TRANSMIT DIVERSITY ENHANCEMENT FOR TACTICAL WIRELESS NETWORKING USING MULTI-CARRIER DISTRIBUTED SPACE-FREQUENCY CODING

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ABSTRACT

The size of handheld radios and sensors are continually shrinking, making multiple antenna scenarios difficult. Generating independent channels with tightly spaced, co-located antennae can also be challenging for small form factor radios. But with increasing miniaturization, SDR's are more intelligent, flexible and adaptive due to their nature of being software defined. By taking advantage of the increasing complexity of these nodes with their superior networking and cognitive applications, organizing multiple, single antenna nodes in a cooperative way one can achieve significant spatial separation and realize full diversity gains, significantly enhancing data throughput capacity. This paper studies a 2-user, Alamouti like, cooperative networking scheme by using a distributed space frequency diversity coding scheme for a multi-carrier (OFDM) waveform. Improved diversity order is shown using simulation and confirmed with demonstrations of over-the-air communications performed on a hardware test bed, illustrating that full space-frequency diversity is achievable. To further enhance performance robustness in multipath fading channels, coherent techniques are used on reception.

1. INTRODUCTION

Wireless networks experience time- and frequency-selective fading effects due to mobility and multipath, respectively. The interference caused by these fading effects can be mitigated using transmitter and/or receiver spatial diversity techniques. Single-user spatial diversity requires multiple co-located antennae at each node, however increasingly smaller node sizes may preclude the availability of multiple transmit/receive antennae required to enable spatial diversity gains. Fortunately an alternative to co-located antennae has been proposed by a number of researchers called *distributed coding*, which can improve diversity performance for spatially separated single-antenna network nodes if they operate in a cooperative way. As a subset of *distributed coding*, a space diversity scheme called *cooperative diversity* can be achieved by creating a *virtual array* when each node shares its antenna. The *virtual array* is formed by 2 or more nodes and has been shown to provide *full spatial diversity* [1]. The repetition-based cooperative diversity algorithms examined in [1] however do not provide comparable diversity performance to space-time coded cooperative diversity [2]. The space-time coded algorithms proposed in [2] provide full spatial diversity order N_u (N_u is the number of cooperating users), exhibit higher diversity order than repetition-based methods, and are favorable to non-cooperative transmissions when the normalized spectral efficiency is $\mathrm{R}_{\mathrm{norm}} < (N_u - 1)/(2N_u - 1)$.

In most existing cooperative diversity methods, perfect channel state information (CSI) is assumed at the receiver. Recently, however, non-coherent schemes which bypass channel estimation have been proposed to provide full diversity for multi-user cooperative transmissions [3]. However, even for non-coherent distributed spatial coding, independent synchronization offsets will be present at the receiving node relative to each transmitter and, if not accounted for, will degrade diversity performance. Consequently, few cooperative schemes are available which are proven to be robust to channel fading and time-frequency synchronization offsets. In this treatise, we extend the work of [3] to orthogonal frequency division multiplexing (OFDM), utilizing a preamble code and pilot symbol aided modulation (PSAM) to provide estimation and correction of any synchronization offsets. Hence, due to the availability of PSAM, we also estimate the mobile multipath channel response to provide coherent operation. We

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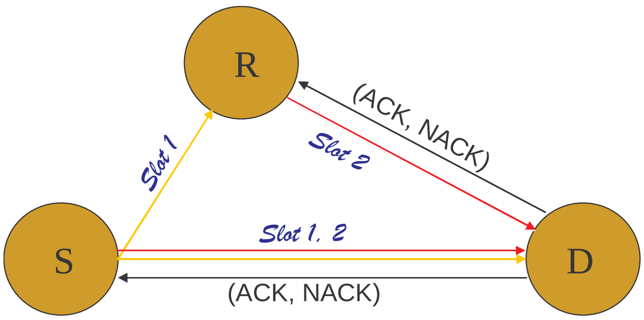

Figure 1: Mutli-user node network structure.

demonstrate that for a 2-user format with multipath fading channels and synchronization offsets, full diversity is achievable.

In Section 2, a simple 3-user model for multi-carrier cooperative networking method used for this work is described. In Section 3, we describe the channel model used and to discuss the independence of the channels for each transmission path. In Section 4, we describe the distributed MIMO test-bed system developed to measure and demonstrate performance of the multi-carrier wideband cooperative networking scheme. Section 5 concludes the paper.

2. MULTI-CARRIER COOPERATIVE NETWORKING

In [4], spatial diversity is suggested for performance advantages in many commercial terrestrial environments, leading us to assume the same advantages can also be realized for ground-based network centric systems. In addition, OFDM is suggested as a robust waveform for many terrestrial communications needs [4]. OFDM has also been proposed for high data rate line-of-sight (HDR-LOS) links over ship networks [5]. In HDR-LOS channels [5] suggests using receive spatial diversity to overcome long haul fade durations common in these links. In ship-to-ship networks, reflections from the water combined with the LOS path, can induce very large attenuation factors in the received signal [6]. Simple receive or transmit diversity (for example, co-located antennae), however, will do little to combat a range fade 10's of meters long. Additionally, shadowing has been shown to cause deep fades (greater than 20 dB) at receivers in terrestrial environments [7]. The OFDM cooperative scheme suggested in this work is designed to operate in such channels with multipath fading in addition to time and frequency synchronization offsets between transmit and receive nodes. The distributed nature of this multi-user coding structure will provide robustness to deep attenuation in the received signal because the relay node can achieve great spatial separation from the source and destination nodes, thereby assuring an independent channel having a high probability that it will not be in the same null as S to D. This section will describe the cooperative networking design and protocols and will describe our OFDM implementation. An assumption is made that each radio node has only a single-antenna and that our application is operating within a rich multi-path channel.

2.1. Cooperative Networking Protocols

The cooperative networking protocols identified by [3] each considers a system of N_u single antenna users combined, such that, diversity is exploited. The configurations utilize multiple transmit nodes for spatial diversity with a single antenna receiver called a destination node. In Figure 1, a basic 3- user network structure illustrates a 2-user cooperative setup, which can easily be extended to N_u-user cooperation. Each of the cooperative networking protocols has a source (S) node which has information to send to a destination (D) and a third node that relays the source information to D in an adjacent time slot. The relay (R) node provides the spatial diversity with S creating a virtual array at D by combining both receptions for processing. The relaying protocol we choose to utilize in this work is the incremental selection relaying (ISR) protocol [3], which means that any R nodes first evaluate the reception for accuracy prior to transmission on a NACK from D. As shown in Figure 2, the ISR scheme uses a time division format with each frame divided into two slots, simply called slot 1 and slot 2 for the transfer of frame Fi. In slot 1, S sends its data to D and D checks the CRC of the reception to determine if the reception was error free. If the reception was error free, an ACK is broadcast to all nodes; if the transmission was not error free, a NACK is returned, prompting R to transmit in time slot 2. This protocol eliminates redundant relay transmissions when an ACK is returned from D, thus the relay transmission will only occur in slot 2 of a given frame when necessary.

In our approach using wideband transmissions, certainly there will be some channels and/or segments of the spectrum that do not require *virtual array* formulation due to error free reception but, most probably there will be other portions of the spectrum that will require the services of a relay. The modifications for OFDM still form a *virtual array* in time; however a *virtual array* is also formed across all sub-carrier groups with the added freedom to form the array across each subcarrier or over groups of sub-carriers. Thus formed, the design of the protocol can be modified to allow the S to have continuous transmission to D in higher quality spectral regions by transmitting new data in slot 2 for ACK'd subcarriers. Implementing such a protocol would also help to minimize R's energy expenditures and improves the instantaneous transmission rate from S to D. This modification however, was not implemented in this work.

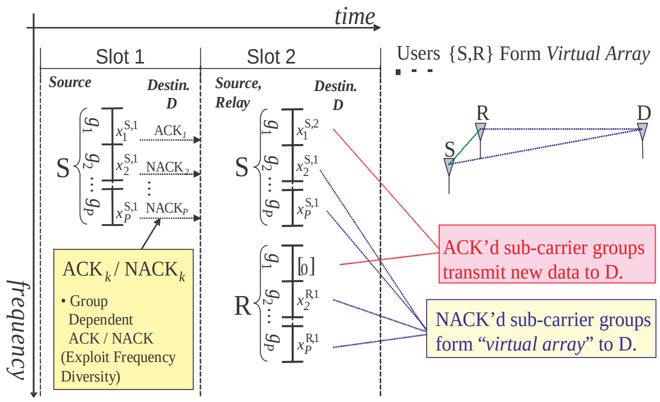

Figure 2: TDD-OFDMA channel access protocol

To devise such a scheme for OFDM, we can divide the data sub-carriers (N_d) into P groups, where the number of sub-carriers per group is $N_{spg} = N_d/P$, where $P \le N_d$. Using a low rate side-channel, just the relays or the source and relay nodes monitor the ACK/NACK status of each group and their slot 2 transmissions form a virtual array only for those sub-carrier groups with a returned NACK from D. We denote this ISR protocol for OFDM as enhanced-ISR (EISR), where only the NACK sub-carrier groups form a *virtual array* with D. In this scheme we denote L_{ACK} as the number of acknowledged sub-carrier groups, where $L_{ACK} \le$ P (acknowledged sub-carrier groups are the groups that do not need *virtual array* formation). This channel allocation approach can be denoted as a hybrid 2-slot TDD-OFDMA structure. If an efficiency enhancement is desired, the protocol could go as follows: In the first frame of slot 1, S transmits, but in slot 2, both S and R transmit, where R transmits on the NACK’d sub-carrier groups and S transmits on the ACK’d and NACK’d groups, providing new data on ACK’d subcarriers. Figure 2 shows the protocol channel access diagram.

In the EISR, assuming both slots are of the same duration denoted as T_1 and T_2, respectively, the total transmission rate $R = R_S(1+N_{ACK}/P)/2$, where R_S is the bit rate of S during slot 1. We can see that if $N_{ACK} = P$, R (= R_S) is maximized, and if $N_{ACK} = 0$, R (= $R_S/2$) is reduced but provides improved diversity order over all sub-carrier channels. Only in the situation where the relay knows the S information instantly and can transmit this information simultaneously with S (during slot 1), can R (= R_S) be maximized when the relay is transmitting. However, this scenario is not practical unless both S and R are connected via a wireline where S and R simultaneously receive data to be transmitted to D. We do not consider this case particularly energy efficient as the relay is always transmitting on all sub-carrier groups.

2.2. Cooperative OFDM Model

We choose to implement cooperative (distributed) spatial coding with OFDM. Multi-carrier (OFDM) waveforms are spectrally efficient and multipath robust, thus providing a natural combination with cooperative networking to enhance data through-put, significantly improve communications in harsh channels and by achieving full spatial gains. An additional benefit of using OFDM is that we can exploit frequency diversity to enhance the through-put efficiency.

Most cooperative networking schemes do not provide robust algorithms that operate well or are clear about their vulnerability to synchronization offsets. [8] develops OFDM in the context of cooperative transmissions with imperfect time and frequency synchronization. From [8] we see the total received signal can be written as

$$r(t) = \sum_{m-1}^{N_u} r_m(t - d_m) e^{j(2\pi f_m t + \theta_m)} + w(t), \tag{1}$$

where d_m, f_m, and θ_m are the time delay, frequency offset and carrier phase, respectively, for the mth transmitter. After cyclic prefix removal and an FFT operation at the receiver, the received signal, as a function of the kth sub-carrier for the ith OFDM symbol, is

$$y_{i,k} = \frac{1}{T_s} \sum_{m=1}^{N_u} A_m \sum_{k'=-N/2}^{N/2} x_{i,k',m} G_{k',m} \int_u^{Ts} e^{j2\pi\left(\frac{k'-k}{T_s}\right)u} du + w_{i,k}, \tag{2}$$

where $A_m = e^{(j2\pi f_m iT + \theta_m)}$ is a phase rotation as a function of i and $x_{i,k,m}$ is the data symbol for the ith OFDM symbol inserted at the kth frequency sub-carrier for the mth transmitter. T_s is the OFDM symbol length. The frequency domain channel coefficients are defined as

$$G_{k',m} = H_{k',m} e^{-j2\pi k' d_m / T_s} \tag{3}$$

A joint ICI mitigation and space-time block decoding scheme is developed in [8] to mitigate the effects of synchronization errors. However, without the removal of synchronization offsets, even the joint scheme in [8] reveals degraded performance (2-3 dB), which is undesirable. In this work, we separate the synchronization and decoding steps by first estimating and removing the synchronization offsets and then estimating the channel, followed by demodulation. The channel estimation and synchronization techniques used for this work are the same as those presented in [9]. We have found these estimators to easily provide sufficient estimation accuracy to enable negligible demodulation performance reductions at D. For our N_u = 2-user cooperative scheme, S and R are assigned unique synchronization preambles and OFDM pilot sequences to

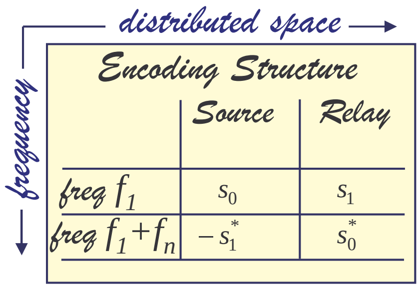

Figure 3: 2-user distributed-Alamouti OFDM encoding

ensure synchronization detection and channel estimation can be robustly performed for both the S and R nodes.

In our relay protocol, the "*virtual array*" is formed when both S and R transmit during slot 2, and the code structure used to form the "*distributed code*" is based on Alamouti's work [10]. Within the OFDM transmission, however, paired information symbols [$s0$, $s1$] are coded across space and frequency (as opposed to space and time like Alamouti's original implementation), reference Figure 3. Our motivation for utilizing a space-frequency coding structure is to enable the virtual array to be formed within a single OFDM symbol if necessary. Figure 4 shows a diagram illustrating the application of distributed-Alamouti code. Assuming negligible synchronization offsets, the received signal following the FFT operation is:

$$\begin{bmatrix} r_0 \\ r_1 \end{bmatrix} = \begin{bmatrix} h_s & h_r \\ h_r^* & -h_s^* \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + \begin{bmatrix} n_0 \\ n_1 \end{bmatrix}, \qquad (4)$$

where h_s and h_r are independent multipath channels from S to D and from R to D, respectively. h_s and h_r are estimated using the pilot symbols as described in [9]. In symbolic form, (4) can be written as $\underline{r} = \boldsymbol{h}\underline{s} + \underline{n}$. Maximum diversity, when coding across frequency, can be achieved with this system but requires the proper choice for the decoding algorithm. Vielmon etal. [11] pointed out that diversity performance varies dramatically when non-perfect correlation ($\rho < 1$) exists between the diagonal entries of the $\boldsymbol{h}$ matrix in (4). In fact, the diversity order can easily be cut in half or more simply by using a sub-optimal decoding algorithm. For this reason we chose to use a maximum likelihood (ML) decoder, which preserves the maximum achievable diversity order [11]. The ML decoding for (4) chooses the $[s_0\ s_1]^T$ symbol pair which minimizes $\|\underline{r} - \boldsymbol{h}\underline{s}\|$. More efficient near-ML decoders can be substituted; however that was not the focus of this work.

2.3. Cooperative OFDM Packet Structure

The packet structure utilized for this work includes a preamble, followed by 56 OFDM symbols per packet. The transmission is structured such that 1 packet is transmitted per slot. Unique m-sequence preambles are utilized to allow the receiver to independently acquire S and R, such that synchronization offsets can be adequately determined for both. Recall that during slot 1, only S transmits, and if we assume that the channel is approximately constant over 2 slots (or packets), then only R needs to transmit on the NACK'd subcarrier groups in slot 2. For this channel assumption (4) reduces to

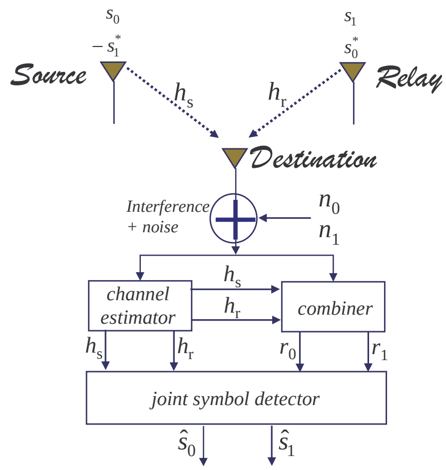

Figure 4: 2-user distributed-Alamouti system

$$\begin{aligned} \begin{bmatrix} r_0 \\ r_1^* \end{bmatrix} &= \begin{bmatrix} h_s & 0 \\ 0 & -h_s^* \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + \begin{bmatrix} n_0 \\ n_1 \end{bmatrix} (slot\,1) \\ \begin{bmatrix} r_0 \\ r_1^* \end{bmatrix} &= \begin{bmatrix} 0 & h_r \\ h_r^* & 0 \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \end{bmatrix} + \begin{bmatrix} n_0 \\ n_1 \end{bmatrix} (slot\,2) \end{aligned} \qquad (5)$$

The receptions for $\underline{r}$ and $\boldsymbol{h}$ in each slot are combined using maximal ratio combining (MRC) and then symbol pairs are detected using the ML decoder described in section 2.2. When the channel is approximately constant over two slots, the diagonal channel entries in $\boldsymbol{h}$ for h_s and h_r can be estimated in slots 1 and 2, respectively, using pilot symbols.

2.4. Cooperative OFDM Waveform Design

The OFDM physical layer waveform is designed to carry N total sub-carriers, with N_n null (unused) sub-carriers and N_{st} sub-carriers for data and pilot information. Here $N_{st} = N_d + N_p$, where N_d and N_p represent the number of data and pilot sub-carriers, respectively. While the preamble is used to acquire coarse timing, frequency, and carrier phase offset information, the pilots are utilized to provide fine estimates of these parameters along with estimation of the time-varying channel response. Additional waveform information can be obtained from [12].

In this work we chose, $N = 256$, $N_n = 64$, $N_p = 20$, and a baseband sample rate, $f_s = 1\text{x}10^6$ samples/sec. We utilize a guard interval, T_g = 15 μsec (N_g = 15 samples), and can choose between M = 4 or 16 for the modulation order. Conservatively, we assume each transmitted packet will need re-acquisition, and thus transmit a preamble in the first portion of every packet. The preamble consists of 4 PN "sub-blocks" in each packet (a sub-block is comprised of 2 PN codes). Each PN sub-block consists of N_{pre} samples. Therefore the total preamble length is N_{pre} x 4 = 1024 samples. An OFDM symbol consists $N + N_g$ = 271 samples. Each OFDM symbol hosts N_d x $\log_2(M)$ data bits. With 56 OFDM symbols per packet, each packet consists of 1024 + (56 x 271) = 16,200 samples and hosts 19,264 (M=4) or 38,528 (M=16) total data bits. With f_s = 1x10^6 samples/sec, a packet is 16.2 msec. and the OFDM waveform can achieve 1.2 and 2.4 Mbits/sec using M = 4 and 16, respectively. In a 750 kHz RF bandwidth, this provides an overall spectral efficiency of 1.6 and 3.2 bits/sec/Hz, respectively for M = 4 and 16. These bit rates can easily be increased due to the modular structure of the OFDM waveform and the flexibility of the "software" defined nature of the test-bed.

3. CHANNEL MODEL

During test bed evaluation of fading performance, we utilized the stochastic zero mean Gaussian Stationary Uncorrelated Scattering (GSUS) model to induce time-varying frequency selective fading according to a COST 207 typical urban (TU) delay profile [13]. The test bed was setup to induce independent multipath profiles from S to D and R to D, respectively. To provide a good statistical representation of a time-varying multipath channel, but consistent with the MRC structure in (5), the channel was held approximately constant during a 2-slot time period, but then changed independently over each subsequent 2-slot interval. While the channel may not change as rapidly on successive 2-slot intervals in practice, this allowed us to test many different multipath channel realizations without excessive simulation time. From Figure 3, paired symbols $[s_0, s_1]^T$ are coded across sub-carriers, such that $f_n = (f_s/N)^* N_{st}/2$. This ensures that the correlation, ρ, along the diagonal entries of $\boldsymbol{h}$ is less than 1, and allows us to test the diversity performance of the ML decoder. Using the GSUS channel model, we simulated the OFDM system using 4- and 16-QAM modulations, with a random timing offset of less than 128 samples and a frequency offset equal to or less than 300 Hz. The synchronization offsets from each transmit node to the receive node are assumed independent.

4. OFDM COOPERATIVE MIMO TEST BED

Our testing platform ("test bed") consists of two dual pentium computers; each computer is populated with two Red River Waverunner Plus cards. Each Waverunner card adds software defined transceiver capability mounted in the PCI backplane. Each transceiver card acts independently and, therefore each computer can be considered as a two channel transceiver. Hence, our setup can support a 2 X 2 MIMO configuration or any combination of 4 channel SIMO or MISO. The transceiver card uses a carrier frequency of 70 MHz and can operate in both a narrowband or wideband configuration. Both receiver and transmitter have SMB connectors to input or output RF energy to external amplifiers and antennae. Our test bed has been run with combinations of antenna's, attenuators and internal and external channel emulators.

The test bed does not run in real time because we run Matlab for baseband processing to achieve faster development cycles, combined with 'C' code that controls the Waverunner card. Our Matlab code generates the baseband transmit signal and, on reception, processes the baseband receive signal, which enables us to invoke our own internal channel models if desired or to use external channel simulators. The interaction between the waverunner card and Matlab takes place through DMA transfers to onboard Waverunner FIFO. The Waverunner provides digital filtering, A/D, D/A processes and up/down conversions.

In Figures 5 and 6, BER performance for the coherent distributed space-frequency coded OFDM system using 4- and 16-QAM, respectively are shown. Two curves are plotted in each figure, one trace exhibits statistics on S results only (denoted by the legend "SRC") and the second trace is for combined S and R results (denoted by the legend "SRC + REL"). For S only, the diversity order = 1, while for S + R, the diversity order = 2. Thus, we see that when the *virtual array* is formed to D using S + R a full diversity order = 2 is realized. This is evident for both the 4- and 16-QAM modulations

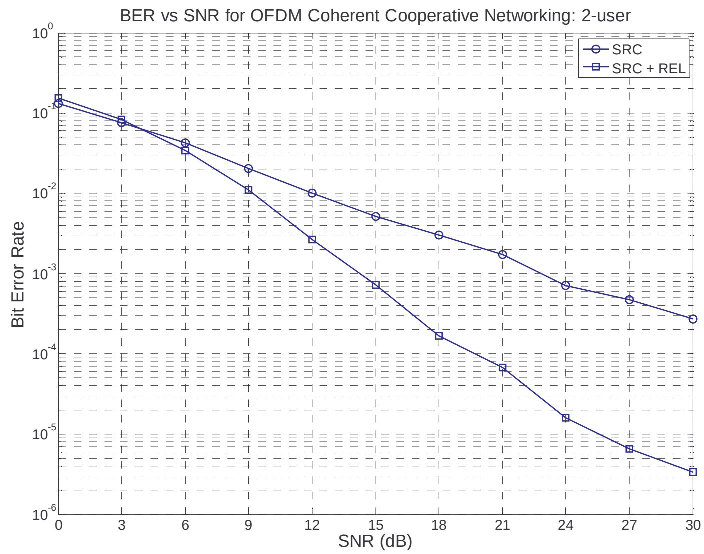

Figure 5: 4-QAM OFDM D-STC BER performance.

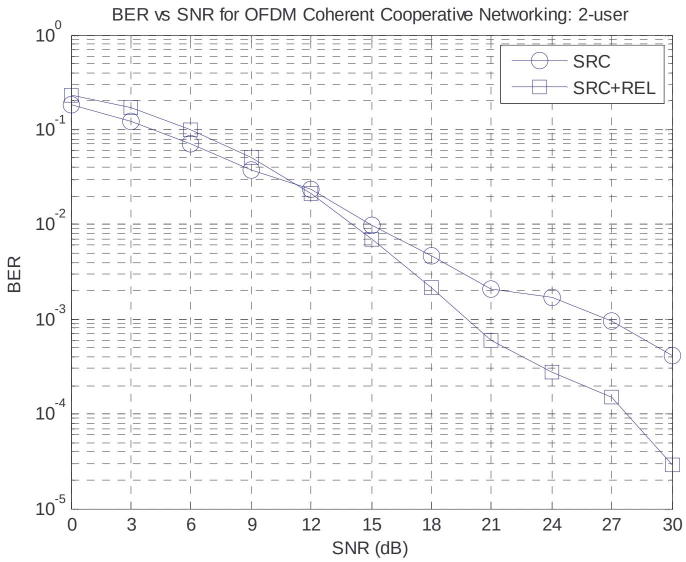

Figure 6: 16-QAM OFDM D-STC BER performance.

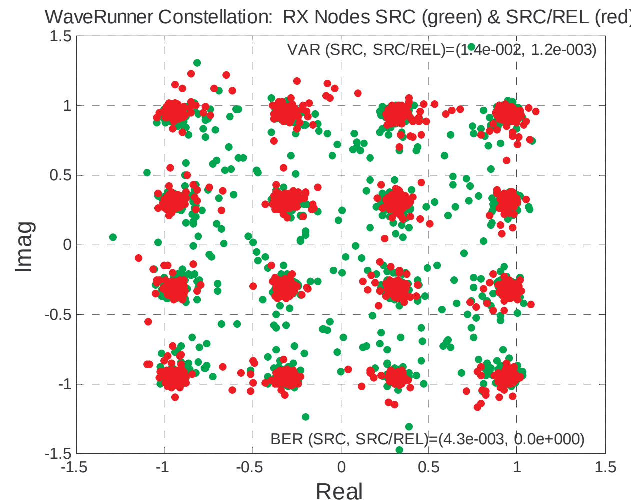

Figure 7: 16 QAM OFDM D-STC transmission showing the source transmission and relay transmission with respective demodulated BER's.

Similarly, the constellation plot shown in Figure 7, S data is in green and R data is in red. In the lower right corner of the graph,the BER's are shown with an independent S BER and a combined S + R BER. BER results gave improvements of up to 3 orders of magnitude for S + R, dependent upon the channel's multipath effects.

5. CONCLUSION

In this paper we presented a technique to provide robust receptions to wideband wireless data transmissions in time-varying multipath channels. The technique utilizes Orthogonal Frequency Division Multiplexing to provide robust multipath operation and applies a distributed space-frequency code to improve diversity. Maximum available diversity is achieved by exploiting the distributed nature of network nodes in a multi-hop network. Simulation and prototyping (with synchronization and channel perturbations) shows approximately a 9-dB and 7-dB SNR improvement is possible at a BER = 10^{-3} for 4-QAM and 16_QAM, respectively, demonstrating a significant diversity improvement.

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