SPACE-TIME REVERSAL TECHNIQUES FOR WIDEBAND MIMO COMMUNICATION

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ABSTRACT

This paper presents a framework for space-time reversal (STR) techniques in wideband MIMO communication systems for both single- and multi- user scenarios. We initially develop and analyze the STR framework in a point-to-point system which serves as a foundation and benchmark for multiuser scenarios. We also investigate an iterative STR scheme and discuss its connections to communication on the eigen modes of the space-time channel. We then explore the applicability of STR techniques in a multiuser setting, both in the broadcast and multiple-access modes. We present an initial set of observations on the convergence of the iterative STR technique in multiuser scenarios and using insights obtained in the single user setting, we propose and compare two different signaling mechanisms for multiuser systems that reliably separate the transmissions to/from different users. The relevant metrics in all the above scenarios are quantified analytically and illustrated with realistic simulation results.

1. INTRODUCTION

A considerable amount of research exists on the applicability of time-reversal (TR) in different fields including underwater communications, acoustic and ultrasound medical imaging, and material analysis (see, e.g., [1–3]). TR techniques for wireless communications have attracted significant attention recently due to their ease of implementation and ability to exploit the multipath nature of wireless channels (see, e.g., [4–6]). In TR, unlike traditional communication protocols, the receiver initiates communication by sending a training signal to the transmitter, and the transmitter then sends data to the receiver using the time reversed (and phase-conjugated) version of its acquired waveform. Under ideal conditions, due to channel reciprocity, this process eliminates the need for channel estimation or equalization at the receiver by focusing the transmitted energy in space and time at the target (receiver) location. For multiple antenna systems, this process can be referred to more aptly as space-time reversal (STR), due to the added spatial dimension.

Although the technique of TR is not new, a comprehensive theoretical investigation of STR for wideband MIMO communication is lacking. This paper attempts to alleviate this gap by presenting a basic framework to analyze STR in both single- and multi-user MIMO systems. In the first half of the paper, we develop and analyze the STR framework in a point-to-point wideband MIMO system which will serve as a foundation and benchmark for multiuser scenarios. We also investigate an iterative STR scheme [7] and characterize its convergence behavior in a point-to-point setting. Specifically, we demonstrate that the iterative STR process can be used to obtain the singular value decomposition (SVD) of the space-time channel. Depending on the originating node of the initial iterative transmission, the iterated STR signals are shown to converge to the left or right singular vectors of the channel.

Our initial interest in STR was sparked by promising results obtained in the context of wireless sensing via the active wireless sensing (AWS) framework [8] which highlighted the potential of STR techniques in multiuser communications. To explore the applicability of STR in any general multiuser setting, we provide some initial analysis and results for a point-to-multipoint setting in both the downlink (broadcast) and uplink (multiple-access) modes, concentrating on the asymmetric scenario with single-antenna users and multiple-antenna base stations. Our results in an asymmetric system with two users suggests that simple iterative STR procedures (see, e.g., [7]) do not provide reliable user separation. However, using the insights obtained in the single user setting, we propose two alternative signaling schemes, one using sinusoidal signals and another employing spread spectrum signals [8], which minimize the inter-user interference.

The rest of the paper is organized as follows. The next section introduces the STR framework for a single user point-to-point wideband MIMO system. In section 3 we present the iterative STR technique and analyze its convergence behavior. Section 4 extends the STR framework to any general point-to-multipoint communication setting. Finally in section 5, we discuss important research directions that are key to realizing STR techniques in practice. Wherever possible, we have included illustrative numerical results to support the analysis.

2. STR FOR SINGLE USER POINT-TO-POINT SYSTEMS

In this section, we develop and analyze the basic STR framework for single user point-to-point systems. We first introduce TR in a simple point-to-point wideband setting in section 2.1 and derive the underlying system equations. We then expand the notion of TR to multi-antenna systems, that is, space-time reversal (STR). Section 2.3 presents the system equations for the multiple antenna narrowband setting whereas section 2.3 analyzes the equivalent wideband case.

2.1. Single Antenna wideband TR

Consider a simple single antenna wideband communication system between two nodes, transmitter A and receiver B. In TR, the receiver B initiates communication by sending a training signal $\tilde{s}_B(t)$ of duration T and bandwidth W to the transmitter A. The received signal at A, $\tilde{r}_A(t)$ can be written as

$$\tilde{r}_A(t) = h(t) * \tilde{s}_B(t) = \int_0^{\tau_{max}} h(\tau)\tilde{s}_B(t-\tau)d\tau \qquad (1)$$

where $h(t)$ denotes the multipath channel between A and B with delay spread $\tau_{max} \ll T$ and $\tau_{max}W > 1$. Without loss of generality, assume that the transmitted signal $s_B(t)$ and the channel $h(t)$ have unit energy.

To simplify further analysis, we first represent $\tilde{s}_B(t)$ as a linear combination of $M = TW$ linearly independent vectors $q_i(t), i = 1, \ldots, M$, which form a complete basis for the given signal space, $\tilde{s}_B(t) = \sum_{i=1}^{M} s_{B,i}q_i(t)$. The equivalent vector representation is then given by $\tilde{\mathbf{s}}_B = \mathbf{Q}\mathbf{s}_B$, where $\mathbf{Q} = [\mathbf{q}_1 \cdots \mathbf{q}_M]$ is the $M \times M$ basis matrix and $\tilde{\mathbf{s}}_B$ and $\mathbf{s}_B$ denote the $M \times 1$ signal vectors. Although the above representation holds true for any complete basis $\mathbf{Q}$ for this M dimensional signal space, we restrict our attention in this paper to the sinusoidal or OFDM basis. Using an OFDM transmission with a cyclic prefix duration larger than the delay spread, the system equation (1) in vector notation is given by

$$\mathbf{r}_A = \mathbf{H}\mathbf{s}_B, \;\; \mathbf{H} = \mathrm{Diag}(h(1), h(2), \ldots, h(M)) \qquad (2)$$

where $\mathbf{r}_A$ denotes the received signal vector at A and the channel coefficients $h(i), i = 1, \ldots, M$, represent the M-pt DFT of the channel $h(t)$.

Node A now time-reverses (and phase-conjugates) the received signal $\mathbf{r}_A$, modulates it with the data bit b and retransmits it to node B. The equation relating the transmitted signal at A, $\mathbf{x}_A = b\delta_A\mathbf{r}_A^*$ to the received signal at B, $\mathbf{y}_B$, is

$$\mathbf{y}_B = \mathbf{H}^T\mathbf{x}_A = b\delta_A\mathbf{H}^T\mathbf{r}_A^* = b\delta_A\mathbf{H}^T\mathbf{H}^*\mathbf{s}_B^* = b\delta_A\mathbf{G}\mathbf{s}_B^* \qquad (3)$$

where δ_A is the energy normalization term and $\mathbf{G} = \mathbf{H}^T\mathbf{H}^* = \mathrm{Diag}(|h(1)|^2, \ldots, |h(N)|^2)$ denotes the effective channel between node A and node B due to TR. Now node B can simply matched filter (MF) to the transmitted signal $\mathbf{s}_B$ to recover the data bit b. Note that the TR process eliminates the channel estimation/equalization requirement at node B.

2.2. Multiple Antenna Narrowband STR

In this case, we consider a narrowband MIMO system with N_A transmit and N_B receive antennas at nodes A and B, respectively. The initial transmitted signal at Node B, $\mathbf{s}_B$ and the received signal at node A, $\mathbf{r}_A$ are related by

$$\mathbf{r}_A = \mathbf{H}\mathbf{s}_B \qquad (4)$$

where $\mathbf{H}$ is the $N_A \times N_B$ MIMO channel matrix whose $\{i, j\}$-th entry $h_{i,j}$ denotes the scalar channel between the i-th transmit and j-th receive antennas. The STR operation at A corresponds to a simple conjugation of the received signal and hence the TR transmission from A, $\mathbf{x}_A = b\delta_A\mathbf{r}_A^* = b\delta_A\mathbf{H}^*\mathbf{s}_B^*$, where δ_A normalizes the energy and b is the transmitted data bit. The final received signal at node B:

$$\mathbf{y}_B = \mathbf{H}^T\mathbf{x}_A = b\delta_A\mathbf{H}^T\mathbf{H}^*\mathbf{s}_B^* = b\delta_A\mathbf{G}\mathbf{s}_B^* \qquad (5)$$

where $\mathbf{G} = \mathbf{H}^T\mathbf{H}^*$ denotes the effective channel between node A and node B due to STR.

2.3. Multiple Antenna Wideband STR

Combining the results from sections 2.1 and 2.2, it is easy to show that the final STR system equation relating $\mathbf{s}_B$ and $\mathbf{y}_B$ for a multiple antenna wideband system using an OFDM transmission is given by

$$\mathbf{y}_B = b\delta_A\mathbf{H}^T\mathbf{H}^*\mathbf{s}_B^* = b\delta_A\mathbf{G}\mathbf{s}_B^* \qquad (6)$$

where the $MN_A \times MN_B$ block diagonal channel matrix $\mathbf{H}$ can be expressed as

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}(1) & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{H}(2) & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{H}(M) \end{bmatrix} \qquad (7)$$

where each $N_A \times N_B$ channel block $\mathbf{H}(i), i = 1, \ldots, M$, denotes the MIMO channel matrix between the N_B transmit and N_A receive antennas for the i-th frequency index. Note that the only difference in the three system equations ((3),(5) and (6)) is the structure of the channel matrix $\mathbf{H}$.

3. ITERATIVE STR

In this section, we introduce the idea of iterative STR (initially proposed in [7]) and analyze the convergence behavior of the iterative process. We then discuss the relevant convergence results for the three cases given in section 2 and present numerical results in section 3.2 to support the analysis.

To derive the system equation for the iterative STR process, we first rewrite the generic STR equation ((3),(5) and (6)) for the three cases discussed in section 2 as

$$\mathbf{y}_{B,1}/\|\mathbf{y}_{B,1}\| = b\delta_A\delta_B\mathbf{H}^T\mathbf{H}^*\mathbf{s}_{B,1}^* = b\delta\mathbf{G}_1\mathbf{s}_{B,1}^* \qquad (8)$$

where the $(.)_1$ notation indicates the iteration index, δ_B ensures that the received signal energy is normalized and $\delta = \delta_A\delta_B$ denotes the combined energy normalization. To simplify further analysis, we assume that the transmitted data bit $b = 1$ in (8) and $N_A = N_B = N$. Repeating the STR process at both the nodes, that is, retransmitting the time-reversed phase-conjugated version of the received signal with the requisite energy normalization, the input-output relationship after n iterations can be written as

$$\mathbf{y}_{B,n}/\|\mathbf{y}_{B,n}\| = \delta^n \mathbf{G}_n \mathbf{s}^*_{B,1} = \delta^n \mathbf{G}^n \mathbf{s}^*_{B,1} \ . \tag{9}$$

In order to analyze the convergence of $\mathbf{G}^n$, we consider the singular value decomposition (SVD) of the initial space-time channel $\mathbf{H}$, $\mathbf{H} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^H$, where $\mathbf{\Lambda}$ is a diagonal matrix containing the singular values $\lambda_i, i = 1, \dots, MN$, of $\mathbf{H}$ and $\mathbf{U} = [\mathbf{u}_1, \cdots, \mathbf{u}_{MN}]$ and $\mathbf{V} = [\mathbf{v}_1, \cdots, \mathbf{v}_{MN}]$ are unitary matrices containing the corresponding left and right singular vectors. Thus from (9), it is easy to demonstrate that

$$\mathbf{y}_{B,n}/\|\mathbf{y}_{B,n}\| \to \mathbf{v}_i \tag{10}$$

for large enough n, where $\mathbf{v}_i$ is the right singular vector corresponding to the largest singular value of $\mathbf{H}$, $\lambda_i > \lambda_k, k = 1, \dots, MN, k \neq i$, and $\mathbf{s}^*_{B,1}$ has a nonzero component in the direction of $\mathbf{v}_i$. Once $\mathbf{v}_i$ has been computed, we can follow a procedure similar to that of the power method used in the numerical computation of eigen values and eigen vectors, and recover the right singular vector corresponding to the next largest singular value by modifying the initial transmission $\mathbf{s}_{B,1} \to (\mathbf{I} - \mathbf{v}_i\mathbf{v}_i^H)\mathbf{s}_{B,1}$. Repeating this process, one can recover all the right singular vectors of the original channel matrix $\mathbf{H}$. Note that employing this same iterative procedure, an STR transmission starting at A can similarly recover all the left singular vectors $\{\mathbf{u}_i\}, i = 1, \dots, MN$, of $\mathbf{H}$.

3.1. Convergence Results for Multiple Antenna Wideband STR

To analyze the convergence behavior of the iterative STR scheme in a general wideband MIMO channel, we first express each channel block $\mathbf{H}(i), i = 1, \dots, M$, of $\mathbf{H}$ in (6) in terms of its SVD as $\mathbf{H}(i) = \mathbf{U}(i)\mathbf{\Lambda}(i)\mathbf{V}^H(i)$, where $\mathbf{\Lambda}(i)$ is a diagonal matrix containing the singular values $\lambda_k(i), k = 1, \dots, N$, of the MIMO channel matrix at the i-th frequency, and the $N \times N$ matrices $\mathbf{U}(i) = [\mathbf{u}_1(i), \cdots, \mathbf{u}_N(i)]$ and $\mathbf{V}(i) = [\mathbf{v}_1(i), \cdots, \mathbf{v}_N(i)]$ contain the corresponding left and right singular vectors, respectively. The effective channel after the n-th iteration $\mathbf{G}_n$ in (9) can now be expressed as

$$\mathbf{G}_n = \begin{bmatrix} \mathbf{V}(1)\mathbf{\Lambda}^n(1)\mathbf{V}^H(1) & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{V}(M)\mathbf{\Lambda}^n(M)\mathbf{V}^H(M) \end{bmatrix} \tag{11}$$

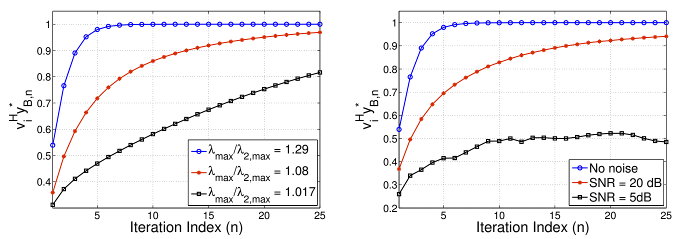
If $\mathbf{H}$ has a dominant singular value, $\lambda_k(i) > \lambda_{k'}(i')$, with $i, i' = 1, \dots, M, i' \neq i$, and $k, k' = 1, \dots, N, k' \neq k$, then the iterated signal $\mathbf{y}_{B,n}$ in (10) converges to the dominant right singular vector, that is

$$\mathbf{y}_{B,n}/\|\mathbf{y}_{B,n}\| \to \mathbf{1}_i \otimes \mathbf{v}_k(i) \tag{12}$$

where $\mathbf{1}_i$ is a column vector of length M containing all zeros except a one at index i and $\otimes$ denotes the Kronecker or tensor product. Thus the iterative STR operation for a wideband MIMO system converges to the tensor product of a sinusoid at a particular frequency and the dominant spatial right singular vector for the MIMO channel matrix at that frequency.

The convergence results for a single-antenna wideband system (section 2.1) or a narrowband multiple antenna system (section 2.2) can be derived in a straight-forward manner from the convergence result given in (12). For a single antenna system ($N = 1$), the received signal $\mathbf{y}_{B,n}$ converges to a sinusoid at a certain frequency. This is in line with the well known fact that sinusoids are eigen vectors of a wideband frequency selective channel. Similarly for a multiple antenna narrowband channel ($M = 1$), $\mathbf{y}_{B,n}$ converges to the largest spatial right singular vector of the MIMO channel matrix $\mathbf{H}$.

3.2. Numerical results



(a) (b)

Fig. 1. Inner product between $\mathbf{y}_{B,n}$ and the dominant singular vector $\mathbf{v}_i$ vs the iteration index n. Effect of (a) the singular value spacing and (b) noise on the convergence behavior.

We now present numerical results that illustrate the convergence behavior of iterative STR. In our simulations, a simple geometric scattering environment with $N_p = 100$ scattering paths was used for a point-to-point wideband MIMO system employing $N = 5$ antennas at both the transmitter A and receiver B with a signaling time bandwidth product $M = TW = 8$. The inner product between the dominant singular vector v_i and the received signal at the n-th iteration, $\mathbf{y}_{B,n}$ as a function of the iteration index n is plotted in Fig. 1. Fig. 1(a) shows the effect of the channel singular value spacing on the convergence of iterative STR. It can be seen that the speed of convergence is sensitive to the ratio of the two most dominant singular values, with larger spacings between them resulting in faster convergence and vice versa. In Fig. 1(b), we illustrate the effect of receiver noise (AWGN) at both nodes on the overall convergence and iterative STR shows significant performance degradation at higher receiver noise levels. In these curves the received $\text{SNR} = \|r_A\|^2/\sigma^2 = \|y_B\|^2/\sigma^2$, where σ^2 is the AWGN variance.

4. STR FOR MULTIUSER SYSTEMS

In this section, we explore the applicability of STR techniques in a multiuser setting, both in the downlink (broadcast) and uplink (multiple-access) modes. We begin by extending the results obtained in section 2 to any asymmetric single-user point-to-point system. We then analyze an asymmetric system with two users in section 4.2, where our initial results suggest that the simple iterative STR procedure given in section 3 does not provide reliable user separation. However, the convergence results obtained in section 3 yield important insights into designing alternative signaling schemes that can provide reliable user separation. Two such schemes, one using sinusoidal signals (frequency tones) and another employing spread spectrum signals are presented in section 4.3. Finally in section 4.3.3, we provide numerical results that illustrate the performance of these two techniques.

4.1. STR for Asymmetric Wideband Channels - Single User

To gain insight into the distributed multiuser setting, we first consider an asymmetric wideband MIMO communication system where node A (base station) has N antennas and node B (user) has a single antenna. Using the results obtained in section 2.3, the system equation (6) for an STR transmission originating at the user node B can be written as

$$\mathbf{y}_B = b\delta_A \mathbf{H}^T \mathbf{H}^* \mathbf{s}_B^* = b\delta_A \mathbf{G}\mathbf{s}_B^* \tag{13}$$

where the $M \times M$ *effective* STR channel $\mathbf{G}$ can be expressed in terms of the $N \times 1$ vector channels $\mathbf{h}(i), i = 1, \ldots, M$, between A and B at the M individual frequencies as

$$\mathbf{G} = \begin{bmatrix} \mathbf{h}^T(1)\mathbf{h}^*(1) & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{h}^T(2)\mathbf{h}^*(2) & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{h}^T(M)\mathbf{h}^*(M) \end{bmatrix}. \tag{14}$$

Similarly, the system equation for an STR transmission originating at the base station A is given by (13) with subscript $B \to A$ and the $MN \times MN$ channel

$$\mathbf{G} = \begin{bmatrix} \mathbf{h}^*(1)\mathbf{h}^T(1) & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{h}^*(2)\mathbf{h}^T(2) & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{h}^*(M)\mathbf{h}^T(M) \end{bmatrix}. \tag{15}$$

Thus the asymmetric iterative STR transmissions

$$\mathbf{y}_{B,n}/\|\mathbf{y}_{B,n}\| \to \mathbf{1}_i \tag{16}$$

and

$$\mathbf{y}_{B,n}/\|\mathbf{y}_{B,n}\| \to \mathbf{1}_i \otimes \mathbf{h}(i) \tag{17}$$

where $\|h(i)\| > \|h(i')\|, i' = 1, \ldots, M, i' \neq i$. Note that the results obtained in (16) and (17) indicate that the iterative STR technique converges to signaling in the strongest spatial direction on the corresponding sinusoid at the base station and signaling on the strongest sinusoid at the user.

4.2. STR for Asymmetric Wideband Channels - Two Users

We now present some initial analysis that indicate that a direct multiuser iterative STR fails to orthogonalize the channels between different users. For a two user example (users B_1 and B_2) employing STR in the downlink, that is, starting transmission at the users, we have

$$\mathbf{y}_B = \begin{bmatrix} \mathbf{y}_{B_1} \\ \mathbf{y}_{B_2} \end{bmatrix} = \delta_A \underbrace{\begin{bmatrix} \mathbf{H}_1^T\mathbf{H}_1^* & \mathbf{H}_1^T\mathbf{H}_2^* \\ \mathbf{H}_2^T\mathbf{H}_1^* & \mathbf{H}_2^T\mathbf{H}_2^* \end{bmatrix}}_{\mathbf{G}} \begin{bmatrix} b_1\mathbf{s}_{B_1}^* \\ b_2\mathbf{s}_{B_2}^* \end{bmatrix} \tag{18}$$

where $\mathbf{s}_{B_1}$ and $\mathbf{s}_{B_2}$ are the initial transmissions, $\mathbf{H}_1$ and $\mathbf{H}_2$ are the channels from the users to the base station, b_1 and b_2 are the data bits and $\mathbf{y}_{B_1}$ and $\mathbf{y}_{B_2}$ are the final received signals at user B_1 and B_2, respectively. Thus, the joint signal vector $\mathbf{y}_B$ converges to the dominant singular vector of $\mathbf{G}$ which will, in general, involve non-zero components from both $\mathbf{y}_{B_1}$ and $\mathbf{y}_{B_2}$. Note that if the two users' channels are orthogonal ($\mathbf{H}_i^T\mathbf{H}_k^* = \mathbf{0}, k \neq i$) then the iterative STR signal converges to a transmission from a single user.

Similarly, using STR in the uplink, that is, starting transmission at the base station, we have

$$\mathbf{y}_A = \delta_{B_1}\mathbf{H}_1^*\mathbf{H}_1^T\mathbf{s}_A^* + \delta_{B_2}\mathbf{H}_2^*\mathbf{H}_2^T\mathbf{s}_A^* \tag{19}$$

where $\mathbf{s}_A$ is the initial transmission from the base station A, and $\mathbf{y}_A$ is the corresponding received. Again in this case, a simple iterative procedure will result in cross products between $\mathbf{H}_1^*\mathbf{H}_1^T$ and $\mathbf{H}_2^*\mathbf{H}_2^T$ in the second iteration and hence $\mathbf{y}_A$ will have interfering contributions from both users.

4.3. Alternative Signaling Schemes for User Separation in Multiuser systems

As the results in section 4.2 indicate, a direct iterative STR scheme does not provide reliable separation between the different users. To combat this, we now present two distinct signaling methods that can provide reliable user separation. The first scheme, based on sinusoidal signaling, is motivated by the observations made in section 4.1 that communicating on frequency tones corresponding to the strongest spatial direction is optimal in a single user setting. The second scheme, based on spread spectrum signals (refer [8]) relies on the fact that distinct users "generate" distinct wideband channels at the base station. The performance of these schemes is illustrated in section 4.3.3 with the help of numerical simulations.

4.3.1. Tone Separation

A simple algorithm for separating the users via distinct frequency tones is given below:

1. If the number of users $K \leq M = TW$, we simply allocate different tones to different users based on their channel power on that tone, that is, i-th tone is allocated to the k-th user if $\|\mathbf{h}_k(i)\|^2 > \|\mathbf{h}_{k'}(i)\|^2, k \neq k'$ where $k, k' = 1, \ldots, K$. This procedure can be repeated over all tones until each user is allocated at least one tone.

2. If the number of users $K > M = TW$, then multiple users are allocated the same tone, based on their largest channel power up to a maximum of N users per tone. If the maximum number of users is reached on any particular tone, we then search for the next strongest tone for

any new user and we repeat this process until each user is allocated at least one tone. In this case, since multiple users use the same tone, interference suppression (using the spatial channel characteristics) is employed to separate the different users on each tone.

3. In both the cases above, the tone allocation can be optimized for different performance criteria (e.g, capacity, reliability) or other fairness criteria.

4.3.2. Spread Spectrum Signaling

An alternate signaling mechanism using spread spectrum waveforms was initially proposed in [8] for the purpose of information retrieval in wireless sensing applications. In this case the users are sensors with single antenna wideband RF front-ends and the base station is a wireless information retriever (WIR) which employs a multiple antenna array. All the users (sensors) transmit their data modulated onto an identical spreading (PN) sequences and the base station (WIR) distinguishes different users using their distinct space-time channels. The aggregate received signal at the WIR from all the K users is first projected onto N uniformly spaced spatial directions and the projected signal on each spatial beam is matched filtered to M uniformly delayed versions of the PN sequence. The resulting MN dimensional vector of matched filtered outputs at the WIR, $\mathbf{r}_A$ is given by

$$\mathbf{r}_A = \mathbf{H}\mathbf{s}_B = \sum_{i=1}^{K} \mathbf{h}_i s_{B,i} \qquad (20)$$

where the $\mathbf{s}_B = [s_{B,1}, \ldots, s_{B,K}]^T$ are the bits transmitted from the K users and $\mathbf{H} = [\mathbf{h}_1, \cdots, \mathbf{h}_K]$ denotes the *angle-delay signature* matrix which represents the effective channel that couples the K users to MN matched filtered outputs at the WIR (see [8] for further details on this scheme).

4.3.3. Numerical Results

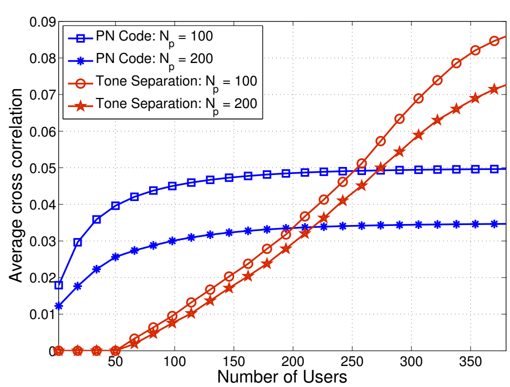


Fig. 2. Average cross correlation between the different users' signals as a function of the number of users. $N = 9$; $M = TW = 64$ tones or PN sequence length; N_p is the number of scatterers in the simulated geometric scattering environment.

The average cross-correlation between the different users' signals for the two algorithms described in sections 4.3.1 and 4.3.2 has been plotted as a function of the number of users K in Fig. 2. As evident, both these techniques offer excellent user separation with lower cross-correlation for rich scattering (larger N_p). The tone allocation scheme has a much better performance with fewer users since separating users on different frequencies ensures that their transmissions are orthogonal. However, with larger number of users, spread spectrum signaling is advantageous since it utilizes all the MN signaling dimensions to separate the users. Note that in both cases low-complexity linear interference suppression techniques (see,e.g. [8]) can help substantially improve the capacity and reliability of STR communication.

5. DISCUSSION AND CONCLUSIONS

This paper presents an initial framework to analyze the performance of STR in both single- and multi-user communication and the next important step is to try to obtain a more complete characterization of the benefits of multiuser STR. Some of the other issues that warrant further investigation are: (i) the analysis of the impact of noise and/or estimation errors on the performance of STR techniques, and (ii) quantifying the effect of the richness of multipath and signal space parameters (M,N) on STR performance.

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