A Robust Pre-Filter and Power Loading Design for Time Reversal UWB Systems over Time-Correlated MIMO Channels

Sajjad Alizadeh, Hossein Khaleghi Bizaki and Reza Saadat

Abstract—Conventional Time Reversal (TR) technique suffers from performance degradation in time varying Multiple-Input Multiple-Output Ultra-Wideband (MIMO-UWB) systems due to outdating Channel State Information (CSI) over time progressions. That is, the outdated CSI degrades the TR performance significantly in time varying channels. The correlation property of time correlated channels can improve the TR performance against other traditional TR designs. Based on this property, at first, we propose a robust TR-MIMO-UWB system design for a time-varying channel in which the CSI is updated only at the beginning of each block of data where the CSI is assumed to be known. As the channel varies over time, pre-processor blindly pre-equalizes the channel during the next symbol time by using the correlation property. Then, a novel recursive power allocation strategy is derived over time-correlated time-varying TR-MIMO-UWB channels. We show that the proposed power loading technique, considerably improves the Bit Error Rate (BER) performance of TR-MIMO-UWB system in imperfect CSI with robust pre-filter. The proposed algorithms lead to a cost-efficient CSI updating procedure for the TR optimization. Simulation results are provided to confirm the new design performance against traditional method.

Keywords—Time Reversal (TR) technique, MIMO channel, Ultra-Wideband (UWB) system, Temporal Correlation, Imperfect CSI, MMSE pre-equalizer.

I. INTRODUCTION

Ultra-wide band (UWB) communication systems have recently received much interest from both research community and industry [1]-[2]. However, due to the wide bandwidth property, UWB systems suffer from a very long delay spread of the multipath channels in indoor environments. Different types of the receiver structure such as RAKE, Transmitted Reference or the Decision Feedback Autocorrelation receivers can be implied [3]-[5] in which each technique has different complexities. To reduce the receiver complexity, non-coherent scheme is developed to bypass the complicated treatments on the UWB channel [6]-[7]. Accordingly, based on the idea of moving the complexity from the receiver to the transmitter, the Time Reversal (TR) preprocessing technique also referred to as the full pre-RAKE combining, which is originated from underwater acoustics and ultra sonic system [8], has been extended to the UWB applications. As a result, the TR technique can

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be used to reduce the long delay spread of the UWB channel. Multiple-Input Multiple-Output (MIMO) solution, employing multiple antennas at the transmitter and receiver, is capable of increasing the data transmission rate by the spatial multiplexing without expanding the bandwidth and power [9]. In order to transmit parallel data streams simultaneously (spatial multiplexing), the Multi-Stream Interference (MSI) of the MIMO channel must be mitigated. The TR solution in the MIMO-UWB systems can mitigate not only the Inter-Symbol Interference (ISI) but also the MSI caused by transmitting several data streams, simultaneously [10]. The main bottleneck in the TR implementation is the necessity of the CSI at the transmitter, because in the TR technique we use the time-reversed version of the estimated CSI as pre-filter. In practice, perfect CSI is not available in transmitter side due to the channel estimation error in time varying channels. In spite of TR's good performance, it is very sensitive to erroneous CSI due to imperfect channel estimation especially in time varying channel. Recently, the TR-based UWB system and its variations have been investigated in some literatures. We have sorted them into two categories:

First category of the researches on the TR pre-coding assumes that perfect CSI is given at the transmitter side [11]-[15]. Authors of [11] proposed an antenna selection scheme for the TR-MIMO-UWB communication system in a perfect CSI case to reduce the number of transmit antenna. Also, a Minimum Mean Square Error (MMSE) equalizer is used for the TR-UWB system with perfect CSI in [12] to mitigate the residual ISI and increase the transmission data rate. An ultra-high data rate TR-MIMO-UWB system with space-time pre-coding has been proposed in [13] based on the Zero-Forcing (ZF) criterion in which the imperfect CSI has not been considered. Similar solution has been provided in [14] with the assumption of the spatial correlation among transmit and receive antenna. Also, the impact of spatial correlation on the TR-MIMO-UWB system has been investigated in [15] where several data streams can be transmitted by using only one antenna in a system named virtual TR-MIMO-UWB. Unfortunately, these methods suffer from the effects of the imperfect CSI in the transmitter, because the time variant channels and imperfect CSI have not been taken into account in these literatures.

Second category of the researches on the TR pre-coding assumes that imperfect CSI is available at the transmitter side [10], [16]-[22]. The effect of channel imperfection on the TR-MIMO-UWB system performance has been evaluated in [10]

for low and high data rate transmissions. Unfortunately, an optimization scheme has not been provided in this literature to overcome the effects of the channel imperfection. In [16]-[19], we had provided the pre-filtering solutions for the channel estimation error compensation in which the time variant channel is not considered. Especially, a power allocation scheme was proposed in [18] to improve the robust pre-filtered TR-MIMO-UWB systems in an imperfect CSI for the quasi-static channels. On the other hand, the robustness of TR technique in imperfect CSI caused by a time varying channel environment has been studied in [20] by experimental results. It has been shown that, if the channel maintains some partial correlation with its previous ensembles, the TR method give a better performance even if the total correlation of the channels is very low. Authors of [20] gave to us an idea to develop our previous works [18] (pre-filtering and power loading in the quasi-static TR-MIMO-UWB systems) for the temporal correlated time varying TR-MIMO channels in an imperfect CSI. Also, a post-time-reversed MIMO-UWB transmission scheme has been proposed in [21] which improves the TR robustness against imperfect CSI caused by channel estimation error when compared with the conventional TR scheme. Finally, an analysis without any improvement solution has been provided in [22] on the effect of the channel estimation error on the performance of the TR-UWB systems.

As it is observed from previous literatures, all of them assume the quasi-static channels in their analysis. In order to increase the TR performance in time varying channels, the pre-processors should be optimized approximately in some symbol duration [23]. On the other hand, the generation of reliable channel feedback in some short symbol time is complicated in time-varying channel and can be led to high bandwidth overhead. From practical implementation point of view, most of the TRs have been designed assuming that the wireless channel can be regarded as constant over a block of data. In mobile applications where the channel is time-varying, the assumption that the channel is constant over some periods only holds approximately and will affects the TR performance that are designed based on this assumption. Hence, a judicious and innovative TR system design that takes the time-varying nature of the channel into account is the key to solve the above problems.

Based on mentioned researches on the TR pre-coding and also, works of [18] and [23], we extend and unify the TR concepts to time varying MIMO channels in an imperfect CSI, which will allow us to improve mobile systems performance, as well as to provide guidelines for future pre-coder designs employing low feedback overhead. On the other hand, a recursive power allocation strategy is proposed to more improve the performance of the proposed robust TR-MIMO-UWB system. According to authors best knowledge, no research has been reported so far about time varying and time correlated TR-MIMO-UWB systems. Therefore, it is essential to analyze and improve the TR-MIMO-UWB systems in mobile applications with imperfect CSI. Our current works can be used for the mobile communication networks, such as Ad Hoc networks and so on. The rest of the paper is organized as follows; we introduce the system model in Section II.

A novel solution based on a MMSE criterion and a novel recursive power allocation scheme are derived for TR-MIMO-UWB system over time varying channels in Section III and IV, respectively. Numerical and simulation results characterizing the performance of the proposed methods are presented in Section V, and finally, conclusions are drawn in Section VI.

II. System Description in Time Correlated Channels

A TR-MIMO-UWB communication system includes a transmitter equipped with antennas and a receiver equipped with antennas is depicted in Fig. 1. Let us consider an impulsive (Impulse Radio) UWB (IR-UWB) system using Binary Pulse Amplitude Modulation (BPAM) with pulse shaping according to the Federal Communications Commission (FCC) desired power spectral density [1]-[2]. The transmitted signal for every input of the MIMO system is represented as,

$$x(t) = \sqrt{E_b} \sum_{k=-\infty}^{+\infty} d_k p(t - kT) \tag{1}$$

where $d_k = \{\pm 1\}$ is the binary transmit symbol, E_b is the bit energy, $p(t)$ is the desired pulse shape, and T denotes the symbol duration. According to Fig. 1, at first, the input signal is converted into N_r streams, pre-equalized with an optimized MMSE pre-equalizer, pre-coded with TR pre-filter, and then sent to N_r transmitting antennas, simultaneously. The resultant signal passes through the multipath MIMO channel and then, is corrupted by an Additive White Gaussian Noise (AWGN). Thus, there are $N_t \times N_r$ multipath channel between transmit and receive antennas. For simplicity of our analysis, we use the tapped delay line (TDL) model with maximum L_g taps [10]-[11]. If τ_d and T are the delay spread of the channel and the symbol duration, respectively, then $L_g \cong \frac{\tau_d}{T}$. In fact, we use a TDL model with equal tap spacing of T. Note that in our application, $\tau_d \gg T$ then we have a frequency-selective model for each multipath channel between transmit and receive antennas. Furthermore, because of using the very short duration pulses, IR-UWB meets extremely resolvable multipath components (MPC) leading to long delay spread τ_d, in that, two multipath components (taps) with delays τ_m and τ_n are resolvable if $|\tau_m - \tau_n| \geq T$. We assume $|\tau_m - \tau_n| \geq T$. Also, the UWB channels are assumed to be time correlated across blocks [23]. The TR pre-filter is used in the spatial multiplexing UWB system in order to cope with the ISI and MSI problems. Since the ultra-high data rate UWB transmission usually requires extremely short symbol time, thus ISI and MSI are very strong. These interferences, especially MSI, are not absolutely eliminated by TR pre-filter [13]. Therefore, to completely eliminate the residual ISI and MSI, a MMSE pre-equalizer, i.e. $\mathbf{F}_{MMSE}$ in Fig. 1, is needed in transmitter as will be considered in Section 3. Both MMSE pre-equalizer and TR pre-filter require the perfect CSI. The CSI can be estimated using the training symbols. The training pattern employed for channel estimation is similar to what is considered in [24], in which at the beginning of every block, the first N_t symbols are assigned as training sequence, once in every $T_f = NT$ seconds, where every block includes
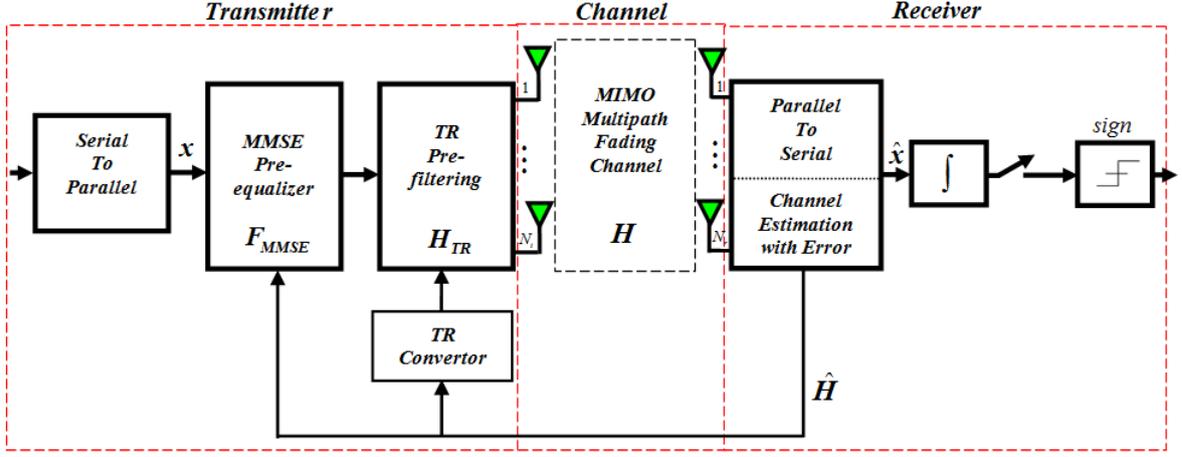
Fig. 1. TR-MIMO-UWB system model.

N symbols. As in [24], the MMSE channel estimation is assumed in this paper. Then, the estimated CSI is fedback to transmitter through the feedback channel. In practice, perfect CSI is not available in the transmitter side due to non-ideal channel estimator. Pre-processors (TR pre-filtering and MMSE pre-equalizing) are influenced by the imperfect CSI effects. Finally, the data stream is detected based on a simple integrate-and-dump receiver with the sampling rate of $\frac{1}{T}$.

The effect of channel estimation error in a time varying channel can be considered as $\mathbf{H}_t = \hat{\mathbf{H}}_t + \mathbf{\Delta H}_t$ where $\mathbf{H}_t$, $\hat{\mathbf{H}}_t$ and $\mathbf{\Delta H}_t$ are the true value, estimated value and estimation error of the CIR at the time instant t, respectively. It is assumed that the entries of $\mathbf{\Delta H}_t$ are i.i.d. random variables with zero mean complex Gaussian noise. The estimated value $\hat{\mathbf{H}}_t$ is converted to the TR pre-filter, as $\mathbf{H}_{TR,t}$, by the TR convertor. This function will be exactly explained after some following basic definitions in next paragraphs of this section. The estimated CIR between i^{th} transmit antenna and j^{th} receive antenna ($i = 1, ..., N_t,\quad j = 1, ..., N_r$) at the time instant t can be denoted as,

$$\hat{h}_{ij,t}(t) = \sum_{l=0}^{L_g-1} \hat{\alpha}_l^{ij,t} \delta(t - \hat{\tau}_l^{ij,t}) \qquad (2)$$

where $\hat{\alpha}_l$ is the estimated fading coefficient of the lth multipath components (MPC), $\hat{\tau}_l$ is the corresponding delay of the lth tap and L_g is the number of resolvable MPCs. The discrete time vector form of CIR in reversed order at the time instant t is denoted as: $\hat{\mathbf{h}}_{ij,t} = [\hat{h}_{ij,t}^{L_g-1}, \cdots, \hat{h}_{ij,t}^l, \cdots, \hat{h}_{ij,t}^0]_{1 \times L_g}$ where $\hat{h}_{ij,t}^l$ is the amplitude of the lth path for the channel between i^{th} transmit antenna and j^{th} receive antenna at time instant t. Also, the estimation error vector of the CIR is defined as: $\mathbf{\Delta h}_{ij,t} = [\Delta h_{ij,t}^{L_g-1}, \cdots, \Delta h_{ij,t}^l, \cdots, \Delta h_{ij,t}^0]_{1 \times L_g}$ where $i = 1, ..., N_t$, $j = 1, ..., N_r$ and $l = 0, ..., L_g - 1$. The probability distribution of the error coefficients are considered as: $\Delta h_{ij,t}^l \sim CN(0, \sigma_e^2)$ where σ_e^2 is the estimation error variance. As in [10]-[11], the estimated CIR and estimation error matrices of size in the time instant t, can be written as:

$$\hat{\mathbf{H}}_t = \begin{pmatrix} \hat{\mathbf{h}}_{11,t} & \hat{\mathbf{h}}_{21,t} & \cdots & \hat{\mathbf{h}}_{N_t 1,t} \\ \hat{\mathbf{h}}_{12,t} & \hat{\mathbf{h}}_{22,t} & \cdots & \hat{\mathbf{h}}_{N_t 2,t} \\ \vdots & \vdots & \vdots & \vdots \\ \hat{\mathbf{h}}_{1N_r,t} & \hat{\mathbf{h}}_{2N_r,t} & \cdots & \hat{\mathbf{h}}_{N_t N_r,t} \end{pmatrix}$$

$$\mathbf{\Delta H}_t = \begin{pmatrix} \mathbf{\Delta h}_{11,t} & \mathbf{\Delta h}_{21,t} & \cdots & \mathbf{\Delta h}_{N_t 1,t} \\ \mathbf{\Delta h}_{12,t} & \mathbf{\Delta h}_{22,t} & \cdots & \mathbf{\Delta h}_{N_t 2,t} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{\Delta h}_{1N_r,t} & \mathbf{\Delta h}_{2N_r,t} & \cdots & \mathbf{\Delta h}_{N_t N_r,t} \end{pmatrix}$$

Note that the size of matrices $\hat{\mathbf{H}}_t$ and $\mathbf{\Delta H}_t$ is $N_r \times N_t L_g$. Also, $\mathbf{C}_{\mathbf{\Delta H}_t} = E\{\mathbf{\Delta H}_t \mathbf{\Delta H}_t^H\}$ is the estimation error covariance matrix and $E\{\mathbf{\Delta H}_t\} = 0$ is assumed. For simplicity of analysis, we assume that the estimation errors of the different sub-channels are statistically independent, that is, they have a common error variance σ_e^2. Thus, we have $\mathbf{C}_{\mathbf{\Delta H}_t} = E\{\mathbf{\Delta H}_t \mathbf{\Delta H}_t^H\} = \sigma_e^2 \mathbf{I}$ where $\mathbf{I}$ is the identity matrix. If the estimated CIR of all sub-channels, i.e. $\hat{h}_{ij,t}$, are known at the transmitter side, time reversed version of them are used to TR pre-filter to pre-equalize the transmitted data. Thus, we can construct the pre-filter matrix based on the time reversed form of the estimated sub-channels by the TR convertor which is a $N_t L_g \times N_r(2L_g - 1)$ matrix in [10]-[11] as

$$\mathbf{H}_{TR,t} = \begin{pmatrix} \overline{\mathbf{H}}_{11,t} & \overline{\mathbf{H}}_{12,t} & \cdots & \overline{\mathbf{H}}_{1N_r,t} \\ \overline{\mathbf{H}}_{21,t} & \overline{\mathbf{H}}_{22,t} & \cdots & \overline{\mathbf{H}}_{2N_r,t} \\ \vdots & \vdots & \vdots & \vdots \\ \overline{\mathbf{H}}_{N_t 1,t} & \overline{\mathbf{H}}_{N_t 2,t} & \cdots & \overline{\mathbf{H}}_{N_t N_r,t} \end{pmatrix}$$

where each sub-matrix $\overline{\mathbf{H}}_{ij,t}$ is an $L_g \times (2L_g - 1)$ Toeplitz matrix defined by [10]-[11] as

$$\overline{\mathbf{H}}_{ij,t} =$$

$$\begin{pmatrix} \hat{h}_{ij,t}^0 & \cdots & \hat{h}_{ij,t}^{L_g-1} & 0 & \cdots & 0 \\ 0 & \hat{h}_{ij,t}^0 & \cdots & \hat{h}_{ij,t}^{L_g-1} & 0 & \cdots & \vdots \\ \vdots & & \ddots & & & \ddots & 0 \\ 0 & \cdots & 0 & \hat{h}_{ij,t}^0 & \cdots & & \hat{h}_{ij,t}^{L_g-1} \end{pmatrix}$$

In fact, for each sub-matrix $\overline{\mathbf{H}}_{ij,t}$, we have

$\overline{\mathbf{H}}_{ij,t} = Toeplitz(TR(\hat{\mathbf{h}}_{ij,t}))$ where $Toeplitz(.)$ and $TR(.)$ are the Toeplitz matrix maker and the time reversed order of a vector, respectively. Therefore, the TR pre-filter by the TR convertor can be written as $\mathbf{H}_{TR,t} = Toeplitz(TR(\hat{\mathbf{H}}_t^H)) = \mathcal{F}(\hat{\mathbf{H}}_t^H)$ where the TR operation is applied on the vectors $\hat{\mathbf{h}}_{ij,t}$ of the matrix $\hat{\mathbf{H}}_t^H$. Also, $(.)^H$ denotes the complex conjugate transpose of the matrix $\hat{\mathbf{H}}_t$. The equivalent TR channel response matrix of size $N_r \times N_r(2L_g - 1)$ is given by

$$\mathbf{H}_t\mathbf{H}_{TR,t} = \begin{pmatrix} \overline{\mathbf{h}}_{11,t} & \overline{\mathbf{h}}_{21,t} & \cdots & \overline{\mathbf{h}}_{N_r1,t} \\ \overline{\mathbf{h}}_{12,t} & \overline{\mathbf{h}}_{22,t} & \cdots & \overline{\mathbf{h}}_{N_r2,t} \\ \vdots & \vdots & \vdots & \vdots \\ \overline{\mathbf{h}}_{1N_r,t} & \overline{\mathbf{h}}_{2N_r,t} & \cdots & \overline{\mathbf{h}}_{N_rN_r,t} \end{pmatrix}$$

where each sub-channel $\overline{\mathbf{h}}_{ij,t}$ is a $1 \times (2L_g - 1)$ auto-correlation $(i = j)$ or cross-correlation $(i \neq j)$ vector. The received symbols vector at the MIMO channel output with MMSE pre-equalizer and TR pre-filter can be written as $\hat{\mathbf{x}}_t = \mathbf{H}_t\mathbf{H}_{TR,t}\mathbf{F}_{MMSE,t}\mathbf{x}_t + \mathbf{n}_t$ where $\mathbf{x}_t$, $\hat{\mathbf{x}}_t$, and $\mathbf{n}_t$ are the transmitted symbols, the received symbols and AWGN, respectively. The vector $\mathbf{x}_t$ contains i.i.d. random variables with zero mean $E\{\mathbf{x}_t\} = \mathbf{0}$ and variance $E\{\mathbf{x}_t\mathbf{x}_t^H\} = \sigma_\mathbf{x}^2\mathbf{I}$ with antipodal modulation. Also, we assume $\mathbf{n}_t \sim CN(\mathbf{0}, \sigma_\mathbf{n}^2\mathbf{I})$ where $\sigma_\mathbf{n}^2 = E\{\mathbf{n}_t\mathbf{n}_t^H\}$. Summarily, the size of the input and output vectors or matrices of each block of Fig. 1 can be presented as follows; the transmitted and received symbol vectors $\mathbf{x}$ and $\hat{\mathbf{x}}$ as well noise vector $\mathbf{n}$ are of size $N_r \times 1$. Also, the MMSE pre-coding matrix $\mathbf{F}_{MMSE}$ and the TR pre-filter matrix $\mathbf{H}_{TR}$ are of size $N_r(2L_g - 1) \times N_r$ and $N_tL_g \times N_r(2L_g - 1)$, respectively. The true value $\mathbf{H}$ and the estimated value $\hat{\mathbf{H}}$ of the channel matrix are of size $N_r \times N_tL_g$. Therefore, the total pre-coding $\mathbf{H}_{TR}\mathbf{F}_{MMSE}$ is a $N_tL_g \times N_r$ matrix.

To analysis the TR-MIMO-UWB system in the time correlated channels, we define $\hat{\mathbf{H}}_{t-\tau}$ as the estimated CIR matrix at the time instant $t - \tau$. In fact, $\hat{\mathbf{H}}_{t-\tau}$ corresponds to the channel state τ seconds earlier than $\hat{\mathbf{H}}_t$. We assume that $\hat{\mathbf{H}}_t$ and $\hat{\mathbf{H}}_{t-\tau}$ are correlated realizations of the estimated channels. Thus, given the outdated CSI, i.e. $\hat{\mathbf{H}}_{t-\tau}$, we can characterize the unknown current CSI, i.e. $\hat{\mathbf{H}}_t$, as introduced in [23],

$$\hat{\mathbf{H}}_t = \rho\hat{\mathbf{H}}_{t-\tau} + \sigma_h\sqrt{1 - \rho^2}\mathbf{E}_t = \rho\hat{\mathbf{H}}_{t-\tau} + \Delta\mathbf{E} \quad (3)$$

where $\sigma_h^2 = E\{\|\hat{\mathbf{h}}_{ij,t}\|^2\}$ is the variance of the channel coefficients. Note that the different sub-channels are statistically independent assumed, that is, they have a common variance. The entries of the matrix $\mathbf{E}_t$ in (3) are assumed to be i.i.d. zero-mean complex Gaussian random variables, i.e. $\mathbf{E}_t \sim CN(\mathbf{0}, \mathbf{I})$. Also, the matrix $\Delta\mathbf{E}$ is the $CN(\mathbf{0}, \sigma_h^2(1 - \rho^2)\mathbf{I})$-distributed uncertainty on the true estimated channel given the outdated CSI, $\hat{\mathbf{H}}_{t-\tau}$. The time correlation coefficient ρ between the time instants t and $t - \tau$ is defined in [23] as,

$$\rho = \frac{E\{\hat{\mathbf{h}}_{ij,t}\hat{\mathbf{h}}_{ij,t-\tau}^H\}}{\sqrt{E\{\|\hat{\mathbf{h}}_{ij,t}\|^2\}E\{\|\hat{\mathbf{h}}_{ij,t-\tau}\|^2\}}} \quad (4)$$

The similar discussion can be presented for the estimation

error matrix $\Delta\mathbf{H}_t$, i.e., we have,

$$\Delta\mathbf{H}_t = \rho\Delta\mathbf{H}_{t-\tau} + \sigma_e\sqrt{1 - \rho^2}\mathbf{E}'_t = \rho\Delta\mathbf{H}_{t-\tau} + \Delta\mathbf{E}' \quad (5)$$

where $\mathbf{E}'_t \sim CN(\mathbf{0}, \mathbf{I})$ and $\Delta\mathbf{E}' \sim CN(\mathbf{0}, \sigma_e^2(1 - \rho^2)\mathbf{I})$. Because the matrix $\mathbf{H}_{TR,t}$ is a function of the matrix $\hat{\mathbf{H}}_t$ as $\mathbf{H}_{TR,t} = \mathcal{F}(\hat{\mathbf{H}}_t^H)$, it can be written as,

$$\begin{aligned} \mathbf{H}_{TR,t} &= \rho\mathbf{H}_{TR,t-\tau} + \sigma_{h_{eq}}\sqrt{1 - \rho^2}\mathbf{E}_{t_{eq}} \\ &= \rho(Toeplitz(TR(\hat{\mathbf{H}}_{t-\tau}^H))) + \Delta\mathbf{E}_{eq} \end{aligned} \quad (6)$$

where $\mathbf{E}_{t_{eq}} \sim CN(\mathbf{0}, \mathbf{I})$ and it is different from $\mathbf{E}_t$ in (3) and $\mathbf{E}'_t$ in (5), even though they have the same statistical properties. Also, $\sigma_{h_{eq}}^2$ is the variance of the TR channel coefficients and $\Delta\mathbf{E}_{eq} \sim CN(\mathbf{0}, \sigma_{h_{eq}}^2(1 - \rho^2)\mathbf{I})$. Finally, we define the conventional TR as the time reversal based MIMO-UWB system in an imperfect CSI without any optimizations. Also, the proposed pre-filter optimization means the application of the conventional TR (time reversal based MIMO-UWB system in an imperfect CSI) with the MMSE optimized pre-filter.

III. ROBUST PRE-FILTER OPTIMIZATION

It is worthwhile to note that the interferences (ISI and MSI) are not absolutely eliminated by TR pre-filter. Especially in ultra-high data rate UWB transmission, we need to extremely short symbol in which leads to strong ISI and MSI. On the other hands, a TR pre-filter works in time domain to raise the SNR, but simultaneously leads to a BER performance floor caused by the ISI and MSI [13]. In this section, we derive a MMSE pre-equalization solution in the presence of the estimation error in time varying channels. The error vector that is needed to be considered for the system illustrated in Fig. 1 should be the difference between the transmitted symbols and the detected symbols, i.e.,

$$\begin{aligned} \mathbf{e}_t &= \hat{\mathbf{x}}_t - \mathbf{x}_t \\ &= ((\hat{\mathbf{H}}_t + \Delta\mathbf{H}_t)\mathbf{H}_{TR,t}\mathbf{F}_{MMSE,t}\mathbf{x}_t + \mathbf{n}_t) - \mathbf{x}_t \end{aligned} \quad (7)$$

where the TR matrix $\mathbf{H}_{TR,t}$ is constructed based on $\hat{\mathbf{H}}_t$ as presented in Section II. The MMSE solution should minimize the cost function $E\{\|\mathbf{e}_t\|^2\} = E\{\|\hat{\mathbf{x}}_t - \mathbf{x}_t\|^2\}$ with respect to $\mathbf{F}_{MMSE,t}$. Therefore, the linear MMSE pre-equalizer can be obtained by solving of (8). Calculation of the conditional expectation, as required in (8), seems to be difficult. We consider an approximately solution to solve it. To do this, we use the correlation model presented in (3), (5) and (6). According to [23], this model describes the time correlation coefficient function of the estimated CSI between the time instants $t - \tau$ and t as $\rho = J_0(2\pi f_d\tau)$ in which f_d is the maximum Doppler frequency. Also, $J_0(.)$ denotes the zero order Bessel function and $\tau = kT; k \leq N$ where k denotes as number of symbol and T is the data symbol duration. Knowledge of the Doppler spread is assumed in the design of the above proposal filter. Derivation of linear MMSE pre-equalization has been carried out in [25], Appendix E and also, an imperfect CSI based derivation has been provided in section 6.2.2 of [25]. Clearly, at first we take the conditional expectation over $\Delta\mathbf{H}_t$, $\Delta\mathbf{E}$ and $\Delta\mathbf{E}_{eq}$ similar to [23], because of using conditional CSI

$$\mathbf{F}_{MMSE,t} = \arg\min\nolimits_{\tilde{\mathbf{F}}_{MMSE,t}} E_{\hat{\mathbf{H}}_t|\hat{\mathbf{H}}_{t-\tau}}\{E_{\mathbf{H}_{TR,t}|\mathbf{H}_{TR,t-\tau}}\{E_{\mathbf{x},\mathbf{\Delta H}_t}\{\|((\hat{\mathbf{H}}_t + \mathbf{\Delta H}_t)\mathbf{H}_{TR,t}\tilde{\mathbf{F}}_{MMSE,t}\mathbf{x}_t + \mathbf{n}_t) - \mathbf{x}_t\|^2\}\}\}$$

$$\text{subject to } E_{\hat{\mathbf{H}}_t|\hat{\mathbf{H}}_{t-\tau}}\{E_{\mathbf{H}_{TR,t}|\mathbf{H}_{TR,t-\tau}}\{E_{\mathbf{x},\mathbf{\Delta H}_t}\{\|\tilde{\mathbf{F}}_{MMSE,t}\mathbf{x}_t\|^2\}\}\} = \sigma_{\mathbf{x}}^2$$

(8)

$$\mathbf{F}_{MMSE,t} = \rho^2(\hat{\mathbf{H}}_{t-\tau}\mathbf{H}_{TR,t-\tau})^H \quad \{\rho^4(\hat{\mathbf{H}}_{t-\tau}\mathbf{H}_{TR,t-\tau})(\hat{\mathbf{H}}_{t-\tau}\mathbf{H}_{TR,t-\tau})^H$$

$$+\mathbf{C}_{\mathbf{\Delta H}_t} + \mathbf{C}_{\mathbf{\Delta E}} + \mathbf{C}_{\mathbf{\Delta E}_{eq}} + \mathbf{C}_{\mathbf{\Delta E},\mathbf{\Delta E}_{eq}} + (\tfrac{1}{SNR})\mathbf{I}\}^{-1}$$

(9)

model as described in (3), (5) and (6) similar to Equation (2) of [23], and then, substitute $\rho\hat{\mathbf{H}}_{t-\tau}$, $\rho\mathbf{H}_{TR,t-\tau}$ and the mutually covariance matrices $\mathbf{C}_{\mathbf{\Delta H}_t}$, $\mathbf{C}_{\mathbf{\Delta E}}$, $\mathbf{C}_{\mathbf{\Delta E}_{eq}}$ and $\mathbf{C}_{\mathbf{\Delta E},\mathbf{\Delta E}_{eq}}$ as the channel imperfections in the Equation 6.24b of [25]. Accordingly, we get the MMSE solution as (9) in which $SNR = \frac{\sigma_{\mathbf{x}}^2}{\sigma_{\mathbf{n}}^2}$ and $\mathbf{C}_{\mathbf{\Delta H}_t}$ is the channel estimation error covariance matrix as $\mathbf{C}_{\mathbf{\Delta H}_t} = E_{\mathbf{\Delta H}_t}\{\mathbf{\Delta H}_t\mathbf{\Delta H}_t^H\} = \sigma_e^2\mathbf{I}$ in which σ_e^2 is the common estimation error variance for all of the sub-channels. Note that we assumed $\mathbf{\Delta E}$, $\mathbf{\Delta H}_t$ and also, $\mathbf{\Delta E}_{eq}$ and $\mathbf{\Delta H}_t$ are statistically independent. Also, according to (6), $\hat{\mathbf{H}}_t$ and $\mathbf{H}_{TR,t}$ are statistically dependent. The covariance matrices can be obtained as,

$$\begin{aligned}
\mathbf{C}_{\mathbf{\Delta E}} &= E\{\mathbf{\Delta E}\mathbf{\Delta E}^H\} = \sigma_h^2(1-\rho^2)\mathbf{I} \\
\mathbf{C}_{\mathbf{\Delta E'}} &= E\{\mathbf{\Delta E'}\mathbf{\Delta E'}^H\} = \sigma_e^2(1-\rho^2)\mathbf{I} \\
\mathbf{C}_{\mathbf{\Delta E}_{eq}} &= E\{\mathbf{\Delta E}_{eq}\mathbf{\Delta E}_{eq}^H\} = \sigma_{h_{eq}}^2(1-\rho^2)\mathbf{I} \\
\mathbf{C}_{\mathbf{\Delta E},\mathbf{\Delta E}_{eq}} &= E\{\mathbf{\Delta E}\mathbf{\Delta E}_{eq}^H\} = \sigma_h\sigma_{h_{eq}}(1-\rho^2)\mathbf{I}
\end{aligned}$$

(10)

With respect to (5), $\mathbf{C}_{\mathbf{\Delta H}_t} = \rho^2\mathbf{C}_{\mathbf{\Delta H}_{t-\tau}} + \mathbf{C}_{\mathbf{\Delta E'}}$ in which $\mathbf{C}_{\mathbf{\Delta H}_{t-\tau}} = E_{\mathbf{\Delta H}_{t-\tau}}\{\mathbf{\Delta H}_{t-\tau}\mathbf{\Delta H}_{t-\tau}^H\}$ is the estimation error covariance matrix at the time instant $t-\tau$. If the perfect CSI is available (ideal channel estimation), Equation (9) is referred to as MMSE pre-filter optimization design in which $\mathbf{C}_{\mathbf{\Delta H}_t} = \mathbf{C}_{\mathbf{\Delta E'}} = 0$.

IV. PROPOSED POWER ALLOCATION SCHEME

In transmission over sub-channels $\overline{\mathbf{h}}_{ij,t}$, it can happen that we are faced with sub-channels that would require enormous transmit power to achieve acceptable bit error rates, especially in an imperfect CSI case. In this case it is beneficial, given the fixed amount of transmit power available, not to aim for equal error rates in all sub-channels, but perform an optimum power loading by minimizing the average bit error rate [25]. Some power allocation schemes are proposed in [26] to reduce the delay spread of the channel impulse response in the TR-MISO-UWB systems. Authors in [26] did not consider imperfect CSI case and also ISI and MSI effects on system performance in which their analysis is true for the ideal and quasi-static channels. Therefore, based on previous findings such as [25] and [27], we propose a new power loading scheme for TR-MIMO-UWB systems by minimizing the average bit error rate (BER) at the receiver in an imperfect CSI scenario and the time varying channels. This novel approach is a development of our previous power allocation work in the quasi-static MIMO channels [18]. The received signal at the MIMO channel output with TR pre-filtering and MMSE pre-equalizing in the

time instant t, according to Fig. 1 can be written as

$$\mathbf{y}_t = (\hat{\mathbf{H}}_t + \mathbf{\Delta H}_t)\mathbf{H}_{TR,t}\mathbf{F}_{MMSE,t}\mathbf{x}_t + \mathbf{n}_t \quad (11)$$

where $\mathbf{\Delta H}_t$ and $\mathbf{n}_t$ are assumed mutually independent and uncorrelated matrices. Also, $\mathbf{x}_t = \frac{1}{\sqrt{N_t}}[x_{1,t}, x_{2,t}, ..., x_{N_r,t}]^T$, $\mathbf{y}_t = \frac{1}{\sqrt{N_r}}[y_{1,t}, y_{2,t}, ..., y_{N_r,t}]^T$ and $\mathbf{n}_t = [n_{1,t}, n_{2,t}, ..., n_{N_r,t}]^T$ are the $N_r \times 1$ transmitted symbols, received symbols and AWGN vectors, respectively. The $N_r(2L_g - 1) \times N_r$ MMSE pre-equalizing matrix $\mathbf{F}_{MMSE,t}$ is given by (9). For simplicity of our analysis, we define the $N_r(2L_g - 1) \times 1$ MMSE pre-equalized transmitted symbols vector $\mathbf{x}_t'$ as $\mathbf{x}_t' = \mathbf{F}_{MMSE,t}\mathbf{x}_t$. Then, the received signal at j^{th} receive antenna in the time instant t can be expressed by (12). The first part of the received signal is the desired data symbol. In this part, the equivalent channel is the autocorrelation of channels. Also, $v_{j,t}$ and $w_{j,t}$ are the interference from other symbols and the interference from the channel estimation error in the time instant t, respectively. In $v_{j,t}$ and $w_{j,t}$ parts, the equivalent channel is the cross-correlation of channels. Therefore, the values of these terms are less than the former (first part of the received signal). Also, $v_{j,t}$ and $w_{j,t}$ terms in (12) appears as interference which degrades the performance of TR-MIMO-UWB system, especially in imperfect CSI. Some of this interference can be reduced by a MMSE pre-equalizer, but, we try to maximize the Signal to Interference plus Noise Ratio (SINR) more than ever by a power allocation scheme. If we define the conditional expectations as,

$$\begin{aligned}
E_{\hat{\mathbf{h}}_{ij,t}|\hat{\mathbf{h}}_{ij,t-\tau}}\{E_{\overline{\mathbf{H}}_{ij,t}|\overline{\mathbf{H}}_{ij,t-\tau}}\{.\}\} &= E_{con}\{.\} \\
E_{\mathbf{\Delta h}_{ij,t}|\mathbf{\Delta h}_{ij,t-\tau}}\{E_{\overline{\mathbf{H}}_{ik,t}|\overline{\mathbf{H}}_{ik,t-\tau}}\{.\}\} &= E_{con-error}\{.\}
\end{aligned}$$

(13)

Then, the SINR at the jth receive antenna in the time instant t is given by (14) in which $\|.\|_F$ denotes the Frobenius norm. By applying the above conditional expectations and using the approximate solution exploited for calculation of (9), also according to (3), (5) and (6), the SINR at the jth receive antenna in the time instant t can be calculated as (15). If we define $\mathbf{R}_{ij,t-\tau} := \hat{\mathbf{h}}_{ij,t-\tau}\overline{\mathbf{H}}_{ij,t-\tau}$ as auto-correlation vector of the channel vector $\hat{\mathbf{h}}_{ij,t-\tau}$ and, $\mathbf{C}_{ik,t-\tau} :=_{k\neq j} \hat{\mathbf{h}}_{ij,t-\tau}\overline{\mathbf{H}}_{ik,t-\tau}$ as cross-correlation vector of $\hat{\mathbf{h}}_{ij,t-\tau}$ with other sub-channels then, the SINR at the jth receive antenna is expressed as (16) in which the estimation errors of the different sub-channels are assumed to be mutually independent, i.e., $\mathbf{\Delta h}_{ij,t} \amalg \mathbf{\Delta h}_{mn,t}$ where $\amalg$ is standing for mutual independence. Performance of the TR-MIMO-UWB system depends on transceiver structure and the received signal properties, e.g., its probability density

$$y_{j,t} = \underbrace{\sum_{i=1}^{N_t} \hat{\mathbf{h}}_{ij,t}\overline{\mathbf{H}}_{ij,t}\mathbf{x}'_{j,t}}_{Signal} + \underbrace{\underbrace{\sum_{i=1}^{N_t}\sum_{k=1,k\neq j}^{N_r}\hat{\mathbf{h}}_{ij,t}\overline{\mathbf{H}}_{ik,t}\mathbf{x}'_{k,t}}_{v_{j,t}} + \underbrace{\sum_{i=1}^{N_t}\sum_{k=1}^{N_r}\boldsymbol{\Delta}\mathbf{h}_{ij,t}\overline{\mathbf{H}}_{ik,t}\mathbf{x}'_{k,t}}_{w_{j,t}}}_{Interference} + \underbrace{n_{j,t}}_{Noise} \tag{12}$$

$$SINR_{j,t} = \frac{E_{con}\{\|\sum_{i=1}^{N_t}\hat{\mathbf{h}}_{ij,t}\overline{\mathbf{H}}_{ij,t}\|_F^2\}}{E_{con}\{\|\sum_{i=1}^{N_t}\sum_{k=1,k\neq j}^{N_r}\hat{\mathbf{h}}_{ij,t}\overline{\mathbf{H}}_{ik,t}\|_F^2\} + E_{con-error}\{\|\sum_{i=1}^{N_t}\sum_{k=1}^{N_r}\boldsymbol{\Delta}\mathbf{h}_{ij,t}\overline{\mathbf{H}}_{ik,t}\|_F^2\} + E\{\|\mathbf{n}_{j,t}\|_F^2\}} \tag{14}$$

$$SINR_{j,t} = \frac{\rho^4\left(\|\sum_{i=1}^{N_t}\hat{\mathbf{h}}_{ij,t-\tau}\overline{\mathbf{H}}_{ij,t-\tau}\|_F^2\right) + \sigma_h^2\sigma_{h_{eq}}^2(1-\rho^2)^2}{\rho^4\left(\|\sum_{i=1}^{N_t}\sum_{k=1,k\neq j}^{N_r}\hat{\mathbf{h}}_{ij,t-\tau}\overline{\mathbf{H}}_{ik,t-\tau}\|_F^2 + \|\sum_{i=1}^{N_t}\sum_{k=1}^{N_r}\boldsymbol{\Delta}\mathbf{h}_{ij,t-\tau}\overline{\mathbf{H}}_{ik,t-\tau}\|_F^2\right) + \sigma_{h_{eq}}^2(1-\rho^2)^2(\sigma_h^2+\sigma_e^2) + \sigma_n^2} \tag{15}$$

$$SINR_{j,t} = \frac{\rho^4\left(\sum_{i=1}^{N_t}\sum_{l=0}^{2L-2}|\mathbf{R}_{ij,t-\tau}(l)|^2\right) + \sigma_h^2\sigma_{h_{eq}}^2(1-\rho^2)^2}{\rho^4\left(\sum_{i=1}^{N_t}\sum_{k=1,k\neq j}^{N_r}\sum_{l=0}^{2L-2}|\mathbf{C}_{ik,t-\tau}(l)|^2 + L\sigma_e^2\sum_{i=1}^{N_t}\sum_{k=1}^{N_r}\sum_{l=0}^{L-1}|\hat{\mathbf{h}}_{ik,t-\tau}(l)|^2\right) + \sigma_{h_{eq}}^2(1-\rho^2)^2(\sigma_h^2+\sigma_e^2) + \sigma_n^2} \tag{16}$$

function (PDF). For $L_g t_s \geq 5nsec$ where t_s is the time resolution of the channel, the average numbers of paths is high, so using central limit theorem, the sum of a large number of independent, zero-mean random variables form a Gaussian PDF for the path gain [28]-[29]. But for $L_g t_s < 5nsec$, path gain PDF is not Gaussian and as the $L_g t_s$ increases, the non-Gaussian shape tends more to Gaussian, and the densities become more bell shaped [29]. According to the above discussion, the average BER of the TR-MIMO-UWB system at the jth receive antenna, assuming BPAM modulation, can be derived approximately from Eq. (16) as [27-29],

$$BER_{j,t} \approx \frac{1}{N_t}\sum_{i=1}^{N_t} Q\left(\sqrt{2SINR_{j,t}p_{i,j}}\right) \tag{17}$$

where $p_{i,j}$, $P_{T,j} = \sum_{i=1}^{N_t}p_{i,j}$ and $Q(.)$ are the transmit power assigned to i^{th} transmit antenna, the total transmitted available power for the jth receive antenna and the Marcum Q-function, respectively. $Q(x)$ is defined as,

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{+\infty}\exp(\frac{-t^2}{2})dt \tag{18}$$

For simplicity of our analysis we assume $\sigma_{\mathbf{x}}^2 = 1$, so that $P_{T,j} = N_t$. The optimum power allocation vector $\mathbf{P}_j = [p_{1,j}, \cdots, p_{N_t,j}]^T$ that minimizes the average BER at the jth receive antenna, when an imperfect CSI is presented, can be obtained by introducing the Lagrange function as [25],

$$L_G = \frac{1}{N_t}\sum_{i=1}^{N_t} Q\left(\sqrt{2SINR_{j,t}p_{i,j}}\right) - \lambda\left(N_t - \sum_{i=1}^{N_t}p_{i,j}\right) \tag{19}$$

With partial derivative we obtain,

$$\frac{\partial L_G}{\partial p_{i,j}} = \frac{-1}{2N_t\sqrt{\pi}}\sqrt{\frac{SINR_{j,t}}{p_{i,j}}}\exp(-SINR_{j,t}p_{i,j}) + \lambda \tag{20}$$

Solving $\frac{\partial L_G}{\partial p_{i,j}} = 0$ for $p_{i,j}$, we can allocate the power to each transmit antenna in a manner that,

$$\left(\frac{1}{SINR_{j,t}}\right)p_{i,j}\exp(SINR_{j,t}p_{i,j}) = \frac{1}{4N_t^2\lambda^2\pi} \tag{21}$$

and finally,

$$p_{i,j}(\lambda) = \left(\frac{1}{SINR_{j,t}}\right)W\left((SINR_{j,t})^2\frac{1}{4N_t^2\lambda^2\pi}\right) \tag{22}$$

where $W(.)$ is the real valued Lambert's W-function defined as the inverse of the function $f(x) = x\exp(x)$ for $x \geq 0$, i.e., $W(x) = a \Leftrightarrow a\exp(a) = x$ [30]. Since the $W(x)$ function is real and concave, the unique solution for power allocation vector to minimize the average BER at the jth receive antenna can be found by the following simple iterative procedure [31].
1. Choose a positive λ, which fulfils,

$$(SINR_{j,t})\left(\frac{1}{4N_t^2\lambda^2\pi}\right) \leq P_{T,j} \tag{23}$$

2. Calculate,

$$\hat{P}_{T,j} = \left(\frac{1}{SINR_{j,t}}\right)W\left((SINR_{j,t})^2\frac{1}{4N_t^2\lambda^2\pi}\right) \tag{24}$$

3. If $\hat{P}_{T,j}$ is not yet sufficiently close to $P_{T,j}$ then multiply λ by $\frac{P_{T,j}}{\hat{P}_{T,j}}$ and go back to step (2).
4. Compute $\mathbf{P}_j = [p_{1,j}, \cdots, p_{N_t,j}]^T$ according to (22).
Note that since $W(x)$ for $x > \frac{-1}{e}$ is a monotonic function then according to (22) the highest powers (max $p_{i,j}$) are assigned to the weakest signals so the SINR values approximately stay constant for all sub-channels. The above algorithm should be iterated for all of N_r receive antenna and then, we achieve the total optimized power allocation vector as $\mathbf{P} = \sum_{j=1}^{N_r}\mathbf{P}_j$. Note that the total available power for data transmission is $P_T = \frac{1}{N_r}\sum_{j=1}^{N_r}P_{T,j}$.

V. SIMULATION RESULTS AND DISCUSSION

To evaluate the performance of the proposed solutions for the TR-MIMO-UWB system, Monte Carlo simulations are conducted in this section. As in [11], the second-order derivative of Gaussian pulse has been used as the transmitted pulse $p(t)$, which is mathematically defined as,

$$p(t) = \left(1 - 4\pi \left(\frac{t - t_c}{T_p}\right)^2\right) \exp\left(-2\pi \left(\frac{t - t_c}{T_p}\right)^2\right) \quad (25)$$

where T_p is a parameter corresponding to pulse width, and t_c is a time shifting of the pulse. In the following simulations, we consider $T_p = 5nsec$, and $t_c = 2.5nsec$. Also, one pulse per symbol is assumed, i.e., symbol duration T is assumed $5nsec$ where is equal to transmission rate of $200Mbps$ and also, sampling time $t_c = 0.167nsec$ is considered. We assume that the signal is transmitted over UWB channel. As in [11], we use the IEEE 802.15.3a CM4 channel model [32]-[33] as a worst case for each channel realization in simulations. Although the channel model CM4 is designed for Single-Input Single-Output (SISO) scenario, the extension to a MIMO configuration is achieved by assuming that the MIMO channel parameters are independent and identically distributed realizations from the same statistical model. We further consider the case of a 2×2 TR-MIMO-UWB system set-up with BPAM modulated data streams. In our simulations, we use the normalized Doppler frequency $f_d T = 0.001$, $f_d T = 0.005$ and $f_d T = 0.01$. Also, the channel estimation error variance $\sigma_e^2 = 0.1$ is assumed. At first, it is necessary that we clarify some phrases mentioned in some simulation results. Phrase "Perfect CSI" means the conventional TR-MIMO-UWB system in perfect CSI. Clearly, this scenario does not need to the optimization schemes. We provide a benchmark curve according to [11]. Phrase "Conventional TR-MIMO-UWB" means the time reversal based MIMO-UWB system in an imperfect CSI without any optimization. Also, "proposed MMSE TR-MIMO-UWB" means the application of the conventional TR (time reversal based MIMO-UWB system in an imperfect CSI) with the MMSE optimized pre-filter. Phrase "Proposed with loading" means the application of the proposed MMSE TR-MIMO-UWB with the power allocation scheme. Finally, "Proposed without loading" is referred to the proposed MMSE TR-MIMO-UWB.

To optimize the TR-MIMO-UWB system performance of Fig. 1 and to mitigate the imperfect CSI effects, we use the proposed robust MMSE solution mentioned in Section 3. Figs. 2 and 3 plot the average BER performances of the 2×2 TR-MIMO-UWB system with proposed optimization for N=5, 10, respectively. Clearly, it can be seen from Figs. 2 and 3 that, our robust MMSE solution exhibits a lower average BER performance when compared to the conventional TR-MIMO-UWB system design. More specifically, from the figures, it can be observed that the proposed method have more advantage for shorter N where the channel time correlation is noticeable, in that, as N increases, the correlation coefficient $\rho = J_0(2\pi f_d \tau) = J_0(2\pi f_d NT)$ decreases and so, the optimized solutions performance is diminished.

Figs. 4 and 5 plot the average BER performances of the 2×2 TR-MIMO-UWB system with proposed optimization for $f_d T = 0.001$ and $f_d T = 0.005$, respectively. As it can be observed from Figs. 4 and 5 that, for lower normalized Doppler frequency, our proposed method has good performance over all values of N while in the higher normalized Doppler frequency, the performance is noticeable for shorter Ns where the channel time correlation is noticeable.
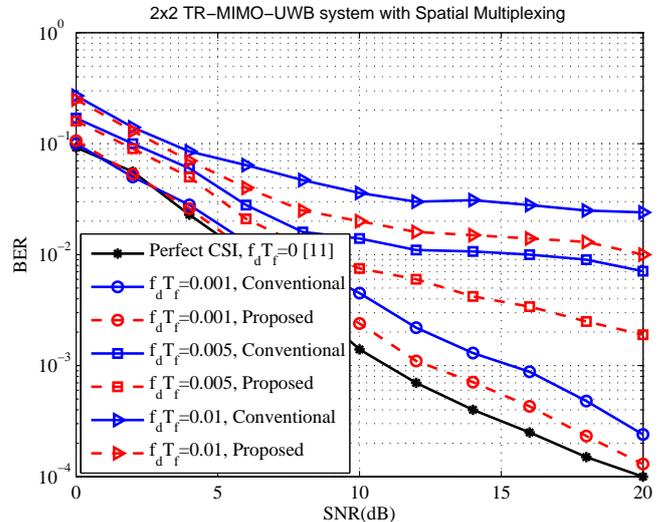

Fig. 2. BER performance of the 2×2 TR-MIMO-UWB system with proposed MMSE optimization for $N = 5$, $\sigma_e^2 = 0.1$ and different Doppler values.
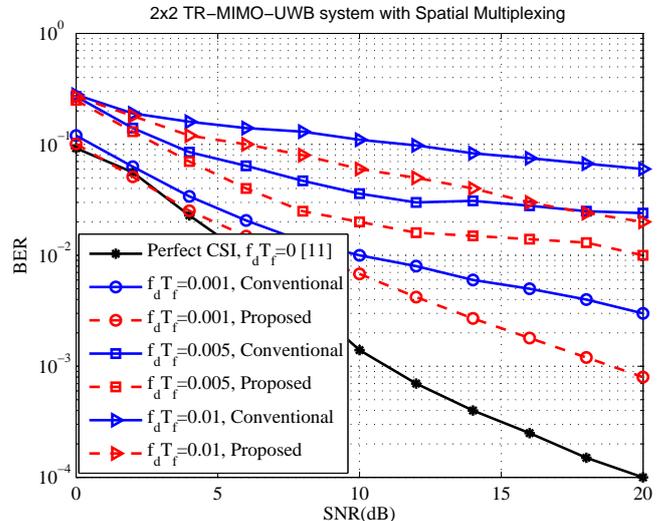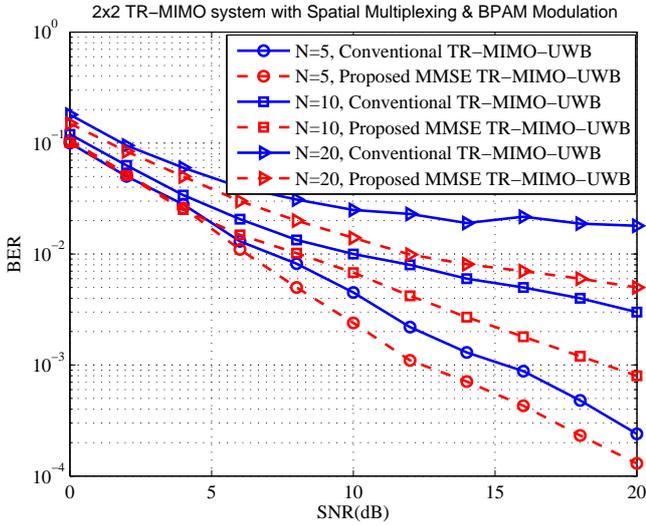

Fig. 3. BER performance of the 2×2 TR-MIMO-UWB system with proposed MMSE optimization for $N = 10$, $\sigma_e^2 = 0.1$ and different Doppler values.

In addition to the MMSE robust optimization scheme, we use the proposed power loading solution mentioned in Section IV to improve the TR-MIMO-UWB system performance more than ever. In Figs. 6-9, we can observe the performance of the proposed power loading for the MMSE robust optimization. As can be seen from these figures, the performance of power

loading is noticeable, especially for high SNR values. Such as, according to Figs. 6-7, for $f_dT = 0.001$, the power loading scheme substantially outperforms the robust optimization method about 2dB SNR in Fig. 6 and 4dB SNR in Fig. 7 both at the average BER=10^{-3}. Also, according to Figs. 8-9, the power loading scheme can be used to increase the TR-MIMO-UWB system performance, considerably. Furthermore, the system performance is mitigated as N increases. Therefore, our proposed method significantly depends on the values of N or the time-correlation coefficient ρ.

Fig. 4. BER performance of the 2×2 TR-MIMO-UWB system with proposed MMSE optimization for $f_dT = 0.001$, $\sigma_e^2 = 0.1$ and different N values.
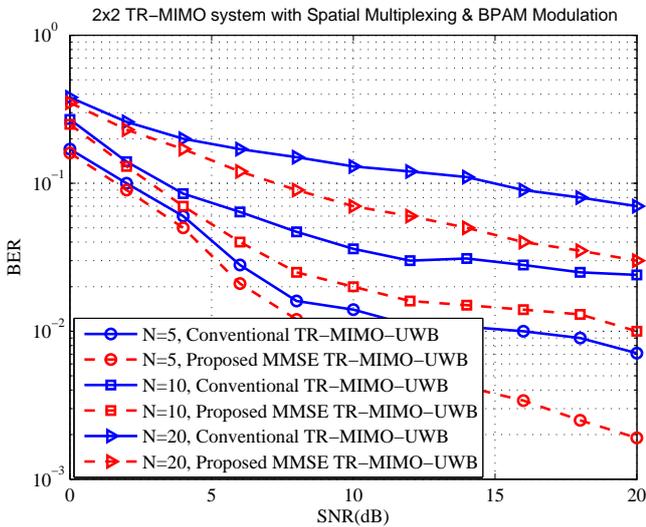

Fig. 5. BER performance of the 2×2 TR-MIMO-UWB system with proposed MMSE optimization for $f_dT = 0.005$, $\sigma_e^2 = 0.1$ and different N values.
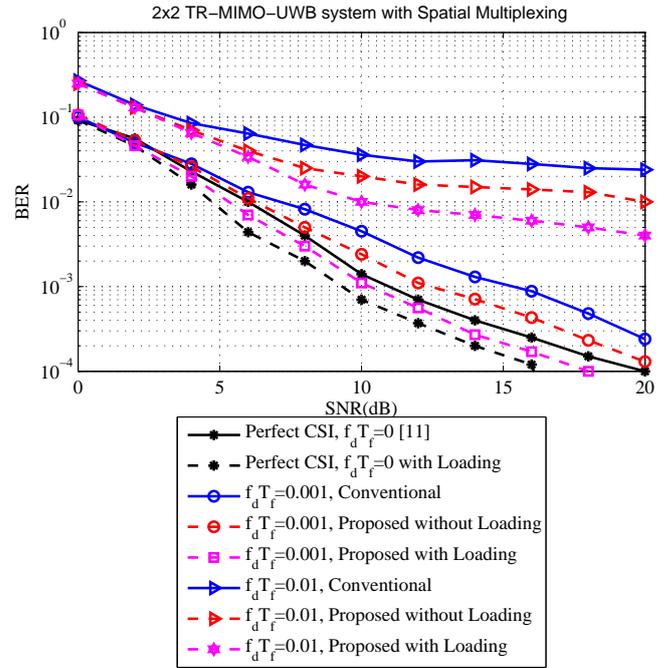

Fig. 6. BER performance of the 2×2 TR-MIMO-UWB system with proposed MMSE optimization and power loading for $N = 5$, $\sigma_e^2 = 0.1$ and different Doppler values.
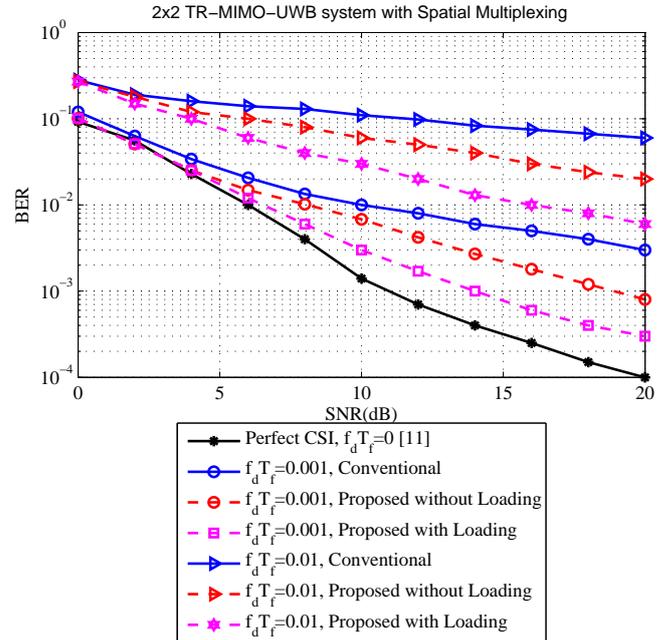

Fig. 7. BER performance of the 2×2 TR-MIMO-UWB system with proposed MMSE optimization and power loading for $N = 10$, $\sigma_e^2 = 0.1$ and different Doppler values.

As we observed from the simulation results, we will confront the weak performance of our methods as the speed of the user or vehicle increases, in that by increasing f_d, the correlation coefficient decreases (it depends by zero-order Bessel function) and so, SINR decreases. As a result, the
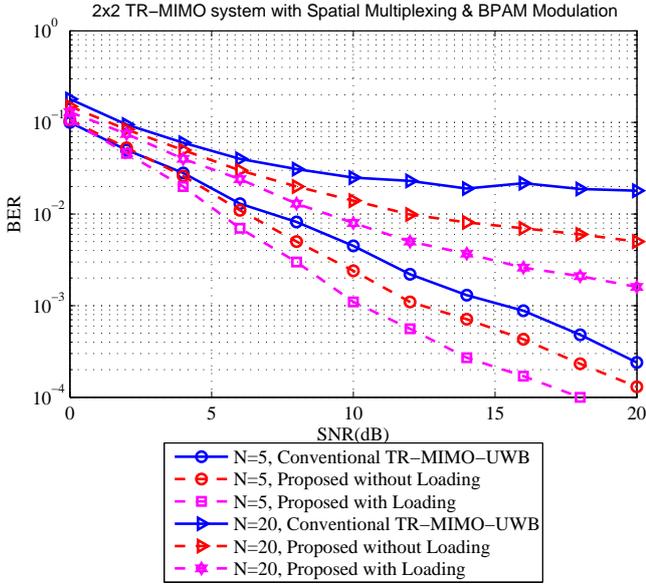
Fig. 8. BER performance of the 2×2 TR-MIMO-UWB system with proposed MMSE optimization and power loading for $f_d T = 0.001$, $\sigma_e^2 = 0.1$ and different N values.
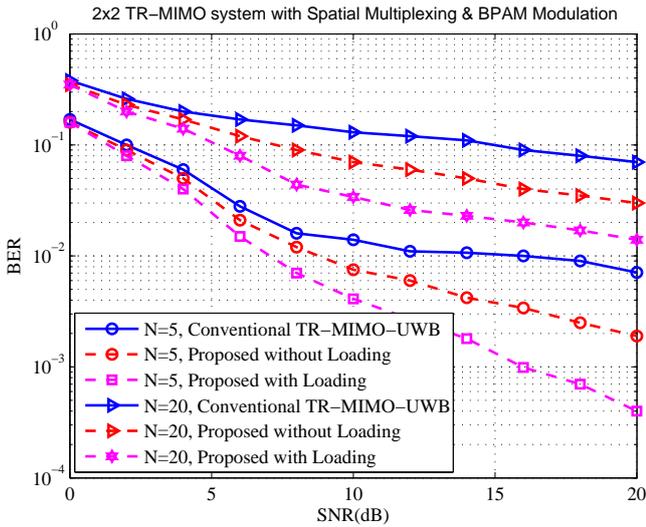

Fig. 9. BER performance of the 2×2 TR-MIMO-UWB system with proposed MMSE optimization and power loading for $f_d T = 0.005$, $\sigma_e^2 = 0.1$ and different N values.

BER increases. Similar discussions can be presented for N. Therefore, the best performance of our solutions is in lower speed of user or lower N values.

VI. CONCLUSIONS

A robust MMSE TR-MIMO-UWB system design that exploits the knowledge of the conditional channel distribution, given the available outdated CSI in τ second ago was proposed in this paper. In proposal solution, once the channel estimation error covariance matrix $\mathbf{C}_{\mathbf{\Delta H}_t}$, outdated CSI and the time correlation coefficient ρ is transmitted from the receiver to the transmitter in the beginning of a data block and then, they are used during that block. This solution mitigates the feedback overhead in time varying channel significantly than traditional method in which we used to feedback the CSI during a data block. We have also shown that our robust approach outperforms the traditional design in terms of BER plots in time varying scenario, especially for high SNR and shorter data block length where the time correlation of the channel is noticeable. Then, the power loading strategy was proposed for the imperfect CSI in the robust optimized MMSE TR-MIMO-UWB system. It was observed that it brought a performance gain in the 2×2 TR-MIMO-UWB system in an imperfect CSI scenario and the robust optimized system.

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