Interleaving Gains for Receive Diversity Schemes of Distributed Turbo Codes in Wireless Half–Duplex Relay Channels

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Abstract. *This paper proposes the interleaving gain in two different distributed turbo-coding schemes: Distributed Turbo Codes (DTC) and Distributed Multiple Turbo Codes (DMTC) for half-duplex relay system as an extension of our previous work on turbo coding interleaver design for direct communication channel. For these schemes with half-duplex constraint, the source node transmits its information with the parity bit sequence(s) to both the relay and the destination nodes during the first phase. The relay received the data from the source and process it by using decode and forward protocol. For the second transmission period, the decoded systematic data at relay is interleaved and re-encoded by a Recursive Systematic Convolutional (RSC) encoder and forwarded to the destination. At destination node, signals received from the source and relay nodes are processed by using turbo log-MAP iterative decoding for retrieving the original information bits. We demonstrate via simulations that the interleaving gain has a large effect with DTC scheme when we use only one RSC encoder at both the source and relay with best performance when using Modified Matched S-Random (MMSR) interleaver. Furthermore, by designing a Chaotic Pseudo Random Interleaver (CPRI) as an outer interleaver at the source node instead of classical interleavers, our scheme can add more secure channel conditions.*

Keywords

Chaotic, interleaver, semi-random, turbo-codes, relay channel

1. Introduction

Radio-wave propagation through wireless channels is a complicated phenomenon characterized by various effects, such as multipath and shadowing. Diversity techniques offer an effective countermeasure against multipath fading by providing the receiver with different versions of the data-bearing signal transmitted over channels with independent channel gains [1]. User-Cooperation is possible whenever the number of communicating terminals exceeds two. Therefore, a three-terminal channel is a fundamental unit in the cooperation communication. Indeed, a vast portion of the research effort has been devoted to the relay channel. The notion of relay channel, proposed by Van der Meulen [2], is a channel with three terminal nodes: source node, relay node and destination node. Cooperative relay channel communications have recently emerged to provide diversity gains or enhance the capacity of wireless systems in faded wireless links without deploying multiple antennas at the transmitter through the use of relay nodes [3]. Cover and El Gamal [4] produced the fundamental cooperative strategies and capacity bounds for Additive White Gaussian Noise (AWGN) single-relay channels, for deterministic relay channels as well as relay channels with feedback. Furthermore, in distributed turbo codes [5], the encoding operations for channel coding are distributed among cooperating nodes; which provides a combined diversity and coding gain.

There are many fundamental relay protocols based on which the source and relay nodes can share their resources to achieve the combination between the cooperative diversity and the highest coding gain for any known coding scheme. One strategy is when a message is broadcast by the source and received simultaneously by the destination as well as relay. Once the relay has received the message, it may then forward the information to the destination with or without re-encoding it again. The destination can combine the information received from both the source and the relay. The decode-and-forward protocol is close to optimal when the source-relay channel is excellent, which practically happens when the source and relay are physically near each other. When the source-relay channel becomes perfect, the relay channel becomes a 2×1 multiple-antenna system. Various practical schemes have been proposed to exploit the benefits of cooperation among nodes [6], [7].

In this paper, we consider turbo codes [8], [9] in a half-duplex decode-and forward relaying system. The system operates in a time-division manner. In the first time-slot of the transmission, only the source sends a coded packet representing N message bits. This transmission is received by both the relay and the destination terminals. After decoding, interleaving and re-encoding, the relay node transmits its own codeword to the destination node in the second time slot. Therefore, the destination considered to operate similar to receiver selection diversity scenario. It receives two noisy observation sequences which are sent from the source and the relay. Different channels are considered, including the Rayleigh-fading channel and the AWGN channel. Large amount of research work has been done on theoretical protocols and practical strategies of various system and network models to study and improve the reliability and efficiency of relay systems. Despite that the distributed coding principles are applied to a half-duplex relay systems in [10], [11], our approach in this paper is different in that our proposed schemes depend mainly on improving the system performance gain due to the relay construction using good interleaver design at the relay node in order to achieve a better system performance.

For this purpose, we first introduce the use of Modified Block S-Random (MBSR) and MMSR interleavers in [12] compared with practical and random interleavers [13], [14] to show the interleaving effect on both Distributed Turbo Codes (DTC) and Distributed Multiple Turbo Codes (DMTC) schemes. Secondly, we have conducted a series of numerical simulations to study the effect of using MBSR and MMSR interleavers at the relay comparing our results with using different other interleavers. From our results, we showed that the interleaving gain at the relay has a better effect on the DTC scheme with best performance giving by MMSR interleaver while for the DMTC scheme; there is no interleaving gain and the performance nearly the same. Then, we present the design of CPRI and use it as an output interleaver at the source node. As its output changes with any very small shift in its initial condition, this interleaver can give some security to the data.

The remainder of this paper is organized as follows. In Sec. 2 the system model is introduced. In Sec. 3 and 4, the detailed analysis of the DTC and DMTC schemes are provided respectively. In Sec. 5, the CPRI and its design with the cooperative turbo schemes is introduced. Simulation and performance evaluation of the proposed schemes are explored in Sec. 6. Finally, conclusions are made in Sec. 7.

2. The System Description

The relay system shown in Fig. 1 consists of three nodes: a source node S, a relay node R, and a destination node D. This system has three directed transmission links: the links from source to destination, source to relay, and a relay to destination link. We suppose that all the channel links in Fig. 1 are with independent fading on all three links, and their average signal-to-noise ratio (SNR) are denoted by γ, γ_{SR} and γ_{RD}, respectively. With $\gamma_{SR} = g_{SR}\gamma$ and $\gamma_{RD} = g_{RD}\gamma$ where g_{SR} and g_{RD} are the source-relay and relay-destination channels gain respectively. Typically, the source to relay and the relay to destination links have a larger SNR than the direct link, i.e., $g_{SR} \geq 1$ and $g_{RD} \geq 1$, where the gains may be due to shorter transmitter-receiver separation. The overall SNR is defined by the SNR of the source to destination link, i.e., by γ.

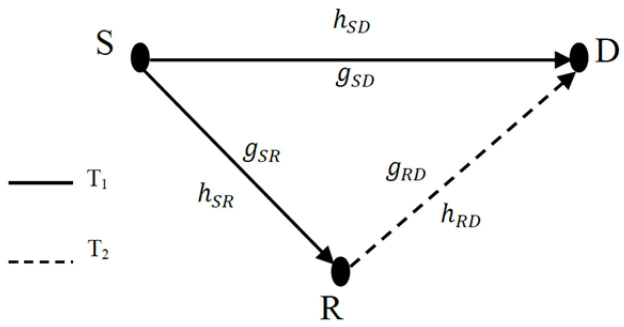

Fig. 1. The relay channel system.

Two phases are required to complete the transmission, during the first phase; the source broadcasts its information to both relay and destination.

In the second phase, the relay processes the received data from the source by using decode and forward protocol and after interleaving it transmits its parity sequence generated from the processed data to destination while the source is in silent mode during this phase. The system is a time division process, in the first time slot (T_1); the received signal z at the relay node is given by.

$$z = \sqrt{g_{SR}}\, h_{SR}\, x_S + n_{SR} \tag{1}$$

where x_S is the symbol transmitted from the source with power P_S during the first slot, n_{SR} is the AWGN term, and h_{SR} is the source-relay channel coefficient. When an AWGN channel is considered, $h_{SR} = 1$. On the other hand, when a Rayleigh fading channel is considered, h_{SR} is a zero-mean complex Gaussian random variable with unit variance, and n_{SR} is also a zero-mean complex Gaussian random variable with variance of $N_0/2$ per dimension. In the second time slot (T_2), after decoding the source signal x_S the relay recodes its interleaved sequence and transmits it to destination node. The received signal at the destination node during the first and second time slots is given by:

$$y = r_{SD} + r_{RD} = h_{SD}x_S + \sqrt{g_{RD}}\, h_{RD}\, x_R + n \tag{2}$$

where x_S and x_R are the symbols transmitted from the source and relay nodes, respectively, both with the power P_S. The S-D and R-D channel coefficients are unity for an AWGN channel, or zero-mean complex Gaussian fading coefficients with unit variance for a Rayleigh fading channel. The noise n has the same distribution as n_{SR}.

3. DTC Scheme Based on Interleaving Gain at Relay Node

3.1 Interleaver Design

Interleaver design of turbo codes depends on different factors such as the SNR and the used frame length N. Turbo code interleaver types fall into two main classes: Random interleavers and Deterministic interleavers. The random interleaver in turbo codes performs reasonable for long block sizes. However, for short block size, the performance of turbo codes with a random interleaver degrades substantially even it performs worse than that of convolutional codes with similar computational complexity. In the case of the SNR factor, for low SNR values, any interleaver works conveniently as long as it guarantees that the two inputs of RSC encoders are sufficiently uncorrelated. On another hand, numbers of interleaver structures have been designed at moderate to high SNR, where the code performance depends on both the interleaver structure and size.

3.2 Modified Block S-Random (MBSR) Interleaver

The block interleaver defined by a matrix with k rows and 1 columns with $\mathbf{N} = \mathbf{k} \times \mathbf{1}$ can break bad low-weight input sequences, as it is limited with one row. Nevertheless, it fails to break many combined lower-weight sequences that appears in several consecutive rows. To solve such problem, MBSR interleaver [12] designed to combine both columns and rows reordering technique with S-random interleaving constraint (spreads elements positions such that any two elements within a window of size S will not be located in a window of size S in the interleaved sequence). This algorithm increases the interleaver ability to break input bad sequences. MBSR interleaver is an improved version of the block interleaver as it can combine the characteristics of block interleaver with that of S-random interleaver.

3.3 Modified Matched S-Random (MMSR) Interleaver

An interleaver can be designed to break low weight input sequence patterns, which produce low weight parity-check sequences at the output of one of the constituent RSC encoders, so that the input sequences to the other constituent encoder will generate high weight parity-check sequences. The MMSR interleaver design [12] combines both S-Random constraint and matched interleavers [13]. In the MMSR interleaver, the designed algorithm depends mainly on removing bad low weight-2, weight-3 and weight-4 input sequences that have significant contribution to the error performance with less complexity.

3.4 DTC Scheme

The major difference between distributed coding and conventional channel coding schemes is that in distributed coding; the overall codeword is constructed in a distributed manner, [5], [11], and [15]. That is, different parts of the codeword in distributed coding are transmitted by different nodes through independent wireless links. This creates additional degrees of freedom, but also poses challenges in code construction. Fig. 2 shows the block diagram of a DTC system, where m is the message vector of length N, $\tilde{m}$ is the decoded message at the relay, $\mathbf{P}_1$, $\mathbf{P}_2$ are the parity vectors of length N at the source and relay, respectively, and π is the used interleaver (MBSR , MMSR) of length N. In a DTC scheme, two RSC encoders are used at the source node and the relay node.

The source broadcasts the coded signals by the first RSC1 to both the destination and relay. The relay decodes the received signals, interleaves and re-encodes them using

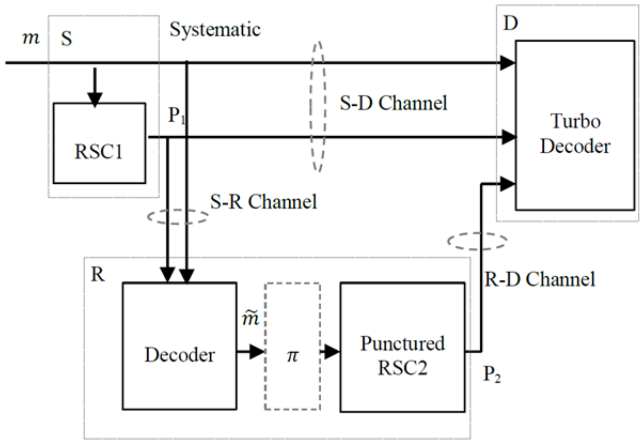

Fig. 2. The proposed DTC scheme with an interleaver at the relay node.

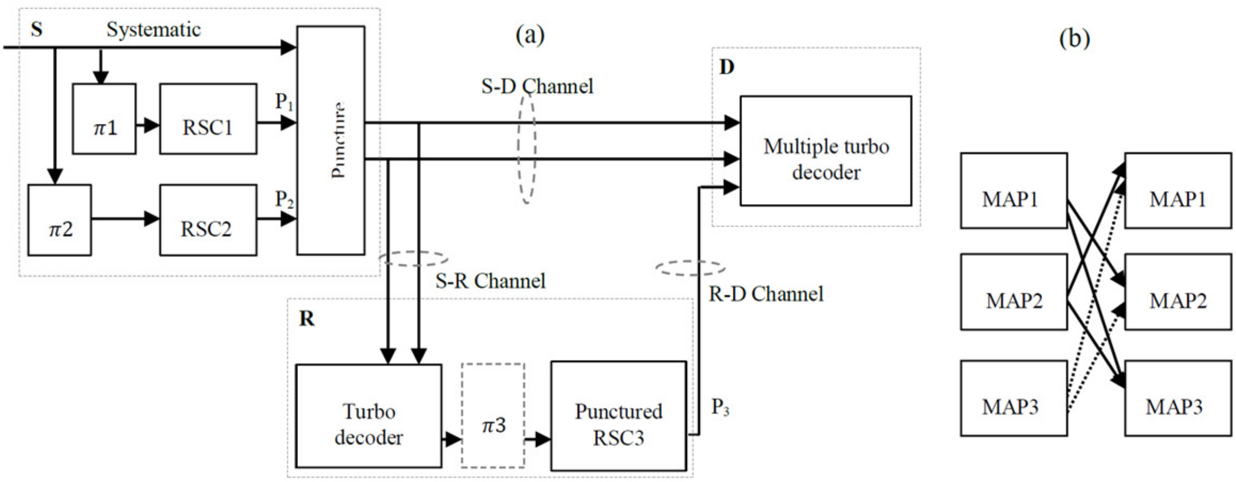

Fig. 3. DMTC scheme with an interleaver at the relay node: (a) DMTC scheme and (b) parallel concatenated decoder.

punctured RSC2 as shown in Fig. 2. The designed MMSR and MBSR interleavers will be used at the relay and compared with other interleavers to measure the effect of better interleaver gain on the system performance. The destination receives two noisy observation sequences consisting of a coded signal transmitted from the source and the second parity transmitted from the relay. Although the source to destination link rate is (1/2), the overall system rate from the destination point of view is $R_{overall} = 1/3$.

As mentioned earlier, the overall average SNR is defined by that of the source to the destination link, given by γ. Also we assume that the relay is located close to the destination node with relay to destination link gain $g_{RD} = 1$ dB. After decoding, the relay can transmit the received data with little power which may add additional diversity to the destination. The overall system is thus similar to an ideal receiver diversity system.

4. DMTC Scheme

Here in this scheme turbo code is used at the source which consists of two simple constituent RSC1 and RSC2 encoders. The first RSC1 encoder is with a direct interleaver ($\pi 1$) hence the second RSC2 encoder is with a random interleaver ($\pi 2$), both with length N as shown in Fig. 3(a). The source node transmits punctured coded symbols to both the relay and the destination nodes during the first transmission period. The relay first performs parallel concatenated turbo decoding to decode the source signal. Then after using the interleaver $\pi 3$ (MBSR, MMSR) of length N, relay re-encodes the interleaved information bits using a RSC3 code during the second transmission period.

The resultant symbols transmitted from the source and relay nodes can be viewed as the coded symbols of a three component parallel concatenated encoder. Thus, at the destination, the punctured turbo code is equipped with more parity bits. The destination decoder now receives two noisy, faded versions of the parallel concatenation of three recursive binary convolutional encoders [16] with different interleaver effects. Fig. 3 depicts the system diagram for the proposed DMTC scheme [17], [18]. Iterative decoding at the destination involves three MAP decoders, with extrinsic information exchange between modules in the manner of multiple-turbo decoder.

As shown in Fig. 3(b) in the extrinsic output of each MAP decoder is fed to the two other MAP decoders. In the first time slot, the received source-destination outputs feed the first and second MAP decoders and the extrinsic output of the MAP1 will feed as a priori input to MAP2 and MAP3, while the extrinsic output of the MAP2 feed as a priori input to MAP1 and MAP3. In the second time slot, the received relay-destination output feed the third MAP3 decoders and its extrinsic output feed as a priori input to MAP1 and MAP2.

5. DTC Scheme with CPRI

The interleaver used in turbo codes depends mainly in two parameters: the interleaver spreading property which is the distance between adjacent bits before interleaving, and the randomness property that provides a non-fixed indexing function which is a good factor for correction in the iterative decoding. It has been found for Turbo-codes that interleavers with some randomness tend to perform better than completely structured interleavers in waterfall region.

Many algorithms build better interleavers intended to efficiently exploit the characteristics of the typical error loops [19]. The description and designing criteria of CPRI whose indexing function follows the chaotic logistic-map behavior will be explained later in this section. In this scheme, another gain of the interleaver can be achieved. A secured DTC scheme based on CPRI is proposed by using CPRI as an outer interleaver at the source and MMSR interleaver at the relay as shown in Fig. 4. In this scheme, the output of the CPRI is controlled by the logistic map initial conditions (secret key); therefore the function of information encryption can be achieved.

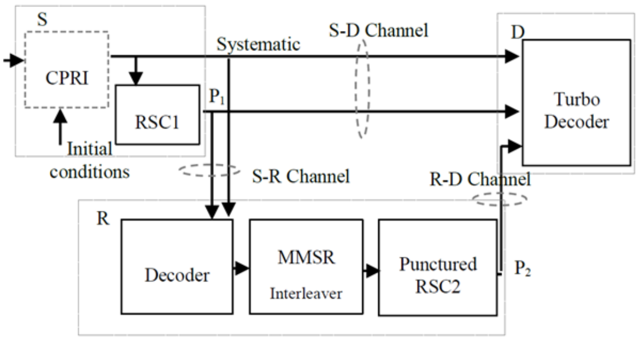

Fig. 4. DTC scheme with CPRI at the source and MMSRI at the relay.

The function of CPRI is to discompose the data in the range of different turbo frames before RSC1 encoder based on the logistic-map pre-shared initial conditions. It decreases the correlation between the decoding sequences generated by different keys and ensures high security of the algorithm. Utilizing chaos as a random number generator and using this sequence as an interleaved sequence has become an important and exciting idea, since it was realized that one could take advantage of the intrinsic features of a chaotic system and turn them into an aperiodic sequence of random numbers. Among the various nonlinear considered chaotic mappings, the most famous is the so-called logistic map, which is the most famous example of 1-D chaotic maps.

$$x_{n+1} = \mu x_n (1 - x_n),\ 0 \le x_n \le 1 \text{ and } 0 \le \mu \le 4 \qquad (3)$$

where μ is the bifurcation parameter, x_n is the initial condition of the map. In this map, the next state x_{n+1} of the chaotic system is fully described only by the present state x_n.

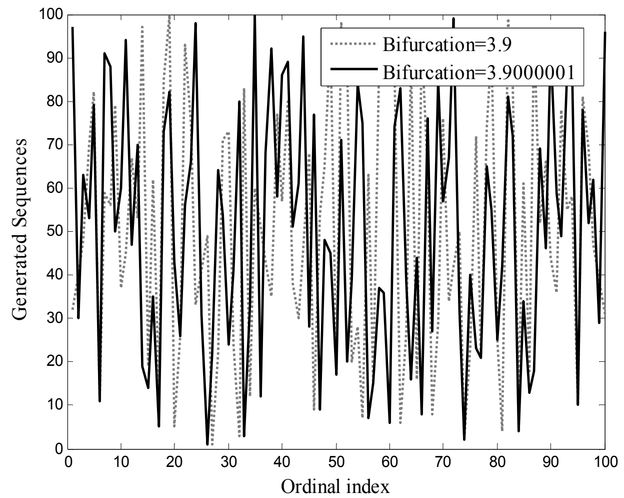

Fig. 5. CPRI output sequence using Logistic-map with different bifurcations, $N = 100$ bits and $x_n = 0.3$.

The logistic-map behaves mostly chaotic when $3.57 \le \mu \le 4$ so by adopting and controlling the logistic-map initial conditions parameters (μ and x_n) we can take full advantages of the Logistic mapping to generate a chaotic pseudo random sequence that can be used as a CPRI. These resulting pseudo-random sequences are very irregular and unpredictable (the more unpredictable, the closer to random). We also note that any small change in the initial condition yields to a significantly different sequence of random numbers as shown in Fig. 5: for a very little shift in the bifurcation parameter it gives a totally different random sequence. Compared to classical interleaver generators, which are periodic, the logistic random number generator is infinite, aperiodic and not correlated.

Another advantage of the CPRI is that during the chaotic mapping only a few parameters are needed being transferred from transmitter to receiver. To build a CPRI according to the chaotic logistic-map, the algorithm can be as follows.

- We should first generate a random vector from the logistic-map for a given data block length N and certain bifurcation μ and initial value x_0 parameter as.

$$x_{n+1} = \mu x_n \left(1 - x_n\right), \; n = 0, 1, 2\ldots, \; N-1 \tag{4}$$

- The next step is that we need to convert this random vector into a random numbers sequence as [20]:

$$R_n = A x_n \left(\bmod \theta\right) \tag{5}$$

where $R_n \in \mathbb{Z}^+$ and θ and A are selected constants. For example, if $A = 10^7$, $x_0 = 0.3$, $\theta = 256$ and $\mu = 3.9$, then from (4) we have.

$$x_1 = \mu x_0 \left(1 - x_0\right) = 3.9 \cdot 0.3\left(1 - 0.3\right) = 0.819\,,$$

$$x_2 = 3.9 \cdot 0.819\left(1 - 0.819\right) = 0.5781321,$$

$$R_1 = A x_1 \left(\bmod \theta\right) = 10^7 \cdot 0.819\left(\bmod 256\right) = 48\,,$$

$$R_2 = 10^7 \cdot 0.5781321\left(\bmod 256\right) = 73. \tag{6}$$

- In our algorithm, we convert the logistic random vector to a random numbers by very simple criteria by sorting this random vector in ascending way then we take the actual position of this sequence.

Fig. 6(a) shows the logistic map orbits with bifurcation parameter ($\mu = 3.99$) and initial value ($x_n = 0.03$) for number of bits ($N = 1000$ bits) where its CPRI sequence randomness is shown in Fig. 6(b) which indicates that this interleaved sequence combines a good randomness characteristics in addition to its secured chaotic behavior.

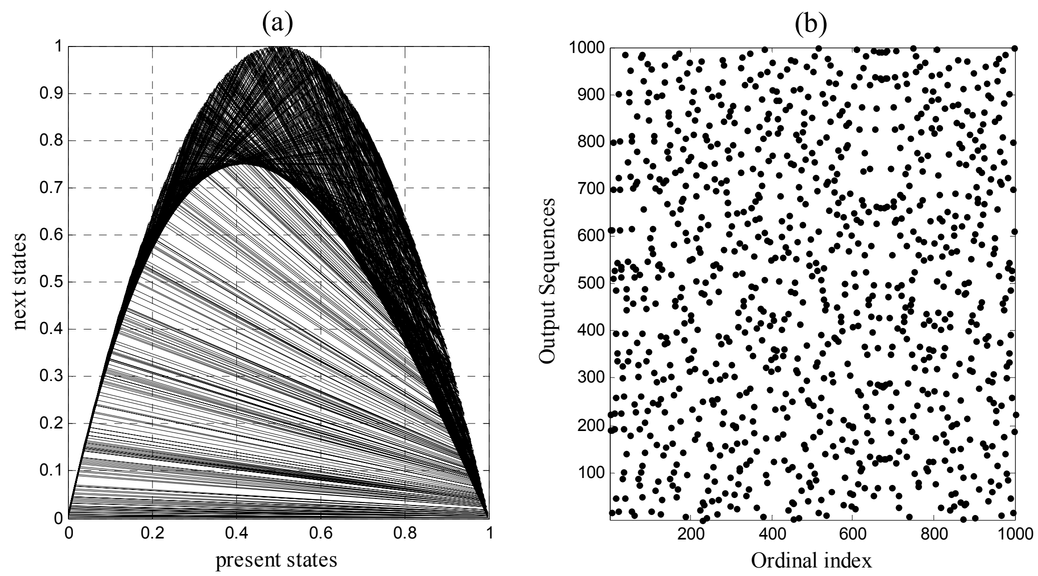

Fig. 6. Logistic-map for $N = 1000$ bits, $\mu = 3.99$ and $x_n = 0.03$: (a) logistic-map orbits and (b) CPRI Interleaved Sequences Randomness.

6. Simulation Analysis

In our simulation, we consider the case that the source to relay link is ideal, i.e., $g_{SR}=1$. Also we assume that n, n_{SR}, h_{SR}, h_{SD}, and h_{RD} are independent of each other, and all the channel coefficients are assumed to be known perfectly at the receiver sides and unknown at the transmitter sides. In the DTC scheme simulated system, the source node transmits the systematic and first parity bits using RSC1 with generators of (1, 5/7) in an octal form. The relay node then transmits second parity bits corresponding to the interleaved message using an interleaver size of $N = 1024$ bits. Thus, at the destination we can have an overall rate-1/3 ($R_{overall} = 1/3$) turbo code. The destination node applies 8-iterations log-MAP decoding after collecting the systematic information bits and the first parity bits from the source in the first time slot, and the second parity bits transmitted from the relay node in the second time slot.

Fig. 7 depicts the BER performance of the DTC system in AWGN channel with the interleaving gain effect of various interleaver types at the relay. From the simulation results comparison, we can show that the performance of the DTC scheme is better than the non-cooperative system. Also when the relay node uses MMSR interleaver, the improvement from the non-cooperative system is about (1.1 dB) at ($BER = 10^{-4}$), and improvement of (0.45 dB), (0.2 dB), and (0.17 dB) for practical interleaver, random and MBSR interleavers, respectively. Also with the same system parameters for fast fading channel Fig. 8 shows that the best BER performance is achieved when the relay uses the MMSR interleaver.

For the simulation of the DMTC scheme, at the source we have used a turbo code with two parallel identical (1, 5/7) polynomials RSC encoders, random interleaver with size of $N = 1024$ bits and punctured code rate $R = 1/2$. At the relay node we use one RSC encoder with (1, 5/7) polynomials giving an overall coding rate ($R_{overall} = 1/3$). Fig. 9 shows the interleaving gain effect on the system BER performance using different interleaver types at the relay node. It is observed that the performances of the three interleavers are almost identical. However, for the higher values of relay-destination channel gain one notices a better difference in performance.

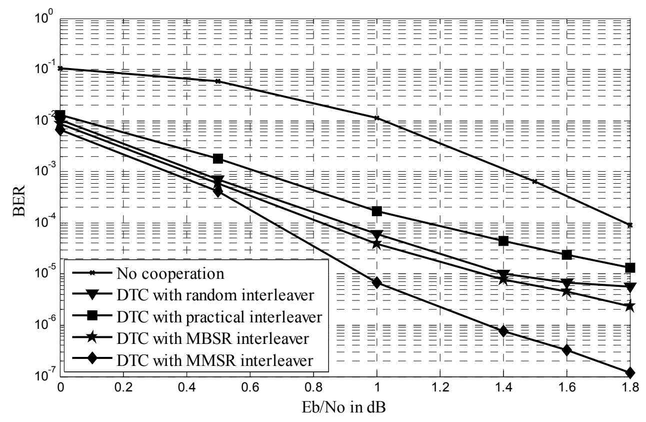

Fig. 7. BER performance comparison of different interleavers at the relay node of DTC scheme in AWGN channel.

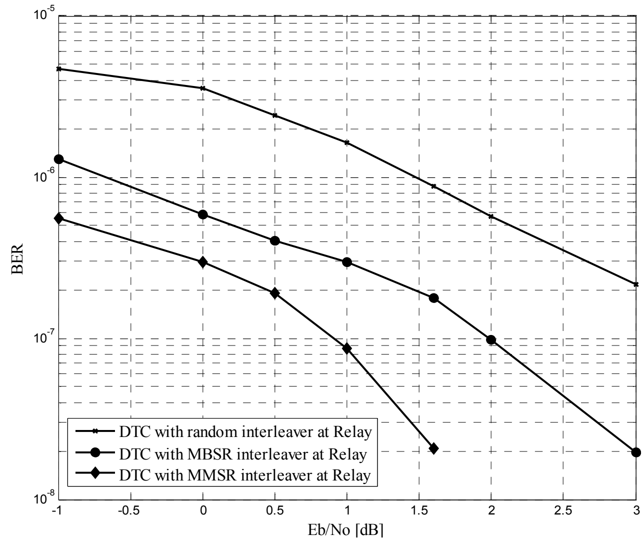

Fig. 8. BER performance of DTC in fast fading channel.

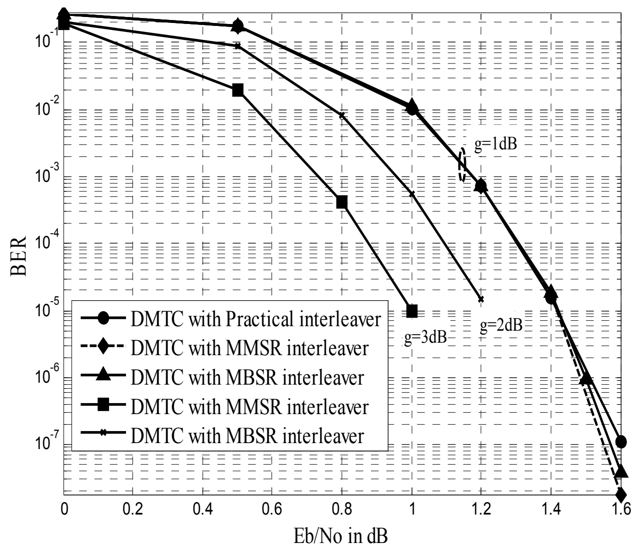

Fig. 9. BER performance of DMTC in fast fading channel.

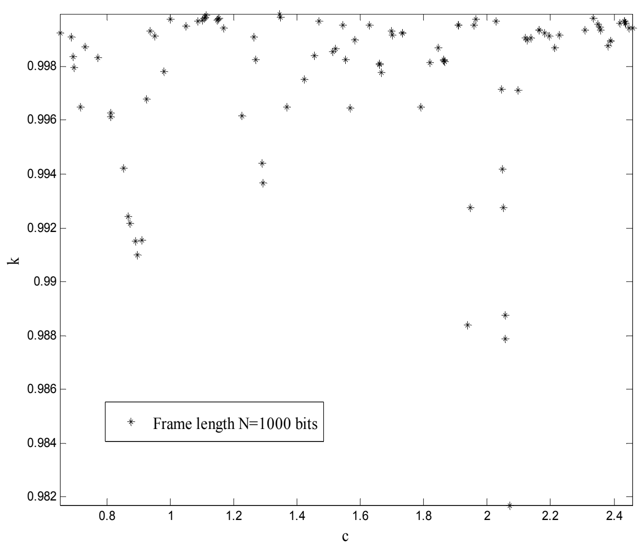

Fig. 10. Logistic-map "0-1" test result for ($\mu = 3.98$ and $x_n = 0.3$).

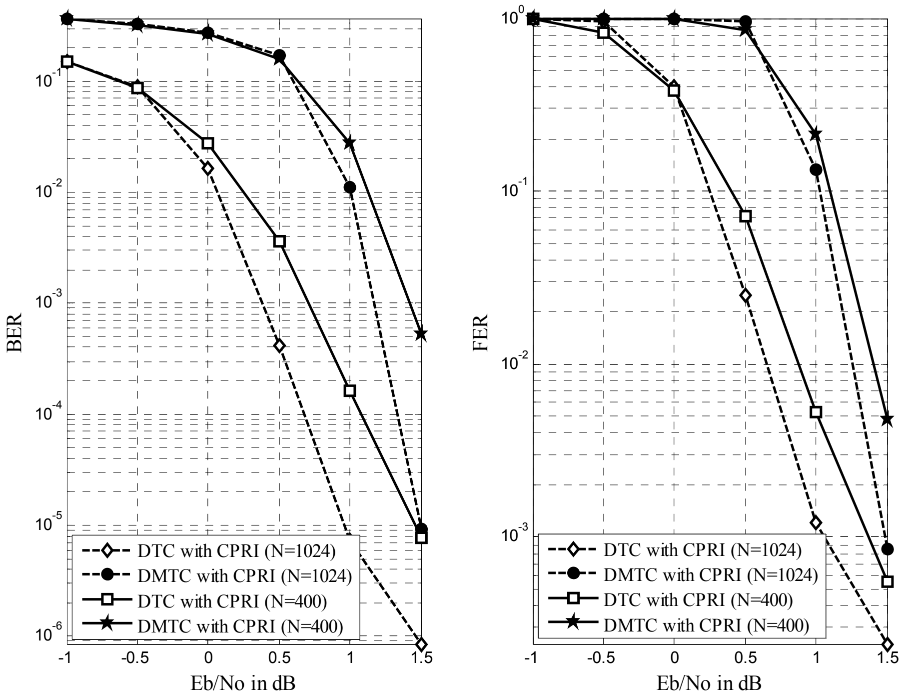

Fig. 11. Performances comparison between DTC and DMTC with CPRI in AWGN channel with N = 1024 and 400 bits.

As the unpredictability of the DTC with CPRI systems principally depends on the logistic map, it is rendering as the most critical and vital component of the system and it is very important to distinguish robustly whether a system is chaotic or not. Many tests can be used for this aim but the results of a much simpler '0-1' test for the presence of deterministic chaos in [21] shows that this test is at least as robust as other methods for the detection of deterministic chaos in a noisy time series. This '0-1' test takes as input a time series of measurements, and returns a single scalar value usually in the range [0, 1]. In the case of an infinite amount of noise-free data, the test result is near to '1' in the presence of deterministic chaos, and zero otherwise. For the used logistic map with bifurcation parameter $\mu = 3.98$ and the initial condition $x_n = 0.3$, the output of its '0-1' test is (0.9988) as shown in Fig. 10 which means that the used logistic map success in the test and have a chaotically behavior.

For the simulation of the DTC scheme based on using CPRI as an output interleaved element at the source, we have used an interleaver sizes of N = 400 bits and N = 1024 bits. For the AWGN channel performances of this scheme compared with DMTC with CPRI, Fig. 11 shows that BER and FER performances of DTC scheme with CPRI are better than the use CPRI with DMTC scheme in both N = 1024 and 400 bits.

7. Conclusion

In this paper, we have presented the effect of the interleaving gain in two turbo relay schemes: DTC and DMTC. Using of better interleavers in distributed turbo coding schemes are expected to be more robust against error propagation since the error performance of turbo codes is very sensitive to the interleaver design. Also combining the chaotic dynamics with the interleaver structure in the CPRI improves both the system secrecy and performance. Our results are consistent with these expectations. It is established that the use of good interleaver has a large effect on the BER performance of DTC scheme with better performance of using MMSR interleaver at the relay than other different interleaver types. But comparing the use of different interleaver types at the relay node in DMTC scheme, the performance is nearly the same. The other interleaving gain is that we can have secured data when we use CPRI as an output interleaver. The analysis demonstrates that the use of this CPRI as an output interleaver in DTC is more helpful than using it at the relay node as we can have better performance with secured data.

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