$$F(\lambda)=\begin{cases}\frac{Nr}{(NK-1)B\overline{\rho}}\sum_{l=1}^{q-1}u_l\left[\exp\left(-\frac{Nrk_l}{\overline{\rho}}\lambda\right)\cdot\sum_{v=0}^{NK-2}\frac{(Nrk_l\lambda)^v}{\Gamma(v+1)\overline{\rho}^v}\right]-1, & \text{for } NK>1\\ \frac{r}{B\overline{\rho}}\sum_{l=1}^{q-1}u_lE_1(rk_l\lambda/\overline{\rho})-1, & \text{for } NK=1\end{cases} \tag{28}$$

For $NK > 1$, from (28), we can get

$$F(0)=\frac{Nr}{(NK-1)B\overline{\rho}}\sum_{l=1}^{q-1}u_l-1=\frac{(M_{q-1}-1)Nr}{(NK-1)B\overline{\rho}}-1. \tag{29}$$

As shown in (29), $F(0)$ of the perfect CSI case may not be positive when K and/or $\overline{\rho}$ are large such that $(M_{q-1}-1)Nr/[(NK-1)B\overline{\rho}]-1<0$. Under this condition, we cannot find a Lagrange multiplier as a root of $F(\lambda)$. Hence, the condition of existence of the Lagrange multiplier for $NK > 1$ under perfect CSI is

$$(M_{q-1}-1)Nr/\left[(NK-1)B\overline{\rho}\right]>1. \tag{30}$$

When the condition is satisfied, the Lagrange multiplier obtained from $F(\lambda)=0$ is unique.

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Interleaved Random Space–Time Coding for Multisource Cooperation

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***Abstract*—In this paper, we propose a novel distributed interleaved random space–time code (IR-STC) designed for multisource cooperation (MSC) employing various relaying techniques, namely, amplify–forward, decode–forward, soft decode–forward, and differential decode–forward. We introduce a two-phase communication regime for our IR-STC-aided MSC and propose a novel structured embedded (SE) random interleaver-generation method. We also characterize the achievable performance of our proposed IR-STC design in conjunction with various relaying techniques communicating over different intersource Nakagami-m fading channels.**

***Index Terms*—Cooperative communications, interleaver division multiplexing, relaying, space–time coding.**

I. INTRODUCTION

Cooperative diversity [1]–[4] relying on a distributed (virtual) multiple-input–multiple-output (MIMO) system is capable of eliminating the correlated-fading-induced spatial diversity gain erosion of colocated MIMO elements. Hence, this novel technique is capable of improving the achievable performance while supporting a high throughput, as well as providing improved cell-edge coverage [5]. It has the potential to beneficially combine the traditional infrastructure-based wireless networks and the ad hoc wireless network philosophy [6]. Recently, the cooperative multiple access channel has attracted substantial research interests, where multiple sources forming a cluster of cooperating nodes communicate with the destination, which is also known as multisource cooperation (MSC) [7]–[9].

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Inspired by the multilayer turbo space–time coding (STC) concept introduced in [10], in [11], we proposed an error-resilient, yet high-throughput, nonorthogonal interleaved random (IR) STC scheme, which was particularly contrived for MSC. Our IR-STC for MSC exhibits several beneficial properties: 1) It achieves a *high-throughput* as a benefit of its high slot utilization efficiency with the aid of the superposition coding concept [12], [13]; 2) it has a *low bit error rate (BER)* due to the powerful iterative receiver employed [14]; and 3) it constitutes a *nonorthogonal* scheme, which is potentially capable of approaching the (cooperative) multiple access channel's capacity [7], [15].

In this paper, we propose a novel structured embedded (SE) interleaver design method, which allows our proposed IR-STC to have the *decentralized* property such that it benefits from operating with the aid of using autonomously generated random interleavers, which facilitates their cooperation without any central controller, even without knowing the number of sources. Furthermore, we investigate several relaying techniques in the context of our IR-STC-aided MSC, such as the amplify–forward (AF), decode–forward (DF), soft decode–forward (SDF), and differential decode–forward (DDF) techniques.

In a nutshell, the novel contribution of this paper is that *we design an SE interleaver-aided decentralized error-resilient, yet high-throughput nonorthogonal IR-STC scheme suitable for MSC and characterize its achievable performance when employing various relaying techniques and encountering Nakagami-m fading intersource channels*.

The rest of this paper is organized as follows: In Section II, we describe the considered MSC scenario, highlight its advantage over single-source cooperation (SSC), and introduce our novel IR-STC architecture designed for MSC. In Section III, we propose an efficient SE interleaver generation method. In Section IV, we investigate the performance of our IR-STC scheme employing different relaying techniques using simulations. Finally, we conclude our discourse in Section V.

Notation: Throughout this paper, lowercase (uppercase) boldface letters will represent column vectors (matrices). The superscripts $(\cdot)^T$ and $(\cdot)^*$ denote transposition and complex conjugation, respectively. The superscripts $(\cdot)^{(1)}$ and $(\cdot)^{(2)}$ denote *Phase-I cooperation* and *Phase-II cooperation*, respectively. The subscript $[\cdot]_{(k)}$ denotes the exclusion of the kth element.

II. IR-STC-Aided MSC

A. Scenario and Assumptions

Consider a cluster of single-antenna sources cooperatively communicating with a destination employing a single receive antenna, resulting in a virtual multiple-input–single-output (VMISO) system. In this VMISO cluster, we assume that we have a total of N cooperating sources (CSs), K active sources (ASs), and $(N-K)$ relaying sources (RSs).[1] Cooperative communications typically entail two phases, as shown in Fig. 1. In *Phase-I cooperation*, the source information emanating from all K ASs is broadcast to all N CSs in a time-division-duplex (TDD) manner under the assumption of perfect synchronization. By contrast, *Phase-II cooperation* is defined as the joint transmission of a combined IR-STC signal by the concerted action of all the N CSs. Indeed, the transmissions in Phase I may also be received by the destination, and this fact provides a further source of diversity. Then, the destination may collect and appropriately combine all the energy for further performance enhancement. Since this paper focuses on the IR-STC analysis and performance characterization, the

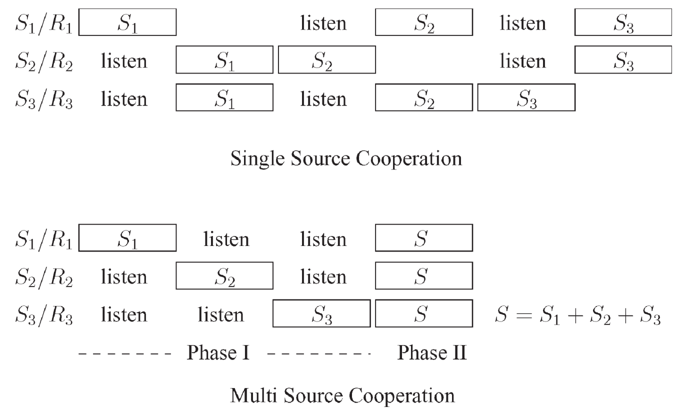

Fig. 1. Slot utilization efficiency of both MSC and SSC, where a cluster using $N = K = 3$ is considered, and S_i/R_i denotes the ith source/relay $i = 1, 2$, and 3, respectively, since source S_i becomes relay R_i when it is not transmitting.

aforementioned additional diversity-combining techniques may be set aside for future work.

As shown in Fig. 1, where $N = K = 3$, in conventional SSC, each source broadcasts its information to all $(N-1)$ CSs during *Phase-I cooperation*, which is followed by joint relaying of their information to the destination by the concerted action of the $(N-1)$ CSs in *Phase-II cooperation*. An entire cooperative transmission phase is concluded when all K ASs completed their cooperation. By contrast, MSC is constituted by a full cycle of information broadcasting from all K ASs to all N CSs during *Phase-I cooperation*, followed by their joint transmission to the destination during *Phase-II cooperation*, where each CS transmits all K ASs' information. Therefore, each CS simultaneously transmits multiple sources of information with the aid of their superposition, resulting in a high throughput. This implies that each source is simultaneously served by multiple CSs, which are chosen to be those that experience a high-quality intersource channel, and hence, the entire set of ASs benefits from a high diversity gain.

We assume that all intersource channels, denoted as $h^{(1)}$, and the source–destination channel, denoted as $h^{(2)}$, experience independent identically distributed Nakagami-m fading [16]. In this paper, the intersource channel $h^{(1)}$ is assumed to be asymmetric,[2] i.e., we have $h_{k,n}^{(1)} \neq h_{n,k}^{(1)}$, where $h_{k,n}^{(1)}$ represents the intersource channel between source k and source n, which tend to be in close proximity of each other. We also assume that the intersource channels benefit from a higher effective signal-to-noise ratio (SNR), i.e., we have $\gamma^{(1)} > \gamma^{(2)}$. Furthermore, the Nakagami parameter $m > 1$ is only used for the intersource channels, where an SNR-based node preselection scheme may be used for spotting the specific CSs benefiting from a high-quality channel.

B. IR-STC Construction: Phase-I Cooperation

As shown in Fig. 2, we assume that each binary phase-shift keying (BPSK)-modulated AS employs two repetition codes, namely, C_1 of rate r_1 and C_2 of rate r_2, which are separated by an AS-specific interleaver π_k. During *Phase-I cooperation*, the kth AS transmits a repetition-coded and randomly interleaved bit stream $x_k^{(1)} = C_2\{\pi_k[C_1(b_k)]\}, \ k \in [1, K]$, based on the information bit stream b_k. Then, depending on whether the intersource channel $h^{(1)}$ is known at all CSs, two different transmission modes can be employed, namely, coherent modulation and noncoherent modulation.

[1]Among a total of N CSs, K ASs actively communicate and relay, whereas the $(N-K)$ RSs constituted by the inactive CSs only relay the K ASs' information.

[2]Since each of the K ASs transmits its information in one *Phase-I cooperation* slot, it is reasonable to assume that the fading envelope is constant in that slot and fades independently for the different slots.

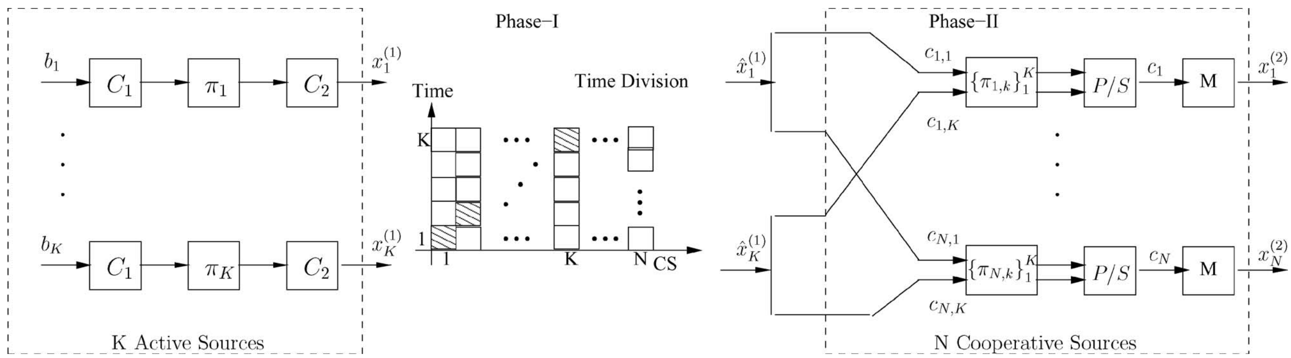

Fig. 2. Block diagram of IR-STC-aided MSC.

1) Coherent Modulation: During the kth of the K number of available TDD timeslots, the nth CS receives the signal transmitted from the kth AS, yielding the received signal $y_{k,n}^{(1)} = h_{k,n}^{(1)} x_k^{(1)} + v_{k,n}, \ k \in [1, K], \ n \in [1, N]_{(k)}$, where $v_k \sim \mathcal{CN}(0, N_0)$ denotes the complex-valued additive white Gaussian noise (AWGN). In this scenario, three relaying techniques are considered.

a) AF: The signal $y_{k,n}^{(1)}$ received by the nth CS is scaled to meet the average power constraint, yielding

$$\hat{x}_{k,n}^{(1)} = \frac{y_{k,n}^{(1)}}{\sqrt{N_0 + \left|h_{k,n}^{(1)}\right|^2}}. \tag{1}$$

b) SDF: The soft value $\mathcal{L}$ of the signal $y_{k,n}^{(1)}$ received at the nth CS is calculated as $\mathcal{L} = 4(|h_{k,n}^{(1)}|^2 x_k^{(1)} + \mathcal{R}\{h_{k,n}^{(1)*} v_{k,n}\})/N_0$ [17]. This is then scaled to meet the average power constraint

$$\hat{x}_{k,n}^{(1)} = \frac{\mathcal{L} N_0}{4\left|h_{k,n}^{(1)}\right| \sqrt{N_0/2 + \left|h_{k,n}^{(1)}\right|^2}}. \tag{2}$$

Equation (2) essentially describes an AF technique in an uncoded or a repetition-coded system, because the soft value $\mathcal{L}$ can be viewed as an equivalent analog-valued received signal.

c) DF: The signal $y_{k,n}^{(1)}$ received by the nth CS is subject to BPSK hard detection, resulting in

$$\hat{x}_{k,n}^{(1)} = \mathrm{sign}\left(\mathcal{R}\left\{h_{k,n}^{(1)*} y_{k,n}^{(1)}\right\}\right). \tag{3}$$

2) Noncoherent Modulation: When $h^{(1)}$ is unknown at the CSs, noncoherently detected differentially encoded BPSK (DBPSK) modulation can be employed. Then, the transmitted bit stream is expressed as $s_k^{(1)}(i) = s_k^{(1)}(i-1) x_k^{(1)}(i), \ i \in [1, M]$, where M is the length of bit stream $x_k^{(1)}$, and $s_k^{(1)}(0) = 1$ is a dummy bit used by the DBPSK detector as a reference. Thus, we have $y_{k,n}^{(1)} = h_{k,n}^{(1)} s_k^{(1)} + v_{k,n}$.

Let us assume the presence of slow fading. Then, $h^{(1)}$ may be considered to be constant over two consecutive bits; hence, noncoherent detection is performed according to

$$\begin{aligned}\hat{x}_{k,n}^{(1)}(i) &= \mathrm{sign}\left(\mathcal{R}\left\{y_{k,n}^{(1)*}(i-1) y_{k,n}^{(1)}(i)\right\}\right) \\ &= \mathrm{sign}\left(\mathcal{R}\left\{\left|h_{k,n}^{(1)}\right|^2 x_k^{(1)}(i) + v'_{k,n}\right\}\right)\end{aligned} \tag{4}$$

where $v'_{k,n} \sim \mathcal{CN}(0, 2|h_{k,n}^{(1)}|^2 N_0)$ is a complex-valued AWGN component having a doubled noise variance in comparison to coherent detection, where the latter relies on accurate channel knowledge.

When comparing these four relaying techniques, (1) and (2) retain the original signal but scale both the signal and the noise component, whereas (3) and (4) assume first detecting and then reconstructing the signal, depending on the channel quality. We refer to the first two techniques as *nonregenerative* relay techniques and to the latter two as *regenerative* relay techniques.

C. IR-STC Construction: Phase-II Cooperation

Following *Phase-I cooperation*, each of the N CSs detects/scales all the K ASs' bit streams according to the aforementioned four relaying techniques characterized by (1)–(4). When considering the nth of the N CSs, the joint IR-STC codeword is constructed as follows.

1) Codeword Generation: First, the nth CS forms K parallel streams $c_{n,k}(i) = \hat{x}_{k,n}^{(1)}[N(i-1)+n], \ i \in [1, M'], \ k \in [1, K]$, where $M' = M/N$ is an integer denoting the number of bits per CS per stream. Then, these K streams are interleaved by K distinct interleavers of the CS-specific interleaver set $\{\pi_{n,k}\}_{k=1}^K$ and parallel-to-serial converted to c_n.

2) Multilayer Mapping: The signal transmitted from the nth CS then becomes

$$x_n^{(2)}(i) = \frac{1}{\sqrt{L_n}} \sum_{l=1}^{L_n} \rho_{n,l} e^{j\theta_{n,l}} c_n\left[L_n(i-1)+l\right] \tag{5}$$

where $i \in [1, M'K/L_n]$, and L_n is referred to as the number of layers contributed by the nth CS, whereas $\rho_{n,l}$ and $\theta_{n,l} \in (0, \pi]$ denote the layer-specific amplitude and phase rotation, respectively. In this treatise, we assume that $L_n = L$, $\rho_{n,l} = \rho_l$, and $\theta_{n,l} = \theta_l$, $\forall n \in [1, N]$. Furthermore, we employ a layer-specific uniform phase rotation of $\theta_l = l \cdot \pi/L, \ l = 1, \ldots, L$, which further assists the receiver in separating the layers.

An *iterative receiver* is employed at the destination of *Phase-II cooperation*, where either optimum but complex maximum-likelihood detection or reduced-complexity suboptimum interference cancellation (IC) may be employed [10]. Employing different relaying techniques requires different amounts of intersource channel knowledge at the destination. For the regenerative relay techniques of (3) and (4), no intersource channel knowledge is required at the destination, whereas for the nonregenerative relay techniques of (1) and (2), intersource channel knowledge is required at the destination. However, for SDF, the knowledge of the intersource channel's magnitude $|h_{s,s}|$ at the destination is sufficient.

D. Effective Throughput of IR-STC

Now, let us discuss the effective throughput of our IR-STC when ignoring the throughput reduction imposed by *Phase-I cooperation* for the sake of a simple argument. In this paper, we employ repetition codes of code rates r_1 and r_2 for both C_1 and C_2. When considering a cluster of N CSs, the overall code rate of IR-STC becomes $r_{\text{IR-STC}} = r_1 \times r_2 \times N$. The effective throughput of the cluster employing multilayer IR-STC may be expressed as $\eta_{\text{IR-STC}} = r_{\text{IR-STC}} \times L$. For example, when $r = 1/8$-rate repetition-coded $N = K = 4$ sources are in a cluster and $L = 7$ layers are superimposed at each CS, an aggregate rate as high as $\eta_{\text{IR-STC}} = 3.5$ is achievable.

III. SE IR-STC DESIGN

Our IR-STC scheme employs a random distributed AS-specific interleaver π_k and a CS-specific interleaver set $\{\pi_{n,k}\}_{k=1}^{K}$ for differentiating the various sources. This random construction is different from that proposed in [18], where each CS transmits a random linear combination of the columns of an existing orthogonal space–time block code.

A. Distributed Interleaver Design

The generation of distributed random interleavers used in our IR-STC-aided MSC should be carried out in an efficient manner, while at the same time maintaining their random nature. In this paper, we propose an interleaver, which we refer to as an SE interleaver. Without loss of generality, we discuss the generation of AS-specific interleavers. The SE interleavers are constructed from three hierarchical layers, namely, from a system-specific base interleaver, an AS-specific base interleaver, and a so-called constituent interleaver set. These interleavers are then subjected to a position sorting operation, all of which are detailed in the succeeding paragraphs.

The *system-specific base interleaver* π^b is a randomly generated interleaver of length Q. Additionally, each AS has a distinct AS-specific base interleaver $\pi_k^b,\ k \in [1, K]$, which has the same length Q as the system-specific base interleaver π^b. The $(k+1)$st AS-specific base interleaver used in the $(k+1)$st TDD slot is an interleaved version of the kth AS-specific base interleaver used in the TDD slot k, which was rearranged by the system-specific base interleaver π^b, as follows: $\pi_{k+1}^b = \pi^b(\pi_k^b)$ and $\pi_1^b = \pi^b$.

The constituent interleaver set of AS k is represented by U number/level of length-Q interleavers, which is formulated as $\pi_k^c = \{\pi^1, \pi^2, \ldots, \pi^U\}$. Each element $\pi^u \in \pi_k^c,\ u \in [1, U]$, of the constituent interleaver set is a distinct length-Q interleaver having the same length as the system-specific base interleaver π^b. The $(u+1)$st constituent interleaver is an interleaved version of the uth constituent interleaver, which was rearranged by the AS-specific base interleaver π_k^b, according to $\pi^{u+1} = \pi_k^b(\pi^u)$ and $\pi^1 = \pi_k^b$.

Finally, the U number of length-Q interleavers are concatenated to form a unique length-UQ interleaver. This is carried out by the constituent interleaver set position sorting operation, as defined by the position mapping function f, which maps the index $q^u \in [1, Q]$ within all the U number of length-Q constituent interleavers $\pi^u \in \pi_k^c,\ u \in [1, U]$, into a single AS-specific interleaver $\pi_k = f(\pi_k^c)$. From a different perspective, this implies unambiguously mapping the UQ number of input bit positions to the interleaved positions $q \in [1, UQ]$. More specifically, the index $q^u \in [1, Q]$ within any of the U length-Q constituent interleavers $\pi^u,\ u \in [1, U]$ is mapped to $q = (q^u - 1)U + u$.

B. Cross-Correlation Evaluation

Let us now demonstrate the equivalence of our proposed SE interleavers to random interleavers in terms of the correlation metric introduced in [19]. In other words, our goal is to demonstrate that despite its significantly reduced memory requirements, the proposed interleaver generation technique does not increase the correlation between the pairs of interleaved information sequences in comparison to using random interleavers.

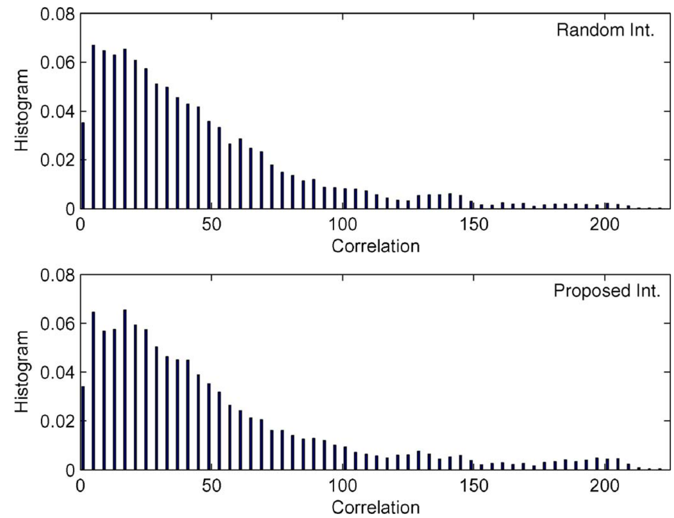

Fig. 3. Normalized average histogram of the correlation for both the random interleavers and our proposed SE interleavers. The total interleaver length was set to $N = 1024$, and we divided it into $U = 4$ constituent interleavers, each having length $Q = 256$. A total number of 100 pairs of interleavers of both random interleavers, and our proposed interleavers were averaged.

The correlation χ between two independently generated random information bit sequences $\mathbf{s}_1$ and $\mathbf{s}_2$ interleaved by two different interleavers π_1 and π_2 is given by the magnitude of scalar product $\circ$ between $\pi_1(\mathbf{s}_1)$ and $\pi_2(\mathbf{s}_2)$, which can be written as $\chi = |\pi_1(\mathbf{s}_1) \circ \pi_2(\mathbf{s}_2)|$. Since evaluating the correlation among all possible pairs of random sequences $\mathbf{s}_1$ and $\mathbf{s}_2$ has a high computational cost, we seek a lower complexity alternative [19]. We represent $\mathbf{s}_1$ as $\mathbf{s}_1 = \sum_{i=1}^{N} \alpha_i \mathbf{b}_i$, where $\alpha_i \in \{\pm 1\}$, and the vector $\{\mathbf{b}_i : \mathbf{b}_i(i) = 1, \mathbf{b}_i(j) = 0\}$ of length N is a vector within the basis set $\mathbf{B} = [\mathbf{b}_1, \mathbf{b}_2, \ldots, \mathbf{b}_N] \subset \mathbb{R}^N$. On the other hand, $\mathbf{s}_2$ can be replaced by generating a set $\mathbf{G} = [\mathbf{g}_1, \mathbf{g}_2, \ldots, \mathbf{g}_N] \subset \mathbb{R}^N$, where each vector $\mathbf{g}_i$ of length N has an entry of $\mathbf{g}_i(j) = -1$ when we have $j < i$ and $\mathbf{g}_i(j) = 1$ for $j \geq i$. Thus, the correlation χ becomes the so-called upper bounded basis correlation vector $\chi^b = [\chi_1^b, \chi_2^b, \ldots, \chi_N^b]$ defined in [19], where each entry $\chi_j^b,\ j = 1, \ldots, N$, is represented as

$$\chi_j^b = \sum_{i=1}^{N} |\pi_1(\mathbf{b}_i) \circ \pi_2(\mathbf{g}_j)| . \tag{6}$$

Fig. 3 demonstrates the normalized average histogram of the correlations recorded for both random interleavers and our proposed SE interleavers. The total interleaver length was set to $N = 1024$, and we divided them into $U = 4$ constituent interleavers, each having a length of $Q = 256$. We averaged the correlations over both 100 pairs of random interleavers and 100 pairs of our proposed SE interleavers. Fig. 3 suggests that statistically speaking, both interleaver families exhibit similar correlations.

IV. SIMULATION RESULTS

In this section, we investigate the performance of our IR-STC-aided $N = K = 4$ MSC employing different relaying techniques and stipulating different assumptions concerning $h^{(1)}$ by varying the Nakagami-m fading parameters. Both $h^{(1)}$ and $h^{(2)}$ are assumed

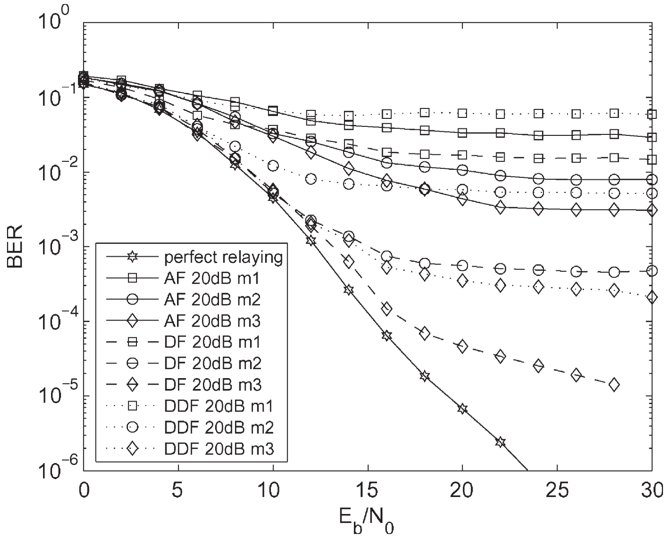

Fig. 4. Comparison of AF, DF, and DDF relaying techniques employed in the four-layer IR-STC-aided MSC scheme when the intersource channel SNR was $\gamma_{s,s} = 20$ dB.

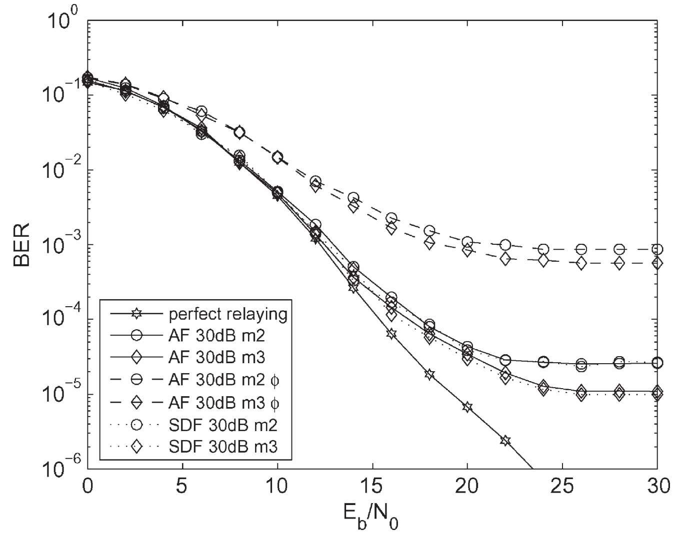

Fig. 5. Comparison of AF, SDF, and AF subject to a carrier phase error at the destination employed in the four-layer IR-STC-aided MSC scheme when the intersource channel SNR was $\gamma_{s,s} = 30$ dB.

to be quasi-static, i.e., constant in every 1024 information symbol block, but they are independently faded between the consecutive blocks. The value of $h^{(2)}$ is assumed to be perfectly known at the destination, whereas the knowledge of $h^{(1)}$ is either explicitly required or dispensed with at both the CSs and the destination, depending on the specific relaying technique employed. In all of our simulations, perfect relaying implies that all K ASs' information bits are perfectly known at all N CSs. Furthermore, the IC-aided iterative receiver used $I = 30$ iterations, and a total code rate of $r = 1/8$ was dedicated to the repetition code C_1 only, which corresponds to the multiplexing-oriented setting of [20].

Fig. 4 characterizes three different relaying techniques, namely, AF, DF, and DDF, employed in our IR-STC-aided MSC scheme, when the intersource channel SNR was $\gamma^{(1)} = 20$ dB. As expected, the higher the value of the Nakagami parameter m, the less hostile the channel fading encountered, which results in an improved BER performance for all the three relaying techniques. For all the three m values considered, DF leads to the best BER performance, whereas the performance attained by DDF is better than that of AF, except for $m = 1$. The worst performance of AF relaying is mainly a consequence of its noise enhancement. To elaborate a little further, the inferior performance of DDF compared with that of DF is a direct consequence of its doubled noise variance, when noncoherent detection was employed. For $m = 1$, the effect of noise enhancement imposed by AF relaying is less severe than that of the doubled noise variance of noncoherent detection encountered by DDF, as evidenced by the results of Fig. 4.

Fig. 5 compares two nonregenerative relaying techniques, namely, AF and SDF, employed in our IR-STC-aided MSC scheme when the intersource channel SNR was $\gamma^{(1)} = 30$ dB. It can be seen that there is only an insignificant difference between these two techniques.[3] However, as discussed in Section II, when the AF technique is employed, the knowledge of $h^{(1)}$ is required at the destination. By contrast, only the knowledge of $|h^{(1)}|$ is required at the destination when SDF is employed. It can be seen in Fig. 5 that when a carrier phase error of $\phi = \pi/16$ is imposed on $h^{(1)}$ at the destination, a significantly reduced BER performance is observed. This implies that SDF is a better relaying technique compared with AF, provided that the CSs are capable of acquiring accurate knowledge of $h^{(1)}$. However, having the knowledge of $|h^{(1)}|$ at the CS is sufficient for ensuring the reliable operation of the AF technique.

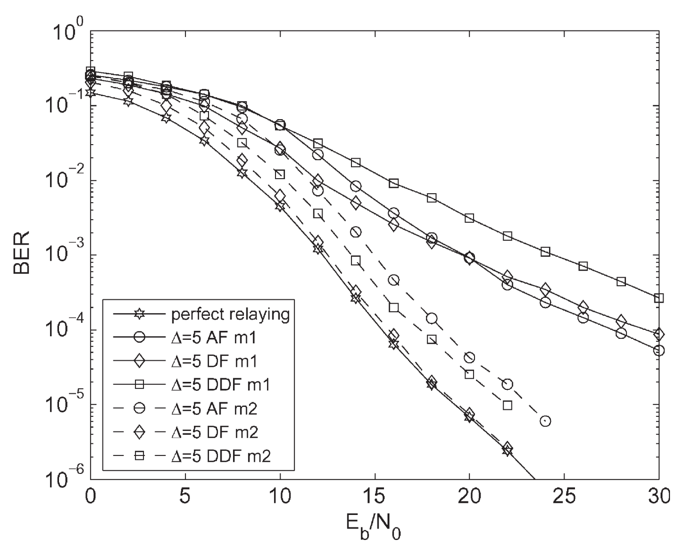

Fig. 6. Comparison of AF, DF, and DDF relaying techniques employed in the four-layer IR-STC-aided MSC scheme having an intersource channel SNR/source–destination channel SNR ratio $\Delta = 5$ when $h^{(1)}$ is subjected to Nakagami fading associated with $m = 1$ and $m = 2$.

All of our previous investigations were based on having a fixed intersource channel SNR. To expound further, Fig. 6 shows three different relaying techniques, namely, AF, DF, and DDF, employed in our IR-STC-aided MSC, when the channel $h^{(1)}$ experiences different Nakagami-m fading and assuming a consistently higher SNR value than that associated with $h^{(2)}$, i.e., we have $\Delta = \gamma^{(1)}/\gamma^{(2)} > 0$ dB. It can be seen in Fig. 6 that for $m = 2$, DF performs consistently better than the other two techniques and approaches the perfect

[3]In uncoded or repetition-coded systems, SDF essentially becomes an AF technique, which is inferior to the DF technique. When a serial concatenated outer channel code is employed, SDF becomes capable of enabling soft channel decoding, and the corresponding extrinsic information $\mathcal{L}$ becomes more reliable. This results in a higher mutual information $I(x_k^{(1)})$, which is equivalent to having a reduced noise variance. Therefore, the achievable performance is expected to be better than that of DF.

relaying performance, namely, that of the system, which regenerates the source information without decision errors. Surprisingly, DDF also performs consistently better than the AF technique. However, when severe Rayleigh fading is encountered, i.e., we have $m = 1$, AF has the best performance at a high SNR, where the effect of noise enhancement is negligible. By contrast, the performance of both DF and DDF is unacceptable, owing to the effects of Rayleigh fading. Therefore, ideally, the specific relaying technique used should be determined according to the specific Nakagami-m fading values encountered. This suggests switching among the different relaying modes.

Remarks: We may now conclude that when the SNR of the $h^{(1)}$ channel is better than that of $h^{(2)}$, DF is the best relaying strategy in the presence of benign fading. When a sufficiently high-SNR benign-faded $h^{(1)}$ channel is experienced, close-to-perfect relaying performance is attainable. The AF technique is only preferable at high SNRs when severe fading is encountered. DDF performs consistently worse than DF due to the doubled noise variance of noncoherent detection. Surprisingly, when the fading is benign, noncoherent DDF without the cost of estimating all intersource channel knowledge outperforms the coherent detected AF technique. Therefore, a preselection of the CSs benefiting from a high-SNR $h^{(1)}$ channel—which typically also have high Nakagami-m values—is important in MSC.

V. Conclusion

In this paper, we have outlined the benefits of our IR-STC and analyzed the achievable performance of our IR-STC-aided MSC that employs various relaying techniques. The advantage of MSC over SSC was revealed, and a novel SE random interleaver-generation method was proposed. Our IR-STC design is capable of achieving a high throughput while maintaining a low BER with the aid of decentralized cooperation. These properties render our IR-STC design eminently applicable for employment in interference-limited high-user-density ad hoc networks in conventional cellular networks assisted by mobile relays complemented by fixed wireless relays, as well as in other application-oriented scenarios.

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