Time Reversal Transmission Potential for Multi-user UWB Communications

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Abstract—In this paper we propose and evaluate the performance of the time reversal technique in impulse radio UWB communications. The evaluation was based on measured channel impulse responses in the UWB frequency band of 3 to 5 GHz of a 4x1 MISO system with both vertical and horizontal polarization at the receiver. The results show that there is a great potential in combining time reversal and UWB technique with respect to both reducing the receiver complexity and improving the system performance. Simultaneous communication is illustrated with 5 users with a BER of less than $10^{-3}$ at an average SNR of 15dB.

I. INTRODUCTION

Ultra wide band (UWB) technology has a strong potential in short range communications. It aims at providing communications with high bit rates and low complexity devices, e.g. [1], [2].

Time reversal (TR) technique has been applied extensively in acoustic, medical and under water communication applications [3], [4]. Because of its simplicity and performance advantages, the idea of applying the TR in wireless communications has gained much attention recently. It is expected that TR can reduce the effect of the inter symbol interference (ISI) significantly without the need of high complexity equalizer at the receiver. Evaluation on the performance of TR based on wireless channel measurement in [5], [6] and [7] among others has shown its great potential. Recently the authors in [8] have proposed an approach using TR with MMSE equalizer to UWB communications. In this reference the use of TR has been illustrated as a promising solution in single user UWB communications.

With difference approach, in this paper we address the applicability of TR in impulse radio UWB transmissions (TR-UWB) as one possible solution to improve the multi-user system capacity and communication range. With the proposed transmission scheme, we show that under certain assumptions, by using TR-UWB the receiver’s complexity can be reduced, while an increase of the system capacity in terms of the number of simultaneous users is achieved. The performance of the proposed scheme is evaluated using recent MIMO UWB channel investigations [11].

The paper is organized in the following way. First we review the TR technique and present the proposed TR-UWB transmission scheme in Section II. The UWB measurement setup and scenarios are briefly presented in Section III. Using the measured channel impulse responses (IR) the TR-UWB performance in terms of the signal to interference ratio (SIR), the number of simultaneous supported users, and the system BER are analyzed in Section IV. Finally the conclusion wraps up the paper in Section V.

II. MULTI ELEMENT ANTENNAS & TIME REVERSAL

A. TR background and performance metrics

The TR technique consists in pre-equalising the transmitted signal by convolving it with a time reversed replica of the complex channel impulse response, $h(-t)^\star$. The mathematical formulation of the received signal of a SISO link using TR can be described as follows

$$s \ast h_{ij}(-t)^\star h_{ij}(t) = s \ast R_{ij}^{auto}(t)$$

where $\ast$ denotes convolution, $\star$ indicates the complex conjugate; $R_{ij}^{auto}$ is the autocorrelation of the channel IR $h_{ij}$ between $i^{th}$ transmitting antenna and $j^{th}$ receiving antenna; $s$ is the transmitted symbol. The received signal at the off-target point has the form

$$s \ast h_{ij}(-t)^\star h_{ik}(t) = s \ast R_{ijk}^{cross}(t)$$

where $h_{ik}(t)$ denotes the IR of the channel from the transmitting point to the off-target point and $R_{ijk}^{cross}$ is the cross correlation of the channel IR $h_{ik}$ and the transmitted signal $h_{ij}$.

TR for SISO system works in the same manner as the traditional pre-Rake system. When there are $N_t$ transmitting antennas (MISO system), under ideal conditions the received signal becomes the sum of $N_t$ IR autocorrelations. The received signals are not only coherently added in the time-delay domain but also in the spatial domain (multiple antennas). Thereby spatial focusing/selectivity and the time compression can be obtained at the same time. Due to the spatial focusing the interference can be reduced and due to the time compression the ISI can be alleviated.

Because of the spatial focusing characteristics of TR, it is possible to simultaneously transmit to more users. A TR system supporting $N_u$ users can be though of as $N_u$ simultaneously operating $N_t \times 1$ MISO systems each one targeting a
difference user. The received signal at the \( j \)th user becomes

\[
y_j = \sum_{i=1}^{N_t} R_{ij}^{auto}(t) \text{Signal}(j) + \sum_{i=1}^{N_t} \sum_{k=1, k \neq j}^{N_t} s_k \cdot R_{ijk}^{cross}(t) + n_j
\]

\[\text{(3)}\]

In the following we use the term "equivalent IR" or \( h_{eq} \) to denote the sum of the autocorrelation \( R_{ij}^{auto} \) in equation (3).

\[
h_{eq}^{t}(t) = \sum_{i=1}^{N_t} R_{ij}^{auto}(t)
\]

\[\text{(4)}\]

The radio scattering environment, which in general makes the propagation channel of each communication link independent and unique, can provide the natural "orthogonal codes", \( h_{ij}(t) \) and \( h_{ik}(t) \), necessary to separate the signals intended for different users, thus minimising the cross-correlation term \( R_{ijk}^{cross} \). Consequently the throughput of the system can be significantly increased.

The instantaneous Signal to Interference Ratio (SIR) used in the following analysis, is calculated as the ratio of the peak power of the signal of interest and the corresponding interference power at the same time lag [7]:

\[
SIR_j = 10 \log_{10} \left( \frac{|\text{Signal}(j)_{\text{peak}}|^2}{|\text{Interference}(j)_{\text{peak}}|^2} \right)
\]

\[\text{(5)}\]

where \(||\) denotes the absolute value operation.

We note here that in order to apply the TR, the channel IR must be known at the transmit side. In a reciprocal channel, the channel estimation from the backward link (from the receiver to the transmitter) can be considered as a solution to estimate the IR of the forward link (from the transmitter to the receiver). This requirement on reciprocal channel can be approximately fulfilled in a systems employing the time-division duplexing (TDD) scheme with a quasi-stationary environment.

B. TR-UWB transmission scheme

In impulse radio UWB technique, the pulse width is much smaller than the effective length of the measured IR, thus the convolution of the signal with the time-reversed IR is essentially equivalent to the multiplication of the time-reversed IR’s main taps with the transmitted UWB pulse. The spectral characteristics of the transmitted TR waveforms are determined by the spectral characteristic of the transmitted pulse waveform. Performance evaluations of the pre-RAKE scheme for SISO UWB system can be found e.g. in [10].

We analysed in more depth the spatial selectivity aspects in multi-user MISO UWB systems employing TR technique. Figure 1 illustrates the working principle of a TR-UWB MISO system for single user. In the TR-UWB system, due to the temporal focusing effect, it is expected that synchronisation to the received signal - correlation peak in Figure 1 right - would be accomplished easier. The receiver does not need to estimate the channel IR and can use a single tap/Rake finger tuned to the major signal peak, thus most of the complexity burden at the receiver is moved to the transmitter.

Spatial focusing is the other main advantage of applying TR in UWB communications and allows the reduction not only of the interference to/from other users but also to/from other wireless communication systems. In the context of a multi-user scenario, the system capacity therefore increases.

C. TR-UWB with the time offset scheme

The TR scheme with simultaneous transmission of independent data streams requires the time-reversed IRs to be aligned at their maximal peak/or the first arrival path, so that one can transmit \( N_u \) independent symbols simultaneously (Figure II-C left). Because of this time alignment, even though the channel IRs are uncorrelated, the magnitude of the IRs cross-correlation \( R_{ij}^{cross} \) is still an order of magnitude smaller than that of the IR autocorrelation \( R_{ij}^{auto} \). In general, the interference at the peak of the signal increases linearly with the number of simultaneous transmissions/users.

Our proposal for interference suppression consists in offsetting in time the time-reversed IRs intended for each user. The transmitted signal intended for the \( j \)th user at the \( i \)th transmitting antenna can be described as

\[
s_j \cdot \text{circshift}(h_{ij}(-t)\ast, \Delta TR(j - 1))
\]

with \( \Delta TR = \Delta t \delta_t \)

\[\text{(6)}\]

where \text{circshift()} denotes the circular shift operation, \( \Delta t \) is the number of shifted taps and \( \delta_t \) is the tap or the time-delay resolution. Figure II-C illustrates the signals transmitted at one transmitting antenna before and after shifting the time-reversed IRs’ main peaks by \( \Delta t = 5 \) taps relative to each other. Hereafter we use the term "TR&S" to denote the shifted time-reversed scheme.

With the TR&S scheme, the taps in the propagation channel containing significant energy are multiplied by taps of the transmitted signal with low energy and vice versa. Thus the interference power is significantly suppressed. Depending on the amount of the time offset \( \Delta TR \), the system capacity is reduced as it requires a longer interval for all symbols to be transmitted. The communication quality for each user is improved due to lower average SIR.

Due to the lack of power control, the interference power as described in equation (3) can be comparable to (or a large fraction of) the intended signal. In our proposed TR&S transmission scheme the time-reversed IR is normalized by the measured wideband power so that the transmitted power intended for each user was equal (equal power control) [7].

The SIR results as a function of \( \Delta TR \) and the number of simultaneous users are given in Section IV.

III. CHANNEL MEASUREMENTS AND DATA ANALYSIS

The channel measurements were conducted with a UWB sliding correlator channel sounder [11]. The measurement bandwidth was 2.5GHz centred at 4.5GHz. The effective delay
Fig. 1. Single user MISO TR-UWB system, $N_t$ transmitting antennas and single user equipped with one receiving antenna. The received signal shows the sum of $N_t$ signal correlations, and illustrates the temporal focusing in TR.

Fig. 2. Signal applied at one antenna for MISO TR-UWB multiple-user scenario: normal TR case (left), proposed shifted TR (TR&S) scheme (right)

resolution was $\delta_t = 0.4$ns. The antennas used were UWB planar monopole antennas with a bandwidth of 2GHz to 15GHz [12]. An array of vertical polarised four elements was used at the ‘fixed device’ (FD), while a single element was used at the user terminal (PC-laptop) with vertical or horizontal polarisation. A more detailed description of the equipment and the investigated environment can be found in [11].

The radio environment was quasi-static during the measurements and only the stationary user device scenarios were used for the results presented in this paper. The environment was a large hallway (17m x 12m x 11m) with two metalised glass walls, two metallic bridges and one staircase structure. The FD antenna was mounted at 6m height above the floor while the PC antenna was moved to five different locations always at 0.8m height above the floor. The effective FD-PC distances were in the range of 6m to 17m. For one type of receiving PC antenna polarization, at one location, 1024x4 channel IRs were captured (1024 is the number of SISO channel IRs, and $N_t = 4$ is the number of antennas at the FD). The obtained channel data was compensated for all system components. In order to make it more natural to the concept of carrier-less UWB signal, the measured complex IRs have been converted into real-valued IRs via standard Hermitian transformation.

From the measurement data we estimated the length of 90% energy window in time-delay domain, $W$, using the power delay profile (PDP). The average value of $W$ was found to be about 100 taps or 40ns. For the purpose of illustration, we used 100 taps starting from the first arrival path, or the main peak of the IR in most case, as the effective length of the IR.

IV. RESULTS AND ANALYSIS

A. Signal detection

As mentioned in Section II-B, for the TR-UWB scheme to work correctly the receiver needs to be synchronized to the received signal peaks. Due to the temporal focusing effect, the fraction of the signal energy used for synchronization is higher than in the case of traditional systems without TR.

We analysed the variation of the Signal to Side lobe Ratio (SSR) The SSR is defined as the power ratio of the main
signal peak to the largest side lobe signal of the equivalent channel IR, \( h^{eq}(t) \). The SSR is calculated as a function of the used IR’s length (number of taps). The results showed that the mean SSR values do not depend on the used IR’s length or receiver antenna polarisation and were in the range of 11dB with a standard deviation of 4.5dB. With a mean SSR higher than 10 dB, the synchronisation to the main received signal peak can be achieved using simple, energy threshold detectors [12] or more complex ones, such as the chip-level post-detection integration schemes [13].

Other way of illustrating the TR temporal focusing capability is to compare the RMS delay spread of the normal channel IR with that of the equivalent channel IR, \( h^{eq} \). Using the measurement data it was found that the median RMS delay spread of the \( h^{eq} \) has reduced by a factor of 1.5 as compared to that of the real channel IR. This result is in agreement with the results shown in [5] and [7].

B. Spatial selectivity with TR&S scheme

First we investigated the dependence of the SIR metric on the number of shifted taps \( \Delta l \) (or \( \Delta TR \)) used in the TR&S scheme (see equation 6). The results showed that above certain offsetting value of \( \Delta l = 5 \) taps (\( \Delta TR = 2ns \)) the SIR becomes saturated at the average value of 27dB, independently on the number of users and the user terminal antenna polarisation. Note that the offset \( \Delta l \) described in Figure II-C can be made dynamic or static. Henceforth, for simplicity we use a static offset time of \( \Delta l = 5 \) taps.

Figure 3 (top) shows the SIR calculated from the measured IRs with the effective IR’s length of 100 taps (40ns). The results for both aligned time-reversed IRs and TR&S schemes are given in multi-user configurations. It is observed that by shifting the transmitted time-reversed IRs intended for each user by 2ns, significant improvement in the SIR can be obtained e.g. the median SIR increases to 23dB from 12dB for 5 simultaneous users scenario.

These results are significant because the separation distance between users/measurement locations was only 15 meters at most [11]. For a 2 users scenario, with UWB signals the mean SIR of the aligned IRs is about 20dB. Whereas for the same value of SIR, with wideband (UMTS) signals the required separation distance is about 300m [7]. This demonstrates a much better spatial focusing performance of the TR for UWB bandwidth (GHz) than for UMTS bandwidth (MHz).

It is observed that with the simple TR-UWB scheme, the SIR was slightly better when vertical polarized receiving antenna was used. However, using the TR&S scheme there was no significant difference in the obtained SIR between the two polarisations. Therefore, our proposed transmission scheme efficiently mitigates the channel effects due to the possible random orientation/polarisation of the user terminal antennas.

C. BER simulation and system throughput

Using the measured channel IRs we simulated the average BER of the multi-users TR-UWB MISO system. At one measured location, the received signal power at the receiving antenna was calculated as the average power of the signal at its peak

\[
P_j = \max(\{h^{eq}_j\})^2
\]  

(7)

The equal power control scheme in Section II-C, is used in the simulations. By varying the noise variance, we can vary the synthetic Signal to Noise Ratio (SNR) at one measured location. The maximum SNR value is limited at 20dB to assure that it is always lower than the measured SNR [11].

For these simulations, we used the bipolar pulse amplitude modulation (BPAM) with the Gaussian pulse shape similar to the investigations in [13]. The pulse width of 0.4ns was chosen. The interval between consecutive transmitted symbols of 40ns was selected and therefore no ISI was considered in the simulation. This interval is also equal to the 90% energy window length of the IRs. Thus the a maximum bit rate per user is 1/40ns=25Mb/s. Perfect synchronization is assumed in the simulation. The received signal of the \( j^{th} \) user has the form described in equation (3). The received symbol is detected based on the ideal decision threshold

\[
\text{Detected bit} = \begin{cases} 
  "1" & \text{if } y_j \geq 0, \\
  "0" & \text{if } y_j < 0 
\end{cases}
\]  

(8)

For each measured IR, some \( N_{\text{symbol}}=10000 \) symbols were simulated in order to have enough data for statistical analysis. For each SNR value, the BER is calculated as

\[
\text{BER} = \frac{\sum_{n=1}^{N_{\text{symbol}}} \sum_{j=1}^{N_u} \text{err}(y_j|s_j) \times N_{\text{symbol}} \times N_u}{N_{\text{symbol}} \times N_u} 
\]  

where \( \text{err}(y_j|s_j) = \begin{cases} 
  1 & \text{if } y_j \neq s_j, \\
  0 & \text{if } y_j = s_j 
\end{cases} 
\]  

(9)

where \( N_u \) in this case is the number of simultaneous users. Figure 3 shows the BER results for the vertical polarised user terminal scenarios. Similar results have been obtained for the horizontal antenna polarisation case. The theoretical BER of the BPAM scheme in additive white Gaussian noise (AWGN) channel is plotted in the same figure for reference. When the time aligned TR scheme is used, the BER performance decreases significantly for a large number of concurrent users. For more than 3 users and at a SNR value of 15dB, the BER already reaches a BER floor of \( 10^{-2} \), Figure 3a. With the proposed TR&S scheme, the BER does increase with the number of users, but at a lower rate and the detected BER floor was below \( 10^{-6} \). At a SNR of 15dB, a BER in the order of \( 10^{-5} \) can be obtained for 5 simultaneous users (Figure 3b).

V. CONCLUSIONS

In this paper we have proposed and evaluated the TR technique in multi-user UWB communications in indoor scenarios. We considered a particular multi-user TR-UWB system consisting of 4 transmitting antennas and up to 5 concurrent users each of them equipped with a single antenna (with either vertical or horizontal polarization). It was illustrated that a median signal-to-interference ratio at each user/location can be as large as 18dB. Using the TR technique, spatial...
and temporal focusing is achieved, the receiver’s architecture
becomes very simple and the required maximum transmit
power can be alleviated. Using the proposed shifted time-
reversed transmission scheme TR&S-UWB, the simulation
results show that under certain assumptions, it is possible
to communicate with 5 users simultaneously with the uncoded
BER as low as $10^{-3}$ when the average SNR at the receiver
is 15dB. These results highlight the strong potential of TR
schemes in MISO-UWB systems.

Evaluating the degradation in the performance of the TR
in UWB system when the error in channel estimation is taken
into account is one of the interesting problems for future work.

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