Distributed Randomized Space-Time Coding for HF Transmission

Matthew Sharp, Anna Scaglione
School of Electrical and Computer Engineering
Cornell University, Ithaca, NY 14853

Stefano Galli
Telcordia Technologies
Piscataway, NJ, 08854

***Abstract*— *We propose an approach that enables increased range and throughput in over-the-horizon (OTH) High Frequency (HF) communications using a novel physical layer node cooperation scheme. By exploiting multiple (and sufficiently spaced apart) low-powered man-portable radios in a collaborative fashion, it will be possible to obtain diversity gains similar to Multiple Input Multiple Output (MIMO) systems and, therefore, to maximize link reliability, to increase communication range for a given throughput and power or, to increase throughput for a given range and power. Our schemes are based on randomized space-time coding in the framework of distributed cooperative networks. In this paper, we compare single and multi-carrier transmission schemes, and we show that, by increasing the number of nodes while keeping the total transmit power fixed, we can approach the diversity obtainable by conventional MIMO schemes. We also observe that the Time-Reversal Space-Time Block Coding scheme (TR-STBC) performs the best among the three schemes we compare. The proposed architecture will provide power savings and diversity gains that will increase the reliability of OTH-HF communications in the absence of terrestrial infrastructure.*

I. Introduction

A. Motivation

US naval preeminence in the open sea is well recognized; however, new challenges arise from the changing requirements for US military intervention throughout the world. One aspect of naval warfare that poses new challenges is the increasing shift of Navy operations towards littoral geography. Specifically, the Navy will have to enhance its ability to access in-theater bases and littoral waters when forward deployed or when attempting to deploy into theater. Moreover, the Navy will also have an increasing role in facilitating intervention on shore, while the Marines will continue to develop expeditionary maneuver warfare capability especially in undeveloped forward areas with limited supporting infrastructure. This shift in the role of the Navy and the Marines will necessitate enhanced OTH communications capabilities that allow secure voice and data communications during ship-to-shore movement, as well as, to the dismounted tactical warfighter in combat conditions over a wide range of distances in complex terrain. However, OTH-HF communications suffer from severe fading, time dispersion, and time-variation. In order to combat these harsh channel conditions, it would be desirable to introduce diversity. Space-time coding schemes are an attractive means for achieving diversity gains, and offer a relatively simple implementation.

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However, the use of space-time coding schemes for the HF channel is problematic since the separation between antennae required to harvest diversity is of the order of several hundred meters and cannot be achieved through a single portable radio. To solve this problem, we propose to use cooperative schemes as an effective means to obtain MIMO gains for the OTH-HF channel. Our schemes exploit multiple and sufficiently spaced apart low-powered man-portable radios in a collaborative fashion by introducing randomization in the space-time coding operation. The use of randomization allows us to obtain decentralized schemes that require the exchange of little or no overhead between the cooperating nodes, and that totally eliminate the need for the nodes to communicate to a central control unit. The design we propose is completely adaptive with respect to the number of transmitters engaged in a mission; hence, military personnel will be able to adjust the system capability in the field and on a case-by-case basis, providing additional flexibility and scalability in coping with diverse mission requirements.

B. Randomized Cooperative Access

Cooperative communication may be desirable in this scenario as multiple portable radios can be used to transmit a common message to a single destination. The spatial separation condition can be satisfied if the cooperating radios are widely spread. Recently, a randomized space-time coding scheme was proposed for distributed cooperative communication in [1]. In most distributed cooperative schemes, overhead control information is required to allocate the codes between cooperative nodes, making the application of these schemes inappropriate for ad-hoc networking scenarios. However, in this randomized space-time coding scheme, each radio transmits a random linear combination of the codewords that would be transmitted by all the antennas in a centralized space-time coding scheme. Hence, the node needs only to determine the transmission schedule, but not the specific code assignment. To determine the schedule, there is no need to have communication feedback from the nodes to the cooperative radios, since the source that issued the request for cooperation can include an appropriate training sequence to synchronize all nodes that are willing to cooperate. The scheme was shown to achieve the performance of a centralized space-time code in flat fading channels in

[1]. These schemes are also suitable for frequency-selective channels and can be adapted to space-time block precoding schemes which reap diversity through multi-path.

Specifically, the protocol would consist of two phases. In the first phase, the source issuing the request for cooperation sends a *Collaboration Request* packet containing a ML sequence for time synchronization, pilot tones for carrier offset estimation, and a known sequence for the cyclic redundancy check (CRC). The nodes would then measure their corresponding SNR's and error rates and accept the request only if both parameters satisfy a certain threshold. There is no feedback at this point, and immediately or shortly after sending the *Collaboration Request*, the source sends the data frame. The second phase then consists of the cooperating radios retransmitting, nearly synchronously, the randomized space-time coded version of the data. We note that the original source can also participate in this second phase.

C. Background

While a number of orthogonal space-time transmit diversity techniques have been proposed for flat-fading channels including Alamouti's scheme [2], the large delay spreads of frequency selective fading channels destroy the orthogonality of the received signals. There has been much work on extending these schemes to frequency-selective channels, such as space-frequency and space-time coding in combination with Orthogonal Frequency Division Multiplexing (SF-OFDM, ST-OFDM) [3], [4], and single carrier schemes such as the Time-Reversal STBC scheme (TR-STBC) [5].

The OFDM modulation scheme with a cyclic prefix can be used to transform frequency-selective fading channels into multiple flat fading channels. For frequency selective channels with large doppler spreads it was shown in [4] that the SF-OFDM scheme outperforms the ST-OFDM scheme but requires the complex channel gains between adjacent subcarriers to remain relatively constant. For frequency selective fading channels, the variations between subcarriers depends on the channel memory D, the power delay profile, and the symbol block size N.

The TR-STBC single-carrier scheme was designed for frequency selective channels and applies Alamouti's scheme to blocks of data. The receiver processes the received blocks with a spatio-temporal matched filter to decouple the decoding of the blocks. All of these schemes assume the channel is constant over the length of the codeword. However, in the case of the HF channel this assumption is not valid.

D. Paper Contribution

The contribution of this paper is the analysis of the performance of distributed cooperative randomized space time coding using single-carrier and multi-carrier transmission schemes with varying delay-spreads and doppler-spreads using the HF channel model. We demonstrate that by increasing the number of cooperating nodes while keeping the total transmit power fixed, we approach the obtainable diversity of the schemes. We further observe that the randomized TR-STBC scheme performs the best among the three schemes we compare.

II. System Model

We consider T cooperating nodes transmitting a common message, $\mathbf{s} = (s[0], ..., s[M-1])^T$, of length M. For the randomized cooperative transmission scheme, each cooperating node transmits a random linear combination of the L columns of the $K \times L$ matrix code $\mathbf{G}(\mathbf{s})$. The columns $\mathbf{x}_l$ of $\mathbf{G}(\mathbf{s})$ correspond to one of the L virtual antennae.

We further consider a doubly selective channel, with a complex baseband equivalent impulse response, $\tilde{h}_j(t,\tau)$, which is the response at time t to an impulse at time $t-\tau$ between the jth cooperating node and a sole receive antenna. The discrete time equivalent channel is given as:

$$\tilde{H}_j[l,k] = \int\int \tilde{h}_j(l/B-\nu,\tau)p(k/B-\nu-\tau)p(-\nu)d\tau d\nu$$

where $p(t)$ is the pulse shaping filter with bandwidth B. We assume that the channel has a finite memory D. The block discrete time model consists of a tall channel matrix $\tilde{\mathbf{H}}_j$ of size $(K+D)\times K$, where

$$\left[\tilde{\mathbf{H}}_j\right]_{l,k} = \tilde{H}_j[l,l-k] \quad (1)$$

The length $K+D$ received signal vector can then be expressed as

$$\begin{aligned} \mathbf{y} &= \sum_{j=1}^{T} \tilde{\mathbf{H}}_j \mathbf{G}(\mathbf{s})\mathbf{r}_j + \mathbf{w} & (2) \\ &= \sum_{l=1}^{L} \underbrace{\left(\sum_{j=1}^{T} \tilde{\mathbf{H}}_j r_{j,l}\right)}_{\mathbf{H}_l} \mathbf{x}_l + \mathbf{w} \\ &= \sum_{l=1}^{L} \mathbf{H}_l \mathbf{x}_l + \mathbf{w} & (3) \end{aligned}$$

where $r_{j,l}$ is the (j,l)th element of the randomization matrix $\mathbf{R}$ with columns $\mathbf{r}_j$ corresponding to random coefficients at the jth cooperating node, and $\mathbf{w}$ is zero-mean complex Gaussian noise. The statistics of the equivalent channels $\mathbf{H}_l$ and the code selection $\mathbf{G}(\mathbf{s})$ determine the diversity obtainable through the scheme. It is important to note that the receiver needs no knowledge of $\mathbf{R}$ and therefore needs only to acquire the parameters of the equivalent L channels $\{\mathbf{H}_l\}$ for equalization. The randomized cooperative transmission scheme is shown in Fig 1.

In [1], it was shown for the flat fading case and using codes $\mathbf{G}(\mathbf{s})$ that achieve full diversity, the full diversity L is achievable if the number of nodes T exceeds the number of virtual antenna L by one extra node. For the case where the $T \leq L$, the diversity obtainable was $O(T)$. Sufficient conditions on the distribution for $\mathbf{R}$ were also given to achieve the diversity. Obviously, since the algorithm is decentralized, the columns of $\mathbf{R}$ must be independent, because the nodes must select them independently. It has also been shown for

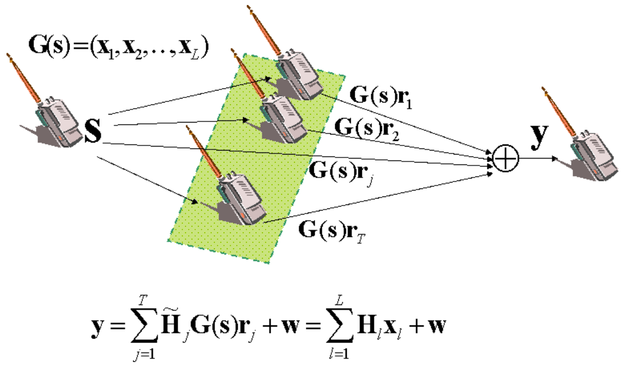

Fig. 1. Randomized Cooperative Transmission Scheme with T cooperating nodes

a time-invariant frequency-selective channel, the achievable diversity could be as large as the number of cooperating nodes T times the channel order D.

In Sections III and IV we express the vectors $\mathbf{x}_l$ for each transmission scheme, and briefly review the schemes. In Section V we outline the channel model and simulation parameters and in Section VI we discuss our simulated results.

III. Single-Carrier Modulation

We analyze two single-carrier schemes, that of Space Time Block Coding (STBC) and Time-Reversal Space Time Block Coding (TR-STBC) [5], in combination with the distributed cooperative randomized scheme.

A. Space-Time Block Coding (STBC)

As stated previously, the randomized single-carrier modulation scheme for doubly-selective channels can be modeled using (2), where the columns of the $K \times L$ code matrix $\mathbf{G}(\mathbf{s})$ can be expressed as:

$$\mathbf{x}_l = \mathbf{A}_l \mathbf{s} + \mathbf{B}_l \mathbf{s}^* \tag{4}$$

and the matrices $\mathbf{A}_l$ and $\mathbf{B}_l$ uniquely specify the particular space time code.

In order to perform linear or decision feedback equalization of a standard space time code, it is necessary to process several blocks of the received data. If we consider Q blocks of data, $\mathbf{S} = vec(\mathbf{s}_0, \mathbf{s}_1, ..., \mathbf{s}_{Q-1})$, where the channel order D is such that $2D \leq QK$, and that guard intervals are placed at the edge of each block, we can express the received signal as:

$$\mathbf{y} = \sum_{l=1}^{L} \mathbf{H}_l \tilde{\mathbf{x}}_l + \hat{\mathbf{w}} \tag{5}$$

where the equivalent tall channel matrix $\mathbf{H}_l$ is the same as in (3) and the vector $\tilde{\mathbf{x}}_l = (\mathbf{I} \otimes \mathbf{A}_l)\mathbf{S} + (\mathbf{I} \otimes \mathbf{B}_l)\mathbf{S}^*$ is the concatenation of the lth columns of $\mathbf{G}(\mathbf{s}_q)$ for $0 \leq q < Q-1$. The Kronecker product is denoted by $\otimes$. For purely frequency selective channels, the channel matrices $\mathbf{H}_l$ would have a Toeplitz structure as opposed to the banded structure when the channels are doubly-selective. To perform linear equalization we introduce the vector $\tilde{\mathbf{y}}$

$$\begin{aligned}
\tilde{\mathbf{y}} &= vec(\mathbf{y}, \mathbf{y}^*) = \mathbf{M}\tilde{\mathbf{s}} + \tilde{\mathbf{w}} \\
\mathbf{M} &= \begin{pmatrix} \sum_{l=1}^{L} \mathbf{H}_l (\mathbf{I} \otimes \mathbf{A}_l) & \sum_{l=1}^{L} \mathbf{H}_l (\mathbf{I} \otimes \mathbf{B}_l) \\ \sum_{l=1}^{L} \mathbf{H}_l^* (\mathbf{I} \otimes \mathbf{B}_l^*) & \sum_{l=1}^{L} \mathbf{H}_l^* (\mathbf{I} \otimes \mathbf{A}_l^*) \end{pmatrix} \\
\tilde{\mathbf{s}} &= vec(\mathbf{S}, \mathbf{S}^*) \\
\tilde{\mathbf{w}} &= vec(\hat{\mathbf{w}}, \hat{\mathbf{w}}^*)
\end{aligned} \tag{6}$$

where $vec(\cdot)$ denotes the column vector formed by stacking the columns of $(\cdot)$, and $(\cdot)^*$ denotes the complex conjugate. Alternatively we can use the following mapping

$$\begin{aligned}
\tilde{\mathbf{y}} &= vec(\Re[\mathbf{y}], \Im[\mathbf{y}]) = \mathbf{M}\tilde{\mathbf{s}} + \tilde{\mathbf{w}} \\
\tilde{\mathbf{s}} &= vec(\Re[\mathbf{S}], \Im[\mathbf{S}]) \\
\tilde{\mathbf{w}} &= vec(\Re[\hat{\mathbf{w}}], \Im[\hat{\mathbf{w}}])
\end{aligned}$$

Using these models, linear and decision feedback equalizers can be designed.

B. Time-Reversal STBC

For the Time-Reversal STBC, first proposed in [5], the transmitter splits the data symbols $\mathbf{S}$ into two blocks $\mathbf{S}_1$ and $\mathbf{S}_2$ each of length $N = MQ/2$ to be transmitted from two antennas. We can then define the vectors $\tilde{\mathbf{x}}_1$ and $\tilde{\mathbf{x}}_2$ in (5) as

$$\tilde{\mathbf{x}}_1 = \begin{bmatrix} \mathbf{S}_1 \\ \mathbf{p} \\ -\acute{\mathbf{S}}_2^* \end{bmatrix}, \quad \tilde{\mathbf{x}}_2 = \begin{bmatrix} \mathbf{S}_2 \\ \mathbf{p} \\ \acute{\mathbf{S}}_1^* \end{bmatrix} \tag{7}$$

where the vector $\mathbf{p}$ consists of zero guard intervals or a training sequence in order to avoid inter-block interference (IBI), and $\acute{(\cdot)}$ denotes the time-reversal operation. At the receiver, the second received block, $\acute{\mathbf{y}}_2^*$, is time reversed and conjugated, then combined with the first received block $\mathbf{y}_1$:

$$\underbrace{\begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} \mathbf{H}_1 & \mathbf{H}_2 \\ \acute{\mathbf{H}}_2^* & -\acute{\mathbf{H}}_1^* \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} \mathbf{S}_1 \\ \mathbf{S}_2 \end{bmatrix}}_{\mathbf{S}} + \underbrace{\begin{bmatrix} \mathbf{w}_1 \\ \mathbf{w}_2 \end{bmatrix}}_{\mathbf{w}} \tag{8}$$

After processing the received signal vector $\mathbf{y}$ with the spatio-temporal matched filter $\mathbf{H}^H$ we have

$$\tilde{\mathbf{y}} = \mathbf{H}^H \mathbf{y} = \mathbf{H}^H \mathbf{H} \mathbf{S} + \mathbf{H}^H \mathbf{w} \tag{9}$$

In this case, with frequency-selective channels constant over the two blocks, the spatio-temporal matched filter perfectly decouples the decoding of the data blocks $\mathbf{S}_1$ and $\mathbf{S}_2$. However, in the case of doubly-selective channels, the structure of the channel matrices is no longer Toeplitz but banded. As shown in [6], the performance of the TR-STBC scheme is much worse in the case of doubly-selective channels and two extensions were proposed for the scheme: 1) shortening the data block length and 2) extending the matched filtering to the time-varying channel.

IV. SPACE-FREQUENCY OFDM

Orthogonal frequency division multiplexing (OFDM) is a practical alternative to single-carrier techniques for communication over frequency-selective channels. For frequency-selective channels, the parallel transmission of data over orthogonal subcarriers with sufficient number of subcarriers and proper length cyclic prefix, results in computationally efficient and simple data detection, due to the circular nature of the channel convolution matrix. However, in doubly-selective channels, the orthogonality of OFDM is lost, and results in inter-carrier interference (ICI) complicating the data detection. In [3], [4] transmit diversity schemes using OFDM were introduced, namely Space-Time OFDM (ST-OFDM) and Space-Frequency OFDM (SF-OFDM). The SF-OFDM scheme was shown to perform better than ST-OFDM in fast fading environments when the doppler spread is large.

A. SF-OFDM

In the SF-OFDM scheme the data symbols $\mathbf{S}$ are coded into a $N \times L$ matrix $\tilde{\mathbf{X}}$ according to code matrix $\mathbf{G}(\mathbf{s})$:

$$\underbrace{\begin{bmatrix} \tilde{\mathbf{x}}_1 & \tilde{\mathbf{x}}_2 & \dots & \tilde{\mathbf{x}}_L \end{bmatrix}}_{\tilde{\mathbf{X}}} = \begin{bmatrix} \mathbf{G}(\mathbf{s}_0) \\ \mathbf{G}(\mathbf{s}_1) \\ \vdots \\ \mathbf{G}(\mathbf{s}_{Q-1}) \end{bmatrix} \tag{10}$$

Each of the columns of $\tilde{\mathbf{X}}$ is then modulated by an N-point inverse discrete Fourier transform (IDFT) and a cyclic prefix N_p ($D \leq N_p \leq N$) is added before transmitting over a frequency-selective channel of order D. Assuming the channel impulse responses remain constant over the entire block interval, the received signal vector $\mathbf{y}$ can be expressed as:

$$\mathbf{y} = \sum_{l=1}^{L} \mathbf{H}_l \mathbf{F}^H \tilde{\mathbf{x}}_l + \mathbf{w} \tag{11}$$

where $\mathbf{F}^H$ denotes the IDFT operation and addition of the N_p length cyclic prefix. For the frequency selective case, the convolutions are cyclic, therefore at the receiver, the multi-path corrupted cyclic prefix is removed and receiver computes the N-point DFT of $\mathbf{y}$. Since the DFT of a cyclic convolution in the time-domain results in multiplication in the frequency domain, the demodulated signal vector $\mathbf{Y}$ is given by:

$$\mathbf{Y} = \sum_{l=1}^{L} \mathbf{\Lambda}_l \tilde{\mathbf{x}}_l + \tilde{\mathbf{w}} \tag{12}$$

where $\mathbf{\Lambda}_l$ is a diagonal subcarrier decoupling matrix whose elements are the DFT's of the respective frequency-selective channel impulse responses $\mathbf{h}_l$. For the case where the code matrix corresponds to the Alamouti space time code [2], the space-frequency decoder can construct the decision estimate vector $\hat{\mathbf{S}}$ as:

$$\begin{aligned} \hat{\mathbf{S}}_e &= \frac{\mathbf{\Lambda}_{1,o}^* \mathbf{Y}_e + \mathbf{\Lambda}_{2,e} \mathbf{Y}_o^*}{(\mathbf{\Lambda}_{1,o}^* \mathbf{\Lambda}_{1,e} + \mathbf{\Lambda}_{2,o}^* \mathbf{\Lambda}_{2,e})} \\ \hat{\mathbf{S}}_o &= \frac{-\mathbf{\Lambda}_{1,e} \mathbf{Y}_o^* + \mathbf{\Lambda}_{2,0}^* \mathbf{Y}_e}{(\mathbf{\Lambda}_{1,o}^* \mathbf{\Lambda}_{1,e} + \mathbf{\Lambda}_{2,o}^* \mathbf{\Lambda}_{2,e})} \end{aligned} \tag{13}$$

where $(\cdot)_e$ and $(\cdot)_o$ correspond to the vectors created from the even and odd components of $(\cdot)$ respectively. In the case of a matrix, $(\cdot)_e$ and $(\cdot)_o$ correspond to the matrices whose diagonal consists of the even and odd elements of the diagonal of $(\cdot)$.

For the case of doubly-selective channels, the matrices $\mathbf{\Lambda}_l$ are no longer diagonal but now have entries on the sub and super diagonals. These banded matrix introduce ICI, complicating the symbol estimation task.

V. SIMULATION MODEL

We now outline the HF channel model and system parameters used in our simulations.

A. Channel Model

In order to establish long distance communication (over the horizon) we may use the HF channel. We model the doubly-selective channel using the Watterson channel model [7]. The model consists of a tapped-delay line modeling the delays τ (on the order of milliseconds) of the multi-path time-varying environment. Specifically, each path is modeled by a tap-gain function $G_v(t)$ characterized by its doppler spread σ_{dv}^2 and doppler shift f_{dv}, i.e. $h(t,\tau) = \sum_{v=1}^{V} G_v(t)\delta(\tau - \tau_v)$. As verified by Watterson, each tap-gain function can be modeled by an independent zero-mean complex-Gaussian stationary random process for each of the two resolvable magnetoionic components, whose power spectral density is the following Gaussian function:

$$\begin{aligned} \nu_v(f) &= \frac{C_{va}(0)}{\sqrt{2\pi\sigma_{dva}^2}} \exp\left[-\frac{(f - f_{dva})^2}{2\sigma_{dva}^2}\right] \\ &+ \frac{C_{vb}(0)}{\sqrt{2\pi\sigma_{dvb}^2}} \exp\left[-\frac{(f - f_{dvb})^2}{2\sigma_{dvb}^2}\right] \end{aligned} \tag{14}$$

where the subscripts a and b correspond to the two resolvable magnetoionic components and the subscript v corresponds to the path number. In our analysis, we use only one Gaussian component for $G_v(t)$ with negligible doppler shift ($f_{dv} = 0$) as recommended in [8]. The ratio of the output power to the input power is then specified by $C_v(0)$. The jth discrete time channel impulse response is then given by:

$$h[m,k] = \sum_{v=1}^{V} G_v[m] p_v[k] \tag{15}$$

where $p_v[k] = p(kT_s - \tau_v)$ is a Nyquist pulse shape with bandwidth B, and $G_v[m] = G_v(mT_s)$ is the vth discrete-time baseband tap-gain function with delay τ_v at time m.

B. System Parameters

The system parameters are chosen according to current military standards [9]. Specifically, we consider alternating blocks of pilot and data symbols, with a a bit-rate of 4.8 kbits/sec, and uncoded 8PSK symbol transmission. The lengths of the probe and data blocks are 16 and 32 symbols respectively. In all simulations the number of virtual antenna $L = 2$.

VI. Performance Comparison

We first consider the randomized cooperative scheme in a purely frequency selective channel with varying number of cooperative nodes. We observed in simulation that complex spherical random vectors had the best performance among the distributions examined for $\mathbf{R}$, hence we let the jth column of the matrix $\mathbf{R}$ be selected uniformly on the surface of a complex hypersphere of radius $\|\mathbf{r}_j\| = \sqrt{2/T}$. We compare the obtainable diversity of the randomized cooperative scheme compared to the centralized scheme with two transmit antenna and one receive antenna for a channel of order $D = 2$, perfectly estimated at the receiver.

In Fig. 3 we show the randomized cooperative scheme for T nodes in the 'poor' channel model as defined in [10], equivalent to 'moderate' conditions in low-latitudes in [8]. The differential time delay $\tau = 2$ ms and doppler spread $\sigma_d^2 = 1.5$ Hz for a two component multi-path fading environment with equal mean attenuation. We assume the channels seen by each antenna are independent with equivalent parameters. At the receiver, we assume the channel is constant over the block and a perfect channel estimate has been obtained at the beginning of each block. We also show the single antenna scheme for comparison.

In Fig. 4 we examine the BER of the randomized cooperative scheme again with T nodes and a fixed $SNR = E_b/No =$ 15 dB, differential time delay $\tau = 0.5$ms for varying doppler spreads and equal mean attenuation of a two component multi-path channel. Fig. 5 shows the same setup but for differential time delay $\tau = 2$ms.

As can be seen in Fig. 2, as the number of cooperating nodes T increases, the diversity approaches the diversity of the centralized scheme with $L = 2$. The TR-STBC and space-time coded scheme with an MMSE equalizer (STC-MMSE) obtain diversity through both space and time with uncoded transmission. As SNR becomes large enough, both schemes will outperform the SF-OFDM scheme which obtains only spatial diversity.

In Fig. 3, we see that the introduction of the HF channel decreases the performance of the schemes, and the BER starts to exhibit an error floor at higher SNR. The TR-STBC scheme significantly outperforms the other schemes for the 'poor' HF channel model. At a bit error rate (BER) of 10^{-3} the TR-STBC scheme provides about 5 dB of diversity gain over the STC-MMSE scheme. By implementing the extensions proposed in [6], the gain could be further increased.

The schemes all deteriorate rapidly as the doppler spread increases, as shown in Fig. 4. Again the TR-STBC scheme has the best performance among the schemes for smaller values of doppler spread. In Fig. 5, it is shown that the TR-STBC and STC-MMSE schemes have increased BER for larger values of delay spread, while the performance of the SF-OFDM scheme is inversely related to the delay spread, as mentioned previously.

The potential power gain from multiple cooperative nodes is omitted from these curves, though this is an obvious benefit

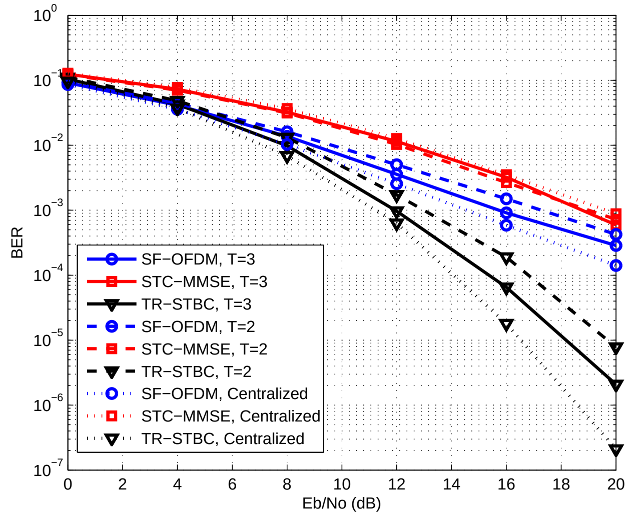

Fig. 2. Randomized Cooperative Scheme for T cooperating nodes for a frequency selective channel with order $D = 2$.

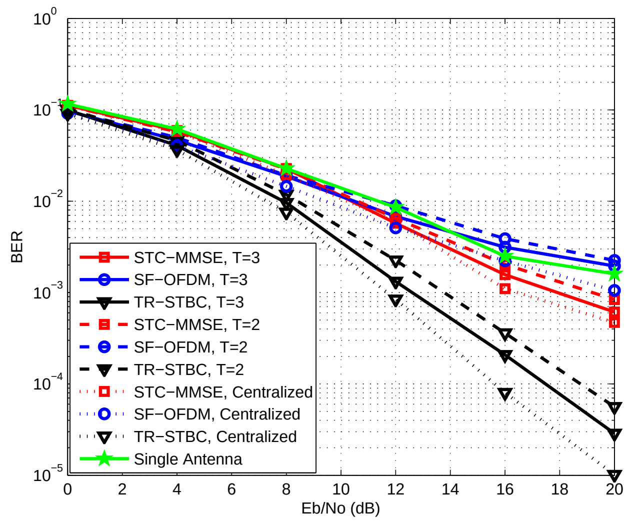

Fig. 3. Randomized Cooperative Scheme for T cooperating nodes for the 'poor' channel model.

of this architecture. Each additional node can potentially produce an additional power gain of 3 dB assuming the path attenuations are of the same order. However, a shadowing model for the large scale fading information is not available in a form that can be easily simulated.

VII. Conclusion

We have demonstrated through simulation that by using a randomized distributed cooperative space time coding scheme over an HF channel, we can achieve the diversity by increasing the number of cooperating nodes while still using the same total transmit power. For the schemes compared here, in the framework of randomized distributed cooperative scheme,

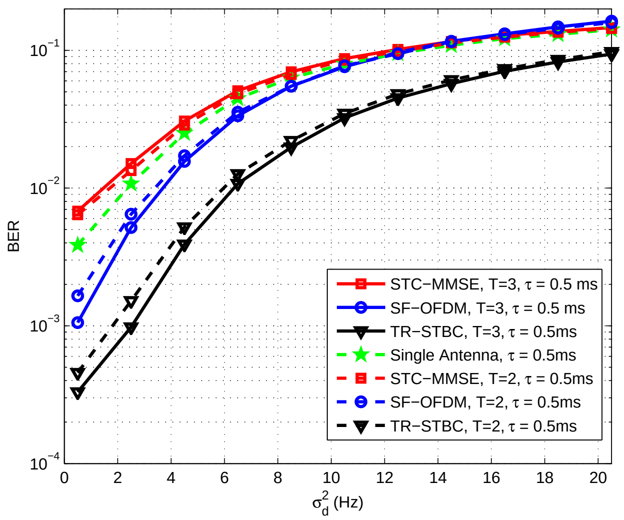

Fig. 4. Randomized Cooperative Scheme for T cooperating nodes for varying doppler spread and differential time delay $\tau = 0.5$ ms.

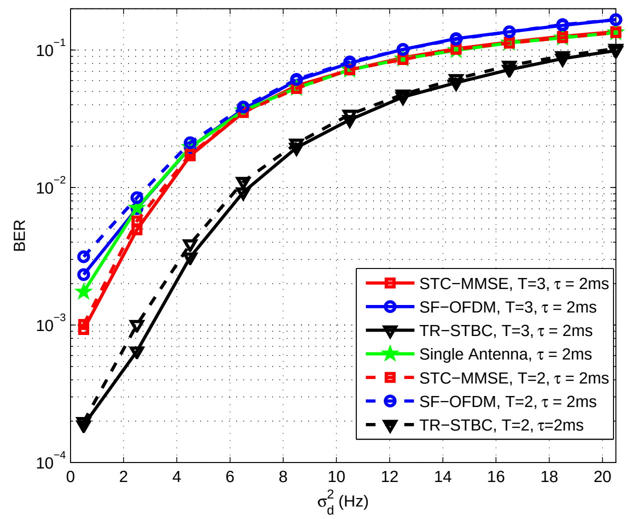

Fig. 5. Randomized Cooperative Scheme for T cooperating nodes for varying doppler spread and differential time delay $\tau = 2$ ms.

using uncoded transmission, it was seen that the TR-STBC performed significantly better than the SF-OFDM and STC-MMSE schemes for various delay spreads and doppler spreads.

The proposed randomized cooperative scheme will extend the reach and capability of Naval forces and, at the same time, will reduce the risk to Sailors and Marines while allowing the Navy to gain increased access to forward areas under all conditions. Shore-based or sea-based forces will be able to increase link reliability and move larger volumes of data over greater distances. Moreover, this capability would give commanders an improved picture of the extended battle area and improve their ability to successfully engage targets at extended ranges. The augmented capabilities that this project aims to give to the Navy will allow them to achieve better battlespace awareness, to synchronize battlespace awareness with combat operations, and to increase the speed of information dispersal throughout the force.

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