Layered MIMO Scheme with Antenna Grouping

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***Abstract*— In this paper we extend our previously proposed layered turbo coded multiple-input multiple-output (MIMO) scheme by introducing new techniques to improve the design of the transmitter and the receiver. These MIMO systems feature two antenna per layer with random antenna grouping, which reduces interference between layers. And multidimensional set partition is applied to encoder design to improve the coding gain. Based on these design techniques, the receiver only uses simple parallel interference cancellation (PIC) with spatial matched filtering (SMF) to separate the signals from different layers. It is shown that the performance of the proposed scheme is within 2 dB of outage capacity and is similar or better than other proposed MIMO schemes using more sophisticated interference suppression techniques.**

I. INTRODUCTION

Recent research in information theory has shown that large gains in capacity and reliability of communications over wireless channels are achievable by exploiting the spatial diversity made possible by multiple antennas at the transmitter and at the receiver. When the number of transmit antennas is large, the space-time trellis coding approach [1] is not applicable due to the high maximum likelihood (ML) decoding complexity. Alternatively, relatively simple space-time block codes (STBC) that achieve full diversity, can be designed utilizing either orthogonal [2] or quasi orthogonal [3] constructions. However, STBC's lack coding gain. Use of codes external to the STBC entail lower overall coding rates. Finally, a third approach is BLAST and its variations, where layered architectures with suboptimal suppression of the interference between layers are usually adopted [4]- [8], etc. BLAST schemes can achieve high data rates, but at the cost of rather complex processing for separation between layers.

Iterative co-antenna interference (interference between different transmit antennas) suppression schemes have been shown to improve the performance of BLAST schemes [6]- [8] compared to non-iterative interference rejection [4] [5]. The penalty is an increase in complexity. Iterative MIMO schemes with good performance appearing in the literature often use either optimum maximum likelihood detection or near optimum spatial separation schemes such as based on minimum mean-square error (MMSE). For example, the turbo-greedy algorithm [8] achieves near capacity performance utilizing ML spatial processing. In another example [7], the decoder supplies soft estimates of the transmitted symbols for co-antenna interference cancellation and for instantaneous MMSE residual interference suppression.

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All aforementioned iterative schemes separate the MIMO channel that consists of n_T inputs and n_R outputs (n_TTn_RR) channel into n_T parallel 1Tn_RR sub-channels. Alternatively, if antennas at the transmitter are grouped such that the MIMO channel is separated into $n_T/2$ (rather than n_T) parallel sub-channels, simple spatial matched filtering (SMF) (rather than adaptive techniques) in conjunction with parallel interference cancellation (PIC) can achieve good performance. Utilizing this approach, a layered MIMO scheme was presented in [9], referred to as *layered turbo space-time coding* (LTST). LTST is an extension of our previous work on turbo space-time codes (turbo-STC) [10], [11]. In this paper we further extend the scheme in [9] by introducing random antenna grouping and multidimensional set partition techniques.

With LTST, the turbo-STC codeword is separated into $n_T/2$ streams and transmitted simultaneously through groups of two antennas. The advantage of doing so is that at the receiver there are fewer layers to separate and that each layer is corrupted only by (n_T-2) interference sources rather than (n_T-1) in the single antenna per layer case. To make up for this loss of performance, single antenna per layer schemes need to employ sophisticated co-antenna interference suppression techniques. We will show that while the complexity of most single antenna per layer signal separation schemes such as [7] and [8], is polynomial in n_T, the signal separation in LTST is linear with n_T.

The dominant error events for layered systems are caused by the channel gain matrix for one layer being nearly "parallel" (opposite to orthogonal) to that of other layer(s). To improve the performance we apply random antenna grouping to form layers. So if for some combination of antennas the layers are nearly parallel, for some other combinations they may not.

Since LTST works at low SNR ($\leq$ 10 dB), the code design criterion is maximizing the minimum Euclidean distance between codewords [12]. According to this design criterion, we apply the multidimensional set partition techniques to design the component codes of the turbo encoder.

The rest of this paper is organized as follows. In Section II we introduce the LTST scheme. The algorithm for iterative interference cancellation and decoding is presented in Section III, together with encoder design considerations. Simulation results are presented in Section IV. Section V draws the conclusions.

II. System Model

Consider a MIMO communication system with n_T transmit and n_R receive antennas (n_TTn_RR) operating over a flat, Rayleigh block fading channel. The output of this MIMO channel is represented by $n_T \times 1$ vectors $\mathbf{r}_t \in C^{n_R}$ that can be expressed

$$\mathbf{r}_t = \mathbf{H}\mathbf{c}_t + \eta_t, \tag{1}$$

where $\mathbf{c}_t$ is $n_T \times 1$ vector of transmitted symbols whose energies are $\mathcal{E}_s$, and the $n_R \times n_T$ matrix $\mathbf{H}$ consists of the channel coefficients. The (i, j) element of $\mathbf{H}$ represents the path gain from transmit antenna j to receive antenna i. The matrix $\mathbf{H}$ consists of complex-valued scalars h_{ij} modeled as zero-mean, mutually independent, identically distributed Gaussian random variables with unit variance. The $n_T \times 1$ vector $\mathbf{c}_t$ contains the symbols transmitted at time t. The noise term η_t is modeled by zero-mean, additive white Gaussian noise (AWGN) with variance $N_0/2$ per dimension.

The proposed LTST structure is shown in Fig. 1 with the top part showing the transmitter. The information data is encoded by a symbol-wise, parallel concatenated space-time turbo encoder, which we will discuss in more details later in section III-C. Briefly, this is a systematic turbo encoder, which generates a codeword matrix that consists of two rows, with each row transmitted through an antenna. One row of the codeword matrix contains systematic symbols, while the other carries the corresponding parity symbols. With this arrangement, the signals received from the two transmit antenna are treated as a single entity and do not need to be separated. The codeword is interleaved *pair-wise* such that columns of the codeword matrix are preserved. This ensures that the codeword symbols associated with each trellis branch (in our schemes one systematic symbol and its corresponding parity symbol) are transmitted in the same time slot. The function of the interleaver is to decorrelate adjacent codeword symbols and avoid possible burst errors after interference cancellation at the receiver. Following interleaving, the two-row codeword is separated into several substreams, which are modulated and transmitted from groups of two antennas. The substream of the signals transmitted from each antenna group is referred to as a *layer*.

The receiver is shown in Fig. 1-b. First, the signals received from different layers are separated by cancelling the estimated signals from other layers (regarded as interference). Then, the separated signals of each layer are re-assembled, de-interleaved to the original order, and passed to the maximum *a posteriori* (MAP) decoders. Soft decisions computed by the decoders are fed back to improve interference cancellation, and the two decoders exchange extrinsic information as in an ordinary turbo decoder. This process repeats for several iterations. The algorithm used at the receiver will be described and analyzed in the next section. The data rate of the proposed scheme is $rn_T \log_2 q$ bits/s/Hz, where q is the cardinality of the symbol constellation and r is the rate of the turbo encoder.

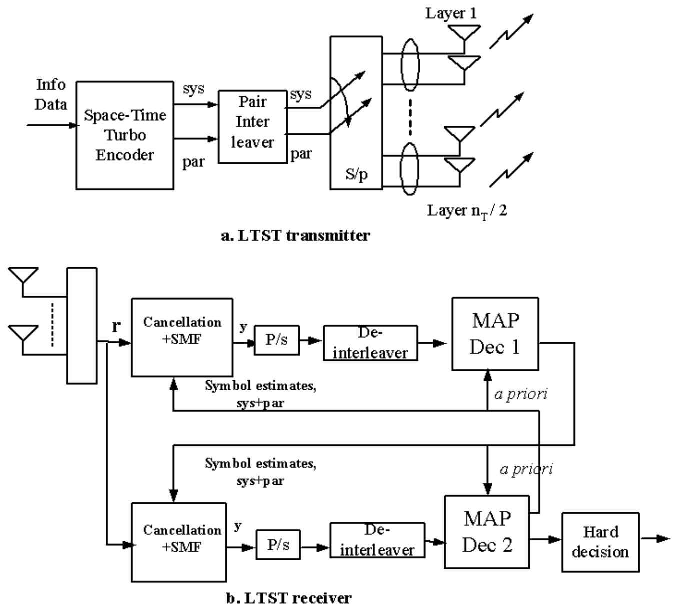

Fig. 1. Structure of the LTST transceiver.

III. LTST Transmitter and Receiver Design

A. Encoder Design

In this subsection we discuss the design considerations of the LTST encoder. It was proved in [12] that the design criterion for space-time codes which work at low SNR is to maximize the minimum Euclidean distance between codewords, the same design criterion as the one for traditional one dimensional trellis coded modulation. This motivates us to use multidimensional trellis coded modulation/set partition techniques [13] [14] to design space-time codes. In particular, consider the set partition for multidimensional phase modulation proposed in [14]. The resultant encoder will not be systematic, and consequently can not be used in a turbo (parallel concatenated) space-time code. We suggest an encoder structure with a new set partition shown in Fig. 2, such that each component encoder is systematic and at the same time ensures that the distance between branches departing and entering the same state in the trellis is at least twice as large as the minimum distance between modulation points, as it does in ordinary set partition. The component convolutional encoder is hand-picked and not guaranteed to be optimal.

B. Decoder

The turbo decoder used in our scheme is similar to the log-MAP decoder for turbo-STC [11]. Similar to turbo-STC, it is necessary to compute *a posteriori probabilities* (APP's) for both the systematic and parity symbols of a codeword. Given the observations for the entire codeword, the log-MAP decoder outputs a set of APP's for each codeword symbol $c_{t,i}$, $i = 1, ..., n_T$, $t = 1, ..., N$, where N is the codeword length or *frame* length. Denote the APP's for $c_{t,i}$ as $P_j = P(c_{t,i} = s_j|$ observations), $j = 1, ..., q$, where $\{s_j,\ j = 1, ..., q\}$ is the

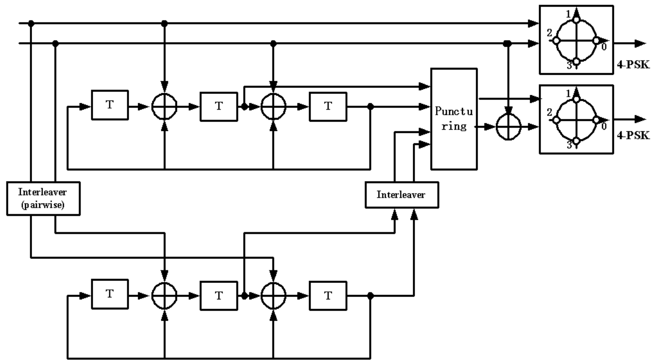

Fig. 2. Structure of the LTST encoder with 2×4PSK set partition.

modulation constellation set. The expected value of symbol $\widetilde{c}_{t,i}$

$$\widetilde{c}_{t,i} = \sum_{j=1}^{q} s_j P_j \tag{2}$$

is used in the co-antenna interference cancellation process as explained below. In the first iteration, when no estimate from the decoder is available, $\{\widetilde{c}_{t,i},\, t = 1, ..., N,\, i = 1, ..., n_T\}$ are set to zero.

C. Interference Cancellation

In LTST, the signals from different layers are separated by cancelling estimated signals from other layers. Essentially, we break up the n_TTn_RR channel into $n_T/2$ parallel 2Tn_RR sub-channels. Suppose the desired signal is supplied by the layer with index i. To simplify notation, we drop the time index t. Also, in the following discussion, we use subscript $\bar{i}$ to denote signals associated with all layers *other* than i. Then (1) can be rewritten as

$$\mathbf{r} = \mathbf{H}_i \mathbf{c}_i + \mathbf{H}_{\bar{i}} \mathbf{c}_{\bar{i}} + \eta, \tag{3}$$

where $\mathbf{H}_i$ is the channel matrix for layer i, an $n_R \times 2$ matrix composed of the two columns of $\mathbf{H}$ pertaining to layer i, and $\mathbf{H}_{\bar{i}}$ is the $n_R \times (n_T - 2)$ matrix that is made up of the rest of the columns of $\mathbf{H}$; $\mathbf{c}_i$ is the 2×1 vector of symbols of layer i, and $\mathbf{c}_{\bar{i}}$ is the $(n_T - 2) \times 1$ vector of symbols from other layers. Denote $\widetilde{\mathbf{c}}_{\bar{i}}$ an estimate of $\mathbf{c}_{\bar{i}}$ computed from (2). Interference cancellation is achieved by subtracting from the received vector $\mathbf{r}$ the estimated contribution of the interference $\mathbf{H}_{\bar{i}}\widetilde{\mathbf{c}}_{\bar{i}}$

$$\begin{aligned} \mathbf{y}_i &= \mathbf{r} - \mathbf{H}_{\bar{i}}\widetilde{\mathbf{c}}_{\bar{i}} \\ &= \mathbf{H}_i \mathbf{c}_i + \mathbf{H}_{\bar{i}}(\mathbf{c}_{\bar{i}} - \widetilde{\mathbf{c}}_{\bar{i}}) + \eta \\ &= \mathbf{H}_i \mathbf{c}_i + \mathbf{H}_{\bar{i}}\mathbf{e}_{\bar{i}} + \eta, \end{aligned} \tag{4}$$

where $\mathbf{y}_i$ is the signal from layer i cleaned of interference, and $\mathbf{e}_{\bar{i}} \triangleq (\mathbf{c}_{\bar{i}} - \widetilde{\mathbf{c}}_{\bar{i}})$ is decision feedback error. From (4), we can see that each layer is a 2Tn_RR MIMO channel with interference. Let

$$\begin{aligned} \mathbf{R}_i &\triangleq E[(\mathbf{H}_{\bar{i}}\mathbf{e}_{\bar{i}} + \eta)(\mathbf{H}_{\bar{i}}\mathbf{e}_{\bar{i}} + \eta)^\dagger] \\ &= \rho \mathcal{E}_s \mathbf{H}_{\bar{i}} \mathbf{H}_{\bar{i}}^\dagger + N_0 \mathbf{I}, \end{aligned} \tag{5}$$

be the correlation matrix of the residual interference plus noise, where the superscript denotes complex conjugate transpose. The relative strength of the interference term is given by the normalized mean square error of the decisions feedback $\rho \triangleq E(|e_{\bar{i},l}|^2)/\mathcal{E}_s$, where $e_{\bar{i},l}$, $l = 1, ..., n_T - 2$, is an element of the vector $\mathbf{e}_{\bar{i}}$. Then the optimum branch metric used in the decoder is

$$\gamma(\mathbf{y}_i, \mathbf{x}_i) = (\mathbf{y}_i - \mathbf{H}_i \mathbf{x}_i)^\dagger \mathbf{R}_i^{-1} (\mathbf{y}_i - \mathbf{H}_i \mathbf{x}_i), \tag{6}$$

where $\mathbf{x}_i$ are the symbols to be tested.

The disadvantage of using (6) as a branch metric lies wherein the high complexity of inverting the matrix $\mathbf{R}_i$, whose dimensions are $n_R \times n_R$. LTST takes a much simpler approach of spatial matched filtering (SMF). Simulation results in section IV demonstrate that in spite of the suboptimal spatial interference suppression, LTST achieves performance close to capacity. Following, SMF, the desired signal for layer i is:

$$\begin{aligned} \widetilde{\mathbf{y}}_i &= \mathbf{H}_i^\dagger \mathbf{y}_i \\ &= \mathbf{H}_i^\dagger \mathbf{H}_i \mathbf{c}_i + \mathbf{H}_i^\dagger \mathbf{H}_{\bar{i}} \mathbf{e}_{\bar{i}} + \mathbf{H}_i^\dagger \eta \\ &= \mathbf{A}_i \mathbf{c}_i + \mathbf{B}_i \mathbf{e}_{\bar{i}} + \mathbf{H}_i^\dagger \eta \\ &= \mathbf{A}_i \mathbf{c}_i + \mathbf{v}_i + \mathbf{z}_i, \end{aligned} \tag{7}$$

where $\mathbf{A}_i \triangleq \mathbf{H}_i^\dagger \mathbf{H}_i$ is a 2×2 matrix; $\mathbf{B}_i \triangleq \mathbf{H}_i^\dagger \mathbf{H}_{\bar{i}}$ is a $2 \times (n_T - 2)$ matrix; $\mathbf{v}_i \triangleq \mathbf{B}_i \mathbf{e}_{\bar{i}}$ and $\mathbf{z}_i \triangleq \mathbf{H}_i^\dagger \eta$ are respectively, 2×1 vectors of the residual interference and noise term post SMF. It is noted that (7) is now an equivalent 2T2R channel model.

Assuming residual interference plus noise, $\mathbf{v}_i + \mathbf{z}_i$, to be AWGN, we use in LTST decoder the following sub-optimum branch metric

$$\gamma(\mathbf{y}_i, \mathbf{x}_i) = (N_0')^{-1} (\mathbf{y}_i - \mathbf{H}_i \mathbf{x}_i)^\dagger \mathbf{H}_i \mathbf{H}_i^\dagger (\mathbf{y}_i - \mathbf{H}_i \mathbf{x}_i), \tag{8}$$

where N_0' is the variance of the elements of the vector $\mathbf{v}_i + \mathbf{z}_i$.The variance of interference plus noise N_0' is needed in (8) for incorporation of the *a priori* information in the MAP decoding, and is computed as

$$\begin{aligned} N_0' &= E[(\mathbf{v}_i + \mathbf{z}_i)(\mathbf{v}_i + \mathbf{z}_i)^\dagger] \\ &= \frac{1}{2}\left(\rho \mathcal{E}_s \cdot \mathrm{tr}(\mathbf{B}_i \mathbf{B}_i^\dagger) + N_0 \cdot \mathrm{tr}(\mathbf{A}_i)\right), \end{aligned} \tag{9}$$

where $\mathrm{tr}(\cdot)$ is the trace operation.

D. Random Antenna Grouping

When the channel gain matrix of one layer is almost "parallel" to that of the other layer(s), the interference between layers will be strong. Consider the SMF used in (7). When the channel gain matrix of $\mathbf{H}_i$ for layer i is orthogonal to $\mathbf{H}_{\bar{i}}$, or $||\mathbf{H}_i^\dagger \mathbf{H}_{\bar{i}}||^2 = 0$, there will be no interference from other layers at all. The notation $||\cdot||^2$ represents the Frobenius norm. Conversely, if for some channel realizations $||\mathbf{H}_i^\dagger \mathbf{H}_{\bar{i}}||^2$ is large, the interference from other layers will be strong. To improve the system performance in these cases, we can alternatively change the combination of antennas in each layer during the transmission, which we refer to as random antenna grouping.

We will use a 4T4R system as an example. Let $\mathbf{H} = [\mathbf{h}_1\ \mathbf{h}_2\ \mathbf{h}_3\ \mathbf{h}_4]$ where $\mathbf{h}_i,\ i = 1, ..., 4$ are columns of $\mathbf{H}$. The combination of antennas in each layer, as it evolves with time, is illustrated in Table I. As a result of random antenna grouping, if at some time interval $||\mathbf{H}_i^\dagger \mathbf{H}_{\bar{i}}||^2$ is large, it is possible that at another time interval with another combination, $||\mathbf{H}_i^\dagger \mathbf{H}_{\bar{i}}||^2$ is small.

TABLE I

EXAMPLE OF RANDOM ANTENNA GROUPING.

time	layer 1	layer 2	H_1	H_2
1	ant 1,2	ant 3,4	h_1h_2	h_3h_4
2	1,3	2,4	h_1h_3	h_2h_4
3	1,4	2,3	h_1h_4	h_2h_3
4	1,2	3,4	h_1h_2	h_3h_4
...	...	...	...	...

E. Complexity Analysis

We now compare the complexity of LTST with that of other MIMO schemes with similar performance. The complexity of interference subtraction and SMF is only $O(n_T)$. Typically, the complexity of the LTST receiver is dominated by the turbo decoder whose log-MAP decoding has a complexity of $O(\nu 2^{\log q})$, where ν is the number of states of the convolutional encoder and q is the modulation size. In contrast, the complexity of ML spatial demodulation is $O(\exp(n_T))$ and that of its simplified version, the turbo-greedy algorithm, is less than $O(\exp(n_T))$, but higher than $O(n_T^4)$ [8]. As another point of comparison, the complexity of the threaded space-time (TST) scheme [7] with MMSE interference suppression is $O(n_T^4)$. Thus for $n_T = 4$, $q = 4$, $\nu = 8$, the complexity of LTST is $O(32)$ compared to $O(256)$ for turbo-greedy and MMSE interference suppression.

IV. SIMULATION RESULTS

Numerical results for the proposed LTST scheme are presented for 4T4R and for 8T8R configurations. For 4-PSK modulation, the data rate for the 4T4R system is 4 bits/s/Hz, and for the 8T8R system it is 8 bits/s/Hz. Both systems are full rate. The channel is assumed to be constant over blocks of 130 channel uses. Consequently, the frame length for 4T4R system is 260 symbols (130 channel uses $\times$ 2 layers), and for the 8T8R system is 520 symbols. The SNR is defined $n_T \mathcal{E}_s / N_0$, i.e., the ratio of the total transmitted power to the noise power.

To determine the number of iterations, a simple stop criterion is used in LTST, where the iterations stops whenever two successive iterations yield the same hard decision. For all the LTST simulation results presented below, the average number of iterations varied from 3 to 5. Numerical results shown for TST and turbo greedy are lifted from [7] and [8], respectively.

Fig. 3 shows the frame error rate (FER) for 4T4R systems. It can be observed that LTST, TST, and turbo-greedy curves are approximately parallel indicating the same space-diversity gain. LTST outperforms turbo-greedy coding by 0.5 dB and outperforms TST by approximately 1.3 dB. It can also be observed that the performances of both LTST and turbo-greedy

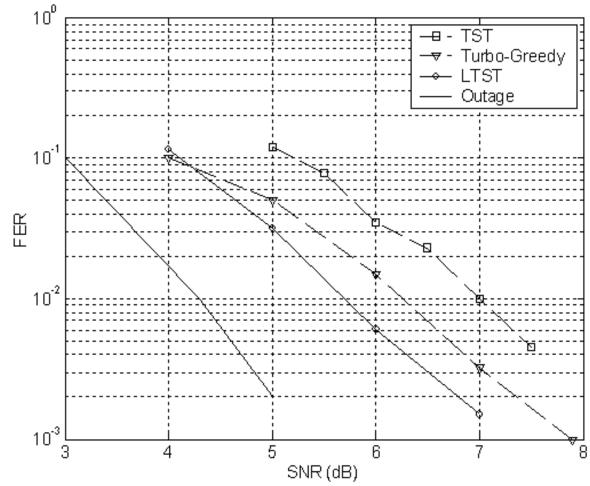

Fig. 3. FER comparison of LTST and other schemes, 4T4R, 4b/s/Hz.

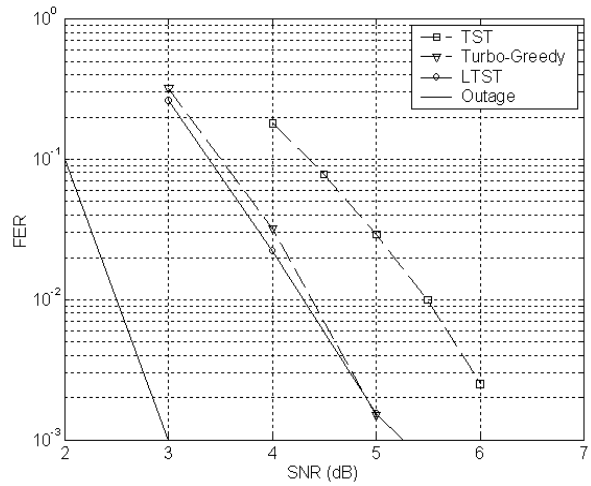

Fig. 4. FER comparison of LTST and other schemes, 8T8R, 8b/s/Hz.

are within 2 dB range of the outage probability. Fig. 4 shows the FER comparison for 8T8R systems. It can be observed that LTST and turbo-greedy coding have similar performance and outperform TST by about 1 dB.

V. CONCLUSION

We presented the method to design a type of simple but efficient iterative MIMO systems. First, two antennas per layer structure is adopted to reduce the number of interferer for each layer. And random antenna grouping is applied to further reduce the interference between layers. To maximize the coding gain, multidimensional set partition is applied to design the encoder. With this design, the resultant LTST scheme avoids high complexity signal separation algorithms such as MMSE and ML, by performing only simple parallel interference cancellation in conjunction with turbo coding. It is shown that LTST achieves performance within 2 dB of outage capacity, but with significantly less complexity than other MIMO schemes with similar performance.

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