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Interleave Division Multiplexing Aided Space-Time Coding for High-Throughput Uplink Cooperative Communications

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Abstract— **In this paper, we design and investigate a novel Interleave Division Multiplexing based Space-Time Code (IDM-STC) in the context of cooperative communications. We outline the particular signalling scheme used for exchanging the necessary information amongst the cooperating MSs and suggest an efficient interleaver allocation scheme, which is capable of uniquely and unambiguously differentiating the different MSs' signals with the aid of their user and antenna-specific interleavers. We then characterize the achievable performance of our proposed IDM-STC design and compare it to that of the traditional G_2 and G_4 Space-Time Block Code (STBC) invoked for cooperative communications. Our cooperative IDM-STC scheme is flexible in terms of forming a cluster of cooperative users, it is power-efficient and capable of maintaining a high rate, in particular when combined with non-uniform power allocation.**

I. INTRODUCTION

Multiple Input Multiple Output (MIMO) systems [1] are capable of providing both diversity and coding gains in the context of Space-Time Codes (STC) [2] as well as of supporting a high multiplexing gain, when using for example Bell-Labs Layered Space Time Architecture (BLAST) [3]. However, at the Mobile Station (MS), it may be impractical to accommodate multiple antennas. Alternatively, the novel concept of cooperative communications allows us to assign the MIMO elements to geographically separated cooperating MSs, which are no longer prone to shadowing-induced correlated fading, leading to the concept of Virtual MIMOs (VMIMO) [4], [5].

Hence STC based VMIMO designs [6] are attractive for employment in cooperative communications, where the cooperating MSs' independently fading signals jointly constitute a STC codeword. Recently, an Interleave Division Multiplexing Space-Time Code (IDM-STC) by Wu and Ping was proposed in [7], where its potential applicability in cooperative communications was also alluded to. The resultant IDM-STC was then investigated and analyzed in [8], where a similar performance was reported to that attained by Alamouti's STBC. This motivated us to design and investigate the proposed IDM-STC in the context of cooperative communications.

Our design of IDM-STC was specifically contrived for cooperative communications by appropriately adopting the Multilayer IDM-STC concept [7], where we treat each cooperating MS as an IDM-STC layer. Instead of using multilevel modulation schemes [9], we employ sigma mapping for creating an error-resilient binary cooperative system. We also design a realistic signalling scheme required for exchanging the information amongst the cooperating MSs and contrast the benefits of IDM-STCs to those of the traditional G_2 and G_4 Space-Time Block Code (STBC) design [10]. More specifically, the novel contribution of this paper is that *we design an error-resilient, yet high-throughput IDM-STC scheme suitable for cooperative communications and characterize its achievable rate, power-efficiency and flexibility.*

The rest of the paper is organized as follows. In Section II, we describe the cooperative scenarios considered and introduce the IDM-STC transceiver architecture designed for cooperative communications. In Section III, we design a practical signalling scheme for exchanging the necessary information amongst the cooperating MSs and suggest an efficient interleaver allocation scheme. In Section IV, we outline the achievable benefits compared to the traditional G_2 and G_4 STBC design. Finally, we conclude our discourse in Section V.

II. SYSTEM ARCHITECTURE

A. Cooperative Scenarios

Consider a cluster of uplink transmitters cooperatively communicating with a destination Base Station (BS) employing a single receive antenna. Similarly, each cooperating transmitter has a single transmit antenna, resulting in a Virtual Multiple Input Single Output (VMISO) system. We define two modes of operation for a cooperating MS of a cluster, namely 1) active, when the MS is conveying both its own information and other cooperating MSs' information; 2) relaying, when the MS is available for conveying other MSs' information.

We assume that the channels amongst the cooperating MSs are "ideal", which assumes that the information exchanged amongst the cooperating MSs is error-free and perfectly synchronized. We assume furthermore that the channels between the cooperating MSs and the BS exhibit independent identically distributed (i.i.d) Rayleigh fading and that the Channel State Information (CSI) is perfectly known both at the BS's and the Relay Station's (RS) receiver. [1]

B. Cooperative Transmitter

In this VMISO system, we assume having a total of N transmit antennas, K cooperating MSs and $(N-K)$ RSs in a cluster, where we have $N \geq K$, as seen in Fig. 1.

The kth MS's transmitted bit stream b_k is firstly channel encoded by C_1 at a rate of r_1, yielding the encoded stream c_k^1. The resultant channel encoded stream is randomly interleaved by a user-specific chip-interleaver π_k^u, resulting in $\hat{c}_k^1$. This stream is then repetition coded by C_2 at a rate of r_2, resulting in c_k^2, which is then S/P converted to N parallel streams and mapped to the N antennas, yielding the information $c_{k,n}^2$ of MS k at antenna n. Then each stream $c_{k,n}^2$, which the MS intends to transmit with the aid of its nth cooperating partner, is again randomly interleaved by an antenna-specific chip-interleaver π_n^a, yielding $\hat{c}_{k,n}^2$, before sending it to the multilayer mapping stage, as seen in Fig. 1.

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[1] Naturally, this is a very demanding assumption, since estimating all the related channels imposes a high complexity. As a first step towards eliminating this demanding assumption, we could consider differentially encoded and non-coherently detected schemes.

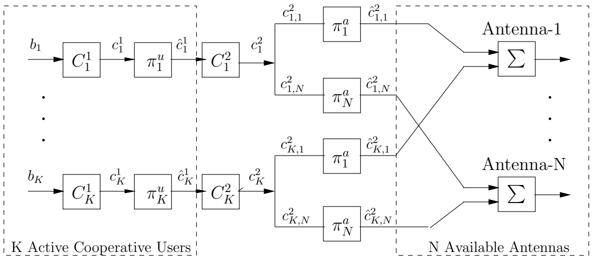

Fig. 1. The K-user cooperative IDM-STC UpLink transmitter

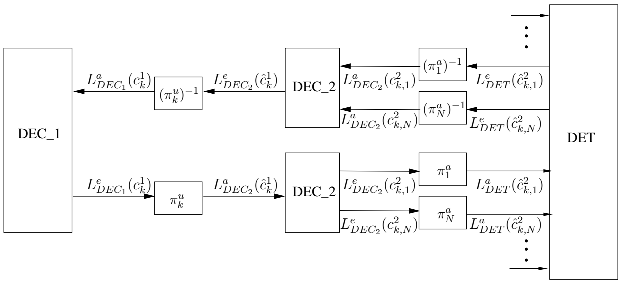

Fig. 2. The iterative IDM-STC UpLink receiver of the K users

1) IDM-STC: In this paper, we employ repetition codes of code-rate r_1 and r_2 for both C^1 and C^2 , respectively, resulting in a total code-rate of $R = (r_1 \times r_2)$. When considering a cluster of N available antennas, the overall rate of the IDM-STC scheme becomes:

$$r_{IDM} \quad = \quad N \times R, \tag{1}$$

which is always less than unity, when we assume $N \leq 1/R$.

We will further consider three typical settings of r_1 and r_2 given a fixed total code-rate R, namely: 1) $r_1 = R$ and $r_2 = 1$, i.e. when we employ the repetition code C^1 only. The interleaver π_k^u and S/P conversion of Fig. 1 ensures that the encoded bits c_k^1 are *randomly* dispersed across both the spatial and the time domain. 2) $r_1 = 1$ and $r_2 = R$, i.e. only the repetition code C^2 is employed and the following S/P conversion of Fig. 1 ensures that the encoded bits c_k^2 are directly mapped to each antenna, since the interleaver π_n^a of Fig. 1 operates after S/P conversion. 3) $r_1 = RN$ and $r_2 = 1/N$.

2) Multilayer mapping: In contrast to classic mapping and modulation schemes, such as PSK and QAM, sigma mapping [11], which are based on the theory of multiuser communications, was designed to generate an approximately Gaussian distributed transmitted signal, which allows the system to approach the Shannon capacity.

Let us hence consider the multilayer mapping of K MSs' cooperative bit streams, i.e. $\hat{c}_{k,n}^2, \forall k$ at the nth antenna. Let us assume that we want to transmit $m_{k,n}$ bits/symbol with the aid of each substream $\hat{c}_{k,n}^2$, where the resultant symbol vector is denoted by $\mathbf{v}_{k,n} = [\hat{c}_{k,n,1}^2, \cdots, \hat{c}_{k,n,m_{k,n}}^2]$. Then the total number of bits/symbol transmitted by all the K MSs that are mapped to the nth antenna, $n = 1, \cdots, N$ is given by:

$$\mathcal{L}_n \quad = \quad \sum_{k=1}^{K} m_{k,n}. \tag{2}$$

We refer the number of bits as the number of layers. The super-symbol vector $\mathbf{s}_n = [\mathbf{v}_{1,n}, \cdots, \mathbf{v}_{K,n}]$ hosting all the K symbol vectors is then weighted by the nth antenna's coefficient $\mathbf{u}_n$ and superimposed to generate the K-MS "super-symbol" in the form of

$$\mathbf{x}_n \quad = \quad \mathbf{u}_n \mathbf{s}_n^T, \tag{3}$$

where $(\cdot)^T$ denotes the transpose and the weighting coefficient vector is given by:

$$\mathbf{u}_n \quad = \quad [\rho_{n,1} e^{j\theta_{n,1}}, \cdots, \rho_{n,\mathcal{L}_n} e^{j\theta_{n,\mathcal{L}_n}}], \tag{4}$$

with the entries of $\rho_{n,m}$ and $\theta_{n,m} \in [0, \pi]$ representing the layer-specific amplitude[2] and phase[3] of the nth antenna's stream, respectively.

We assume that the number of layers $\mathcal{L}_n$ and the weighting coefficient vector $\mathbf{u}_n$ is the same for all of the N antennas, which implies that we have $\mathcal{L}_n = \mathcal{L}, \forall n$ and $\mathbf{u}_n = \mathbf{u}, \forall n$. Furthermore, we employ a layer-specific uniform phase rotation so that the $\mathcal{L}_n$ number of layers are uniformly phase-rotated on the two-dimensional signal space.

C. Turbo Receiver of IDM-STC

The discrete-time received signal y is given by:

$$\begin{aligned} y &= \mathbf{h}\mathbf{x} + \nu, \\ &= \mathbf{h}\mathbf{U}\mathbf{s} + \nu, \end{aligned} \tag{5}$$

where we have:

$$\begin{aligned} \mathbf{h} &= [h_1, \cdots, h_N]_{1 \times N}, \\ \mathbf{s} &= [\mathbf{s}_1, \cdots, \mathbf{s}_N]^T_{N\mathcal{L} \times 1}, \\ \mathbf{U} &= \mathrm{diag}[\mathbf{u}_1, \cdots, \mathbf{u}_N]_{N \times N\mathcal{L}}, \end{aligned}$$

where $\mathbf{h}$ denotes the i.i.d Channel Impulse Response (CIR) vector of the VMISO system. Each entry $\mathbf{u}_n = \mathbf{u}$ in $\mathbf{U}$ can be viewed as a complex-valued scaling vector of the transmitted binary signal vector $\mathbf{s}_n$ corresponding to the nth antenna imposing an amplitude scaling and phase rotation action. Finally, $\nu \sim \mathcal{N}_c(0, \sigma_n^2)$ in Eq. (5) is a complex-valued Additive White Gaussian Noise (AWGN) process having $\sigma_n^2 = N_0/2$ per dimension. We rewrite Eq. (5) as:

$$y \quad = \quad \mathbf{H}\mathbf{s} + \nu, \tag{6}$$

where $\mathbf{H} = \mathbf{h}\mathbf{U}$ is the equivalent CIR matrix. Hence, by using sigma mapping, a binary system is constructed, which facilitates a real-valued processing at the receiver side.

The turbo receiver consists of a Soft In Soft Out (SISO) Detector (DET) and a bank of K individual SISO decoders (DEC), as seen in Fig. 2. The SISO DET employs the low complexity Soft Interference Cancellation (SoIC) scheme of [12].

Let us now consider the ith bit s_i of the transmitted super-symbol vector $\mathbf{s}$. Then Eq. (6) can be written as

$$y \quad = \quad H_i s_i + \xi, \tag{7}$$

where $\xi = \sum_{j \neq i} H_j s_j + \nu$ represents the interference plus noise. In a binary system the real part (Re) of $H_i^* y$ constitutes sufficient statistics for estimating s_i, where $(\cdot)^*$ denotes the conjugate, resulting in:

$$Re(H_i^* y) \quad = \quad |H_i|^2 s_i + Re(H_i^* \xi). \tag{8}$$

We denote the soft estimate of a variable a by $(\hat{a})$. Then, the soft estimate $Re(H_i^* \hat{\xi})$ and its variance $\mathbf{V}[Re(H_i^* \hat{\xi})]$ are given by:

$$Re(H_i^* \hat{\xi}) \quad = \quad H_i^{Re} \hat{y}^{Re} + H_i^{Im} \hat{y}^{Im} - |H_i|^2 \hat{s}_i, \tag{9}$$

$$\begin{aligned} \mathbf{V}[Re(H_i^* \hat{\xi})] &= (H_i^{Re})^2 \mathbf{V}(\hat{y}^{Re}) + (H_i^{Im})^2 \mathbf{V}(\hat{y}^{Im}) \\ &\quad - |H_i|^4 \mathbf{V}(\hat{s}_i) + 2 H_i^{Re} H_i^{Im} \phi, \end{aligned} \tag{10}$$

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[2] The rationale of allocating a different power $\rho_{n,m}$ to each of the $\mathcal{L}_n$ layers is philosophically similar to that of the multilevel coding concept, where we create a number of different protection levels and detect them by gleaning extrinsic information from the previously decoded levels using multistage decoding.

[3] The associated phase rotation has two benefits, namely that of 1) reducing the Peak-to-Average Power Ratio (PAPR) of the transmitted "super-symbol" $\mathbf{x}_n$; 2) making the "super-symbol" having $\mathcal{L}_n$ layers more distinguishable for the detector.

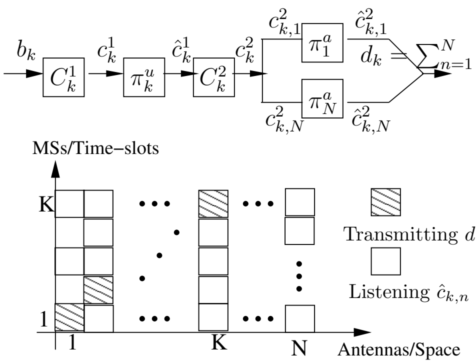

Fig. 3. The Phase-I cooperation of the K-user UpLink IDM-STC

where we have $\phi = \sum_{i=1}^{N\mathcal{L}} H_i^{Re} H_i^{Im} \mathbf{V}(\hat{s}_i)$ and $Im(\cdot)$ represents the imaginary part of a complex number. The soft estimate $\hat{y}^{Re}$ and its variance $\mathbf{V}(\hat{y}^{Re})$ may be expressed as:

$$\hat{y}^{Re} = \sum_{i=1}^{N\mathcal{L}} H_i^{Re} \hat{s}_i, \tag{11}$$

$$\mathbf{V}(\hat{y}^{Re}) = \sum_{i=1}^{N\mathcal{L}} (H_i^{Re})^2 \mathbf{V}(\hat{s}_i) + \sigma_n^2. \tag{12}$$

We remark that Eq. (11) and Eq. (12) also hold for the imaginary counterpart. The soft estimate $\hat{s}_i$ can be represented as $\hat{s}_i = \tanh(L_{DET}^a(s_i)/2)$, while its variance is given by $\mathbf{V}(\hat{s}_i) = 1 - \hat{s}_i^2$. Thus, the extrinsic information $L_{DET}^e(s_i)$ is given by:

$$L_{DET}^e(s_i) = 2|H_i|^2 \frac{Re(H_i^* y) - Re(H_i^* \hat{\xi})}{\mathbf{V}[Re(H_i^* \hat{\xi})]}. \tag{13}$$

Then the extrinsic information $L_{DET}^e(s_i)$ of each bit s_i detected by the DET is sorted in the required order for creating the sequence $L_{DET}^e(\hat{c}_{k,n}^2)$. This is used as *a priori* information to be forwarded to the DECs, which computes the more reliable extrinsic information $L_{DEC_1}^e(c_k^1)$ for the next iteration. The iterations are terminated, when a predefined termination criterion is satisfied.

III. IDM-STC IN COOPERATIVE COMMUNICATIONS

A. Phase-I Cooperation

Before transmitting the cooperatively combined IDM-STC signals, all cooperating MSs' information should be exchanged, which we refer to as Phase-I cooperation. We assume the employment of a Time Division Duplexing (TDD) system, where this information is exchanged using different time-slots.

Let us now elaborate further on the Phase-I cooperation scheme of Fig. 3 designed for the IDM-STC arrangement. In time-slot k, MS k transmits a sigma mapped symbol $d_k = \sum_{n=1}^N \hat{c}_{k,n}^2$ to all the cooperating MSs. Then the nth cooperating receive antenna detects d_k, extracts $\hat{c}_{k,n}^2$ and ignores $\hat{c}_{k,i}^2, \forall i \neq n$. Since $N \leq 1/R$, we have a sufficiently high degree of freedom for detecting each bit of d_k using the turbo receiver introduced in Fig. 2. After successfully exchanging information across all the K MSs, the nth antenna transmits $\hat{c}_{k,n}^2$ of all the K cooperating MSs of Fig. 1.

Thus, the initial Phase-I cooperation of IDM-STC imposes a K-slot transmission overhead, which is equal to the number of cooperating MSs K, upon exchanging information amongst the cooperating MSs. Hence, as far as the entire TDD system is concerned, setting aside K time-slots for Phase-I cooperation may be viewed as reducing the effective throughput by K time-slots for the sake of achieving Nth-order diversity.

B. Effective Throughput

1) Traditional STBC: Consider having $K = 2$ or $K = 4$ cooperating MSs in a cluster using a traditional G_2 STBC [2]:

$$\mathbf{G}_2 = \begin{bmatrix} -x_2^* & x_1 \\ x_1^* & x_2 \end{bmatrix}$$

or G_4 type STBC [10]:

$$\mathbf{G}_4 = \begin{bmatrix} -x_4^* & -x_3^* & -x_2^* & x_1^* & -x_4 & -x_3 & -x_2 & x_1 \\ -x_3^* & x_4^* & x_1^* & x_2^* & -x_3 & x_4 & x_1 & x_2 \\ x_2^* & x_1^* & -x_4^* & x_3^* & x_2 & x_1 & -x_4 & x_3 \\ x_1^* & -x_2^* & x_3^* & x_4^* & x_1 & -x_2 & x_3 & x_4 \end{bmatrix}.$$

The traditional STBC used in cooperative communications operates as follows: 1) the cooperating MSs first exchange their information, which requires K time-slots; 2) given that all MSs now have the signals of all other MSs, conventional STBC transmission of $x_k, \forall k$ takes place using all $N = K$ antennas of the K MSs according to the above matrices.

For the sake of achieving a high throughput, each symbol x_k can be modulated to an $\mathcal{M}$-ary modulation constellation, where we have $\mathcal{M} = 2^m$ and m denotes the number of bits/symbol. The effective throughput per user excluding the overhead of the Phase-I inter-MS data exchange can thus be defined as:

$$\eta_{STBC} = \frac{r_{STBC} \times \log_2 \mathcal{M}}{K}. \tag{14}$$

2) IDM-STC: In the IDM-STC scheme considered, the overhead imposed by the Phase-I cooperation is constitute by K slots, which is equivalent to the traditional STBC. The effective throughput per user, excluding the overhead of IDM-STC may be expressed as:

$$\eta_{IDM} = \frac{r_{IDM} \times \mathcal{L}}{K}, \tag{15}$$

where r_{IDM} was defined in Eq. (1) and the number of layers $\mathcal{L}$ was defined in Eq. (2).

C. Interleaver Allocation

In our IDM-STC based cooperative scheme, we employ the so-called embedded interleavers of [13], where the kth MS's user-specific interleaver π_k^u constitutes a further interleaved version of the $(k-1)$st MS's interleaver π_{k-1}^u using a common "base" interleaver π^u, hence their relationship may be expressed as $\pi_k^u = \pi^u(\pi_{k-1}^u)$. This is the same for the antenna-specific interleaver allocation, where we have $\pi_n^a = \pi^a(\pi_{n-1}^a)$ and π^a is the common "base" interleaver. These two "base" interleavers are generated randomly in this paper.

IV. BENEFITS OF IDM-STC

In this section, we compare our IDM-STC based cooperative communications scheme to the traditional G_2 and G_4 STBC scheme [10]. We assume that the channels between the $N = K$ cooperating MS transmitters and the BS receiver are i.i.d narrowband Rayleigh fading channels and perfect CSI at the BS receiver. Two scenarios are investigated, namely 1) *Fast fading*: the channels exhibit a normalized Doppler frequency of $f_d = 0.02$. 2) *Block fading*: the channels remain constant over each block but change between different blocks.

We stipulate furthermore that the information exchange amongst MSs is error-free. The transmission frame length in our simulations was set to 800 bits and the maximum number of iterations used was $I = 20$.

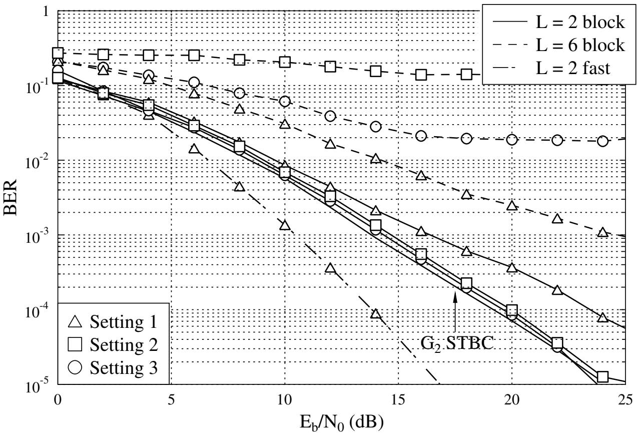

Fig. 4. Comparison of the three typical code-rate settings of IDM-STC to that of G_2 STBC in cooperative communications.

A. Investigation of IDM-STC

In this subsection, we illustrate IDM-STC having three typical values of C^1 and C^2 as mentioned in Section II, given a fixed total code-rate of $R = 1/4$ compared to the G_2 STBC benchmarker represented by the solid line seen in Fig 4, where we have $K = N = 2$. The three code-rate settings are 1)$r_1 = 1/4$ and $r_2 = 1$; 2)$r_1 = 1$ and $r_2 = 1/4$; 3)$r_1 = 1/2$ and $r_2 = 1/2$.

As seen in Fig 4, in the block-fading scenario, both Setting 2 and 3 have a similar BER as the G_2 STBC, implying that these two IDM-STCs are capable of achieving full transmit diversity, as the G_2 STBC. By contrast, Setting 1 has the worst performance, since it is unable to guarantee that the coded bits equally allocated to the transmit antennas, because they may be mapped by the S/P to the same antenna, resulting in a loss of transmit diversity gain. However, when fast fading is encountered, Setting 1 is superior in comparison to the G_2 STBC, since both transmit diversity and time diversity are available.

When a sufficiently high number of layers, such as $\mathcal{L} = 6$ is employed, Setting 1 was seen to be best in Fig 4, while Setting 2 is incapable of supporting the high throughput of Setting 1, which was 3 bits/symbol. This implies that Setting 1 is a high-throughput multiplexing-oriented configuration, while Setting 2 is a low-throughput diversity-oriented configuration. In our forthcoming simulations, we employ Setting 1 aiming at achieving a high rate.

B. Benefit 1 - Power Efficiency

In this subsection, we consider uniform power allocation.

1) Comparison to G_2 STBC: Fig. 5 shows the BER performance of the G_2 STBC scheme using various M-ary modulation schemes and IDM-STC invoking a total code-rate of $R = 1/4$ and having different number of layers. For fast fading, a single-MS, single-layer system having $N = 2$ distributed antennas using IDM-STC was simulated, which served as a benchmarker. Clearly, Fig. 5 suggests that the IDM-STC had a steeper BER slope, when the number of layers $\mathcal{L}$ was as high as 6 and a significant E_b/N_0 gain was observed at $BER \leq 10^{-4}$. In this case, the effective throughput of IDM-STC was $\eta_{IDM} = 6/4$ according to Eq. (15), which is equivalent to G_2 STBC using 8PSK modulation. However, the effective throughput of IDM-STC will be lower than that of a G_2 STBC using a 4 bits/symbol modulation scheme. By contrast, in the block fading scenario characterized in Fig 5, the IDM-STC is inferior to G_2 STBC, when the number of IDM-STC layers obeys $\mathcal{L} \geq 4$.

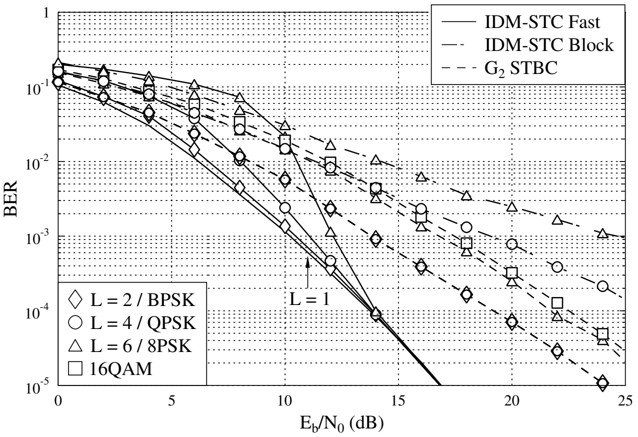

Fig. 5. BER performance of G_2 STBC and IDM-STC having $R = 1/4$ over both fast fading and block fading in cooperative communications.

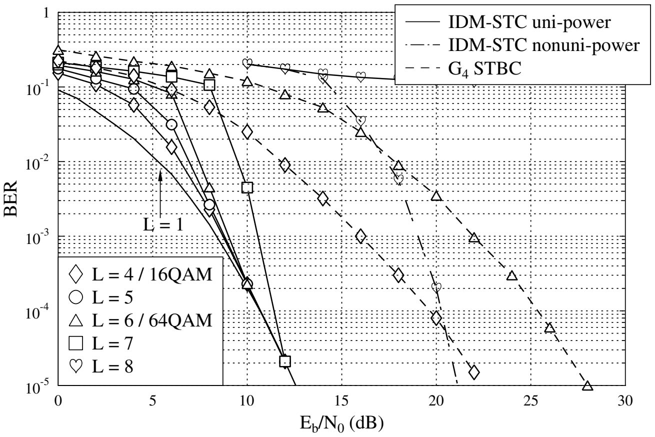

Fig. 6. Performance of G_4 STBC and IDM-STC over fast fading in cooperative communications, where $\mathcal{L} = 4, 5, 6, 7$ layers corresponding upto 7 bits/symbol transmission were supported. Additionally, with the aid of non-uniform power allocation, $\mathcal{L} = 8$ layers can be supported.

2) Comparison to G_4 STBC: Let us now compare IDM-STC having $R = 1/8$ to the above G_4 STBC in cooperative communications, where we have $K = N = 4$. Fig. 7 shows the achievable BER performance of IDM-STC in the block-fading scenario. Although a reduced performance was observed for IDM-STC compared to that of the fast-fading scenario of Fig. 6 owing to the lack of time diversity, they are both superior to that of the G_4 STBC. In Fig. 6, a single MS assisted by $N = 4$ distributed antennas using IDM-STC was characterized, which served as a benchmarker. It can be seen in both Fig. 7 and Fig. 6 that the maximum number of layers $\mathcal{L}$ supported was $\mathcal{L} = 7$, which is equivalent to a G_4 STBC scheme using a large and hence error-sensitive 128-QAM constellation, while requiring a lower power than the 4 bit/symbol G_4 STBC aided 16-QAM scheme, as observed at $BER \leq 10^{-5}$.

Thus a significant power gain can be observed compared to the G_4 STBC both under fast-fading as well as block-fading conditions. In this case we have $r_{IDM} = r_{STBC} = 1/2$, implying that IDM-STC does not suffer a rate loss in comparison to G_4 STBC.

C. Benefit 2 - Achieving an Increased Throughput

In this subsection, in addition to uniform phase rotation, non-uniform power allocation is also considered. In this paper, no attempts were made to formally optimize the power allocation scheme. Instead, the following simple non-uniform power allocation strategy [14]

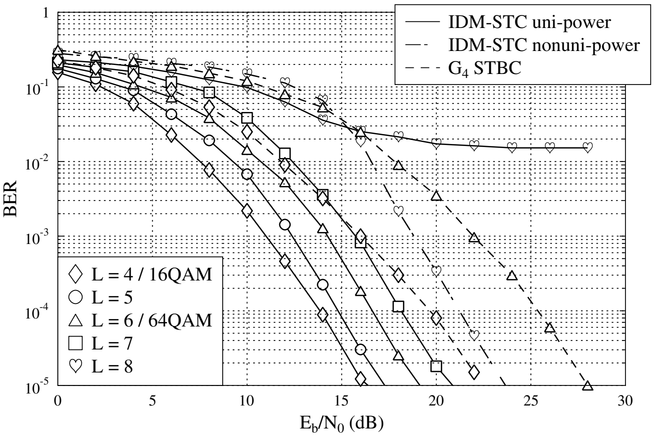

Fig. 7. Performance of G_4 STBC and IDM-STC over block fading in cooperative communications, where $\mathcal{L} = 4, 5, 6, 7$ layers corresponding upto 7 bits/symbol transmission were supported. Additionally, with the aid of non-uniform power allocation, $\mathcal{L} = 8$ layers can be supported.

η	G_4 / IDM-STC	Δ_1^f/Δ_1^b	Δ_2^f/Δ_2^b
4/8	$\mathcal{M} = 16$ / $\mathcal{L} = 4$	9 / 6	- / -
5/8	$\mathcal{M} = 32$ / $\mathcal{L} = 5$	9 / 5	- / -
6/8	$\mathcal{M} = 64$ / $\mathcal{L} = 6$	14 / 4	24 / 9
7/8	$\mathcal{M} = 128$ / $\mathcal{L} = 7$	8 / 2	23 / 7
8/8	$\mathcal{M} = 256$ / $\mathcal{L} = 8$	-1 / -1	4 / 4

TABLE I

THE POWER GAIN Δ IN dB OF IDM-STC COMPARED TO G_4 STBC IN COOPERATIVE COMMUNICATIONS, WHERE Δ_1, Δ_2 DENOTES THE POWER GAIN CORRESPONDING TO 16-QAM AND 64-QAM IN G_4 STBC, RESPECTIVELY. THE SUPERSCRIPT f AND b DENOTE FAST FADING AND BLOCK FADING, RESPECTIVELY.

was adopted[4]. Consider the length-$\mathcal{L}$ weighting coefficient vector $\mathbf{u}$, which obeys:

$$\rho_{m+1}^2 = \rho_m^2/\beta, \qquad (16)$$

while ensuring that $\sum_{m=1}^{\mathcal{L}} \rho_m^2 = P_n$, where we refer to $\beta \geq 1$ as the scaling factor and P_n is the maximum total power of the nth transmitter antenna, which is assumed to be equal for all N different antennas.

Returning briefly to Fig. 6 and Fig. 7, they also show the achievable BER performance of IDM-STC, when using non-uniform power allocation. Upon investigating the most appropriate values of β experimentally, $\beta = 1.2$ was found to be adequate and the number of layers for which an adequate BER performance was attainable was found to be as high as $\mathcal{L} = 8$, corresponding to a 256-QAM modulated 8 bits/symbol G_4 STBC scheme, while requiring a lower power than the 6 bits/symbol G_4 STBC aided 64-QAM scheme.

The achievable power gain of IDM-STC used in cooperative communications was summarized in Table I, where Δ was the E_b/N_0 gain of IDM-STC at $BER = 10^{-4}$ over conventional G_4 STBC scheme having identical-throughput, i.e. we had $\Delta = (E_b/N_0)_{STBC} - (E_b/N_0)_{IDM}$.

D. Benefit 3 - Flexibility

The design flexibility of IDM-STC allows the employment of an arbitrary number of antennas. This implies that IDM-STC based cooperative communications can be used in diverse cooperative scenarios. More explicitly, when $R = 1/8$ IDM-STC was used, the system was capable of supporting $K = 2, 3, 4, 5$ cooperative MSs without designing different matrices when the traditional STBC code was employed.

Suffice to say, however that in most practical scenarios having a diversity order of more than five attains a near-AWGN BER performance and hence there is limited benefit in further increasing the diversity order, i.e. the number of cooperating antennas, in particular, when considering the effective throughput reduction imposed by the Phase-I inter-MS cooperation. This flexibility is beneficial in terms of forming a flexible cluster of cooperating MSs, allowing MSs to freely join or disjoin the cluster of cooperation.

V. CONCLUSION

In this paper, we analyzed the achievable IDM-STC performance in cooperative communications. The Phase-I inter-MS data-exchange was designed and an efficient interleaver allocation scheme was suggested. Compared to the traditional STBC based cooperative design, our proposed system is power-efficient and is capable of achieving a high throughput, especially in the case of non-uniform power allocation. Our scheme is flexible in terms of forming a cluster of cooperating MSs.

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[4] This power allocation strategy under consideration was derived in the context of capacity region assuming capacity-achieving codes.