bit/s/Hz). By assigning unit power to each modulated symbol, system II also has a slightly higher power efficiency ($1/1.7784 = 0.5607/\text{bit}$) than system I ($1/1.7398 = 0.5748/\text{bit}$), which means that system II uses less average power to transmit one bit source information.

Figure 8 shows SER performance comparisons between system I and system II over rapid fading channels. The simulation system configuration is the same. System II outperforms system I almost 4 dB at SER of 7×10^{-5} . The performance comparison between system I and system II in quasi static channels shows a similar result, as in Figure 9.

Therefore, given the roughly same overall information rate and power efficiency, by allocating more redundancy in the source code, the joint source and space time decoding has more iterative decoding gain. However, it also needs to be noted that the better performance of system II is achieved at the cost of higher computation complexity because the number of the states in both VLEC trellis and STTC trellis increases. The complexity of system II is roughly 4 times in STTC decoder and 2 times in VLEC decoder compared with system I. Also, different from rapid fading channel, the quasi static channels provide no additional diversity gain. As a result, system II has a less performance gain over system I in quasi static fading channels.

7. CONCLUSIONS

In this paper, a joint decoder is proposed for serial concatenated source and space time code. VLEC and Rec-STTC are employed with redundancy in both codes. By iterative information exchange, the concatenation system achieves additional decoding gain without bandwidth expansion. Simulation shows that SER of joint decoding scheme is greatly reduced, compared to the separate decoding system in both quasi static and rapid fading channels. The proposed decoder is also shown to be effective with channel estimation errors. Finally, We find that given certain overall effective information rate and transmit power, introducing redundancy in source code can provide more decoding gain than reducing the bandwidth efficiency of STTC, though with increased decoding complexity.

REFERENCES

- [1] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," *IEEE Transactions on Information Theory*, vol. 44, no. 2, pp. 744–765, 1998.
- [2] V. Buttigieg and P. G. Farrell, "Variable-length error-correcting codes," *IEE Proceedings: Communications*, vol. 147, no. 4, pp. 211–215, 2000.
- [3] N. Demir and K. Sayood, "Joint source/channel coding for variable length codes," in *Proceedings of the Data Compression Conference (DCC '98)*, pp. 139–148, Snowbird, Utah, USA, March–April 1998.
- [4] K. P. Subbalakshmi and J. Vaisey, "Optimal decoding of entropy coded memoryless sources over binary symmetric channels," in *Proceedings of the Data Compression Conference (DCC '98)*, p. 573, Snowbird, Utah, USA, March–April 1998.
- [5] A. H. Murad and T. E. Fuja, "Joint source-channel decoding of variable-length encoded sources," in *Proceedings of the IEEE Information Theory Workshop (ITW '98)*, pp. 94–95, Killarney, Ireland, June 1998.
- [6] Q. Chen and K. P. Subbalakshmi, "An integrated joint source-channel decoder for MPEG-4 coded video," in *Proceedings of the 58th IEEE Vehicular Technology Conference (VTC '03)*, vol. 1, pp. 347–351, Orlando, Fla, USA, October 2003.
- [7] R. Bauer and J. Hagenauer, "On variable length codes for iterative source/channel decoding," in *Proceedings of the Data Compression Conference (DCC '01)*, pp. 273–282, Snowbird, Utah, USA, March 2001.
- [8] A. Hedayat and A. Nosratinia, "Performance analysis and design criteria for finite-alphabet source-channel codes," *IEEE Transactions on Communications*, vol. 52, no. 11, pp. 1872–1879, 2004.
- [9] S. X. Ng, J. Y. Chung, and L. Hanzo, "Turbo-detected unequal protection MPEG-4 wireless video telephony using multi-level coding, trellis coded modulation and space-time trellis coding," *IEE Proceedings: Communications*, vol. 152, no. 6, pp. 1116–1124, 2005.
- [10] S. X. Ng, J. Wang, L.-L. Yang, and L. Hanzo, "Variable length space time coded modulation," in *Proceedings of the 62nd IEEE Vehicular Technology Conference (VTC '05)*, pp. 1049–1053, Dallas, Tex, USA, September 2005.
- [11] S. X. Ng, J. Wang, M. Tao, L.-L. Yang, and L. Hanzo, "Iteratively decoded variable length space-time coded modulation: code construction and convergence analysis," *IEEE Transactions on Wireless Communications*, vol. 6, no. 5, pp. 1953–1962, 2007.
- [12] S. X. Ng, F. Guo, and L. Hanzo, "Iterative detection of diagonal block space time trellis codes, TCM and reversible variable length codes for transmission over Rayleigh fading channels," in *Proceedings of the 60th IEEE Vehicular Technology Conference (VTC '04)*, vol. 2, pp. 1348–1352, Los Angeles, Calif, USA, September 2004.
- [13] V. B. Balakirsky, "Joint source-channel coding with variable length codes," in *Proceedings of the IEEE International Symposium on Information Theory (ISIT '97)*, p. 419, Ulm, Germany, June–July 1997.
- [14] S. Benedetto and G. Montorsi, "Unveiling turbo codes: some results on parallel concatenated coding schemes," *IEEE Transactions on Information Theory*, vol. 42, no. 2, pp. 409–428, 1996.
- [15] D. Divsalar and F. Pollara, "Serial and hybrid concatenated codes with applications," in *Proceedings of the International Symposium on Turbo Codes*, pp. 80–87, Brest, France, September 1997.
- [16] D. Tujkovic, "Recursive space-time trellis codes for turbo coded modulation," in *Proceedings of the IEEE Global Communication Conference (GLOBECOM '00)*, vol. 2, pp. 1010–1015, San Francisco, Calif, USA, November–December 2000.
- [17] L. R. Bahl, J. Cocke, F. Jelinek, and J. Raviv, "Optimal decoding of linear codes for minimizing symbol error rate," *IEEE Transactions on Information Theory*, vol. 20, no. 2, pp. 284–287, 1974.
- [18] T. Okuda, E. Tanaka, and T. Kasai, "A method for the correction of garbled words based on the Levenshtein metric," *IEEE Transactions on Computers*, vol. 25, no. 2, pp. 172–178, 1976.