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SHORT COMMUNICATION

Generalized analysis of MU-MISO time reversal-based systems over correlated multipath channels with estimation error

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ABSTRACT

In this letter, we analyze the performance of multi-user multiple-input single-output time reversal (MU MISO TR)-based systems in a generalized framework. The considered propagation is correlated in both the space and the frequency domains, and channel estimation errors (CEEs) at the transmitter side are also taken into account. We derive a novel average signal-to-interference-plus-noise (SINR) formula in closed-form for TR-based systems. This formula is based on the exact expressions of the expectations of the powers of the desired signal, the inter-symbol interference (ISI) and the inter-user interference (IUI) components. These expressions allow us to reveal, for the first time, properties of time reversal which remained unknown up to now. More precisely, CEE has no influence on the ISI in terms of average power, whereas it degrades the power of the desired message-bearing signal. Moreover, irrespective of the central tap, the other taps of the IUI are independent from the effects of both inter-user correlation and CEE. Our analytical results are validated in both ultra-wideband and conventional broadband channels. Finally, these results are numerically compared to previous works.

1. Introduction

Due to the fast development of wireless communications, trends for the design of energy efficient and green networks are emerging [1,2]. The time reversal (TR) technique is one of the most popular forms of linear precoding, especially for ultra-wideband (UWB) systems over multipath channels. It is considered as a beamforming technique [2–14]. TR tightly focuses the energy of all the taps of the propagation channel, in the time and space domains at the intended terminals by utilizing the time-reversed of channel impulse response (CIR) to prefilter transmit signals. Since the TR technique exploits the channel propagation diversity at the transmitter side, to perform focusing, complex equalizers as well as large numbers of antennas can be avoided at the receiver side.

Due to the focalization property of TR, much research efforts have been put recently on the analysis of TR-based transmission [5–11]. Popovski et al. [6] give approximate derivations of ISI and IUI for TR-UWB system. The performance analysis of a MISO TR UWB system with a decision feedback equalizer is also found in [7]. The analysis conducted in [2,5,11] considers specific wideband channels where the average power of each tap decays exponentially. However, the applications of TR techniques can be completely extended to conventional broadband systems as shown in [11–13]. In fact, a channel with a narrower bandwidth has a smaller multipath delay spread [14]. Such channel has a lower diversity and a lower multiplexing gain [15,16]. In broadband systems, the transmission bandwidth is reduced as well as the amount of scattering in the propagation channel, in comparison with the bandwidth and the channel of UWB systems. For TR-based broadband systems in particular as well as for generalized TR-based systems, the correlation should therefore be taken into account. Furthermore, in practice, the accuracy of the estimated channel plays an importance role in determining the performance of TR systems. Although the effects of CEE on TR have been studied in [8–10], there have been no works conducting the analysis for multi-user systems assuming imperfect CIR condition.

In this letter, we take into account a MU MISO TR-based system model that is *generalized* by considering (i) the frequency selective channel that has arbitrary power in each tap, (ii) the correlation at both transmitter and user sides, and (iii) the channel estimation errors.

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In fact, most previous works do not analyze this general system. This directly motivates us to determine in this letter the exact generalized closed-form expressions for the desired signal, ISI and IUI terms, respectively. Based on such closed-form derivations, we first show that CEE and inter-user correlation do not impact the average power of ISI whereas CEE explicitly decreases the average signal power. For the IUI component, we find that the effect of correlation on the central tap is distinct from the effects of the other taps. More precisely, the average power of the taps of the IUI excluding the power of the main tap is immune to the effects of inter-user correlation and CEE. Finally, the validity of our analysis is verified by means of Monte-Carlo simulation and the comparison with a previous work [5].

2. System description

We consider a TR-based system consisting of a BS equipped with M transmit antennas and N single-antenna users. In the multipath channel, we assume that the maximum length of each CIR is L. Thus, the CIR between the mth transmit antenna and the nth user is

$$h_{mn}(t)=\sum_{l=1}^{L}\alpha_{mn}^{(l)}\delta(t-\tau_{mn}^{(l)}),\quad (1\le l\le L) \tag{1}$$

where $\alpha_{mn}^{(l)}$ and $\tau_{mn}^{(l)}$ are the amplitude and the delay of the lth tap, respectively. The CIR can be discretized in the time domain as a vector $\mathbf{h}_{mn}\in\mathbb{C}^{L\times 1}$ in which $E[h_{mn}[l]]=0$, $E\left[\left|h_{mn}[l]\right|^2\right]=E\left[\left|\alpha_{mn}^{(l)}\delta(t-\tau_{mn}^{(l)})\right|^2\right]=\sigma_{mn,l}^2$, and $E[\cdot]$ represents the expectation operator. We can arrange the propagation channels in an $MN\times L$ matrix form as

$$\mathbf{H}=[\mathbf{h}_{11}\ldots\mathbf{h}_{M1}\ldots\mathbf{h}_{1n}\ldots\mathbf{h}_{Mn}\ldots\mathbf{h}_{1N}\ldots\mathbf{h}_{MN}]^T. \tag{2}$$

The transmit antenna and inter-user correlations should be taken into account because of the validation of our analysis in low scattering environments. The correlation can be included into the channel model by introducing transmit and receive correlation matrices following the well-known Kronecker model [17]. This correlation model is widely applied in the literature for correlated multi-antenna systems. In our system, we assume that the distances between the BS and users are large, and only antennas from the same equipment (either the transmitter or the receiver) are correlated, due to scattering and electromagnetic coupling. In other words, the correlation between transmit antennas and receive antennas can be omitted. We also assume that all channels convey the same average power. The Kronecker model is used to take into account the correlation in the channel matrix $\mathbf{H}$. The expression of $\mathbf{H}$ is therefore given by

$$\mathbf{H}=((\mathbf{R}_U^{1/2})^T\otimes\mathbf{R}_T^{1/2})\mathbf{H}_w, \tag{3}$$

where the inter-user and transmit correlations are represented by the real positive-define matrix $\mathbf{R}_U\in\mathbb{R}^{N\times N}$ and the real positive-define matrix $\mathbf{R}_T\in\mathbb{R}^{M\times M}$, respectively. $\mathbf{H}_w\in\mathbb{C}^{MN\times L}$ is the channel matrix of the independent CIRs. Note that $\otimes$ denotes the Kronecker product, and the correlation matrix follows the general model with arbitrary positive coefficients (i.e. $\rho_{T,mm'}\in\mathbb{R}$). We provide hereafter an example of transmit correlation matrix $\mathbf{R}_T$

$$\mathbf{R}_T=\begin{bmatrix}1&\rho_{T,12}&\cdots&\rho_{T,1M}\\ \rho_{T,21}&1&\cdots&\rho_{T,2M}\\ \vdots&\vdots&\ddots&\vdots\\ \rho_{T,M1}&\rho_{T,M2}&\cdots&1\end{bmatrix}. \tag{4}$$

Moreover, in practice, only imperfect estimates of the CIRs are available at the transmitter side. The true channel $\mathbf{h}_{mn}$ is an unknown parameter to the transmitter. We model the impact of channel estimation errors as follows

$$\hat{\mathbf{h}}_{mn}=\mathbf{h}_{mn}+\mathbf{e}_{mn}, \tag{5}$$

where $\hat{\mathbf{h}}_{mn}\in\mathbb{C}^{L\times 1}$ and $\mathbf{e}_{mn}\in\mathbb{C}^{L\times 1}$ are the vectors of independently and identically distributed (i.i.d) variables denoting the estimated channel and error vectors respectively. With a nonnegative factor ψ, we define

$$E\left[\left|e_{mn}[l]\right|^2\right]=\psi E\left[\left|h_{mn}[l]\right|^2\right], \tag{6}$$

$$E\left[\left|\hat{h}_{mn}[l]\right|^2\right]=\hat{\sigma}_{mn,l}^2, \tag{7}$$

Based on the TR scheme [2–5], we define $g_{mn}\in\mathbb{C}^{L\times 1}$ as the pre-filtering vector for the message-bearing signal with the transmit power p_n

$$\hat{g}_{mn}[l]=\sqrt{p_n}\hat{h}_{mn}^*[L+1-l]/\sqrt{\sum_{m=1}^{M}E\left[\left\|\hat{\mathbf{h}}_{mn}\right\|^2\right]}. \tag{8}$$