One-bit time reversal using binary pulse sequence for indoor communications

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ABSTRACT

Time reversal (TiR) is a pre-filtering technique that exploits the propagation channel state information in order to reduce the complexity of a user's terminal in a communication system. TiR transfers the system complexity to the base station and has been proposed for ultrawideband (UWB) communications in highly dispersive multipath environments. In TiR-UWB two complex tasks must be carried out by the base station. The first is the estimation of the channel state information of the user's terminal, and the second is the generation of the time reversed channel signal. In this paper, the use of a correlation receiver for the estimation of the multipath components (MPCs) of the propagation channel is proposed. Then, a novel binary time reversal (BTiR) method that makes use of the resolvable MPCs to simplify the transceiver tasks is introduced. When using BTiR the communication system can be regarded as a direct sequence spread spectrum (DSSS) scheme in which the spreading chips are provided by the propagation channel. The performance of the proposed BTiR scheme is assessed by using measurements of UWB spatial channels in a typical indoor environment.

1. Introduction

Impulse radio ultra wideband (IR-UWB) technology has been proposed for high data rate short-range communications aiming at low power consumption and simple implementations [1]. However, collecting the received signal energy in highly dispersive multipath channels such as those exhibited in indoor environments is a challenging task because ultra wide bandwidth results in a high sampling frequency, hundreds of channel multipath components (MPCs) and a large delay spread. Time reversal (TiR) has been proposed in acoustics and then applied in electromagnetics and wireless data communications [2–10]. By using TiR-UWB the hardware and processing complexity is transferred to the base station. In addition, TiR is optimum in the sense that it maximizes the electromagnetic field strength at a given location and reduces the effective channel delay spread by coherent combination of the MPCs. Different realizations of TiR with single/multiple inputs and/or single/multiple outputs (SISO, SIMO, MISO, and MIMO) have been proposed [8–12]. All these schemes apply two important tasks. The first task is performed in the uplink and we refer to it as channel sounding; here, the user's terminal sends short channel sounding pulses to the base station and the channel information is obtained thereby. The second task is performed in the downlink and we refer to it as TiR signal generation; here, the data are
modulated by the TiR signal and transmitted through the propagation channel. In this manner, the user’s terminal receives a single multipath tap instead of several delayed ones. This single tap has an amplified signal level because of the spatial coherent combination of the different channel MPCs. Obviously, this single tap has short delay spread and shows spatial focusing on the intended user’s terminal, the latter characteristic being particularly useful in multiuser scenarios. By implementing TiR-UWB the user terminal can be a very simple correlation scheme with only one correlator branch [8].

The recording of the channel pulse response (channel sounding task) can be done by using high speed digital sampling systems, which require high signal-to-noise ratio (SNR) and complex hardware with high power consumption [8]. The highly complex TiR signal can be generated using a programmable wave generator [13–17]. The system complexity can be reduced if a narrow band transmission is applied [18], however the spatial focusing and the temporal resolution are reduced. For UWB signals, the complexity can be reduced by transmitting a part of the TiR signal [19] or by using optimal one bit transmitted pulse [20].

In this paper, these complexities are reduced by using a simplified scheme based on suboptimum receiver and transmitter tasks that are applied in the base station. First, we propose the use of a correlation receiver at the base station to record the channel pulse response necessary for the TiR technique. The correlation receiver’s main feature is the reduced sampling rate at the output of the correlator, which results in improved signal-to-noise ratio (SNR) due to the integration and sampling. Then, we applied the channel information obtained in this manner to the implementation of TiR in the base station. Here, a new TiR transmission technique is proposed. We refer to this novel technique as binary time reversal (BTIR). In BTIR each transmitted data bit for downlink is modulated by a sequence of binary short pulses (chips) of constant amplitude, and then the signal is transmitted through the propagation channel. The performances of the TiR and BTIR schemes are evaluated and compared to each other by using ultra-wideband channels measurements taken in a laboratory environment. The systems performances in terms of temporal and spatial focusing are analyzed by assuming a static channel during the sounding task and transmission; to show the operating concept of the proposed method the effects of noise are neglected. To ensure the statistical robustness of these methods the system performance was evaluated over hundreds of measured channels. We note that, the channel sounding and TiR operations are conducted at the base station and the user terminal is a simple pulse transmitter in the uplink and a simple peak signal detector in the downlink.

For the sake of simplicity, the proposed BTIR scheme is presented herein for SISO channels only; however, it can be developed for MIMO, MISO, and SIMO channels as well. The rest of the paper is organized as follows: Section 2 presents the TiR concept and its performance factors definition. In Section 3, an indoor measurement setup is described, which provided the channel data including the spatial properties necessary for the evaluation of TiR schemes. In Section 4, the structure of a single branch correlation receiver and the way of extracting the channel MPCs are discussed. In Section 5, the BTIR scheme is introduced whereas its performance analysis and comparison with the TiR scheme are presented in Section 6. Section 7 concludes this paper.

2. Time reversal

Different implementations of ultra wideband communications can be considered. The most well known techniques are orthogonal frequency division multiplexing (OFDM) and impulse radio (IR). IR provides large bandwidth for a single transmitted signal. Thus high temporal resolution is achieved and large number of MPCs can be resolved. For a UWB channel, the tapped delay line model can be used to represent the channel impulse response (CIR) as

$$h(t) = \sum_{k} a_k \delta(t - \tau_k)$$

where $a_k$ is the amplitude and $\tau_k$ is the corresponding delay of the $k$th MPC; $\delta(t)$ is the Dirac delta function. Due to the low transmitted power in UWB communications, it is necessary to collect the received signal energy from the multipath taps ($a_k$) to improve the signal quality. This task requires a complex Rake receiver with large number of correlation receiver branches. TiR UWB is an alternative solution. It is a pre-filtering technique that exploits the estimated CIR, $\hat{h}(t)$, to shape the transmitted data bits. In this technique, each transmitted signal is formed by a time reversed pulse shape of the channel given as

$$x_{TiR}(t) = d_j A \hat{h}(-t)$$

where $d_j$ is the $j$th transmitted data bit that can take the values of $\pm 1$ for a binary data in bi-phase modulation, $\hat{h}(-t)$ is the estimated TiR signal, and $A$ is the amplification factor of the transmitted signal that provides a constant energy value. After passing through a rich multipath channel, the received signal in the TiR scheme can be expressed as

$$y(t) = x_{TiR}(t) \ast h(t) + n(t)$$

where $\ast$ denotes the convolution operation, and $n(t)$ is additive white Gaussian noise. The convolution term might be regarded as the autocorrelation of the CIR if the time reversal signal was the ideal reverse form of $h(t)$. However, the drift of the TiR signal from the original $h(t)$ causes the loss of the autocorrelation peak and increases the temporal sidelobes.

The performance of the received signal in the TiR-UWB channel can be evaluated in terms of the focusing gain, the temporal sideloeb, and the spatial focusing. The focusing gain (FG) is defined as the ratio of the largest peak power in the TiR channel to the largest peak power in the pulse channel, considering equal transmitted energy. The temporal sideleobe is the ratio of the main peak power in the TiR system to the strongest sidelobe power. This characterizes the inter-symbol interference of the communication system and limits the data rate. The spatial focusing is the discrimination factor for the intended user
from the other users in the environment. It is evaluated by comparing the peak power received by the intended user with the peak power of the other users in the vicinity. This property can be used for user discrimination in a multiuser communication scenario, with the physical propagation channel being the discriminating factor.

The performance factors defined above depend on the signal bandwidth, the delay spread of the channel, the distribution of the angle of arrivals (AoAs), and the approximation used for the estimation of the TiR signal [13,14]. For an infinite bandwidth signal with perfect estimation of the TiR signal and large delay spread, the sidelobes are very small and the signal in the TiR channel appears as a spike signal.

3. Channel estimation

In order to study the performance of a TiR system by including the statistics of the propagation channel, a standard UWB channel model (a model issued by IEEE 802.15.4, for instance) appears to be a good candidate. However, the evaluation of TiR-UWB requires channel realizations with spatio-temporal properties, which regrettably are not provided by the standards. To overcome this drawback, we carried out a set of measurements in an indoor laboratory environment. These information are used for the performance analysis of the time reversal techniques.

The layout of the measurement environment is shown in Fig. 1. The transmitter antenna was placed in the corridor at 1.5 m height from the floor. The receiving setup was placed in the office room with the antenna at 1.5 m height. For spatial focusing measurements, the receiving antenna can sweep a rectangular area by using a positioner system within 400 mm × 600 mm area with a resolution of 50 mm × 25 mm, respectively. The antennas are both conical monopoles (CMA118/A) with omni-directional patterns. The channel measurements were carried out using a vector network analyzer (VNA) in the frequency range of 0.7–6 GHz with 1601 frequency points. The measured channels can neglect the noise effects because of the synchronized transmit/receive system and the narrow bandwidth of 100 kHz used during the whole channel scanning.

![Fig. 1. Measurement scenario in an indoor laboratory environment.](image)

In total, 243 channel realizations were recorded. The channel measurements were conducted during the time without any activity around the lab thus all channels can be regarded as static. The inverse Fourier transform was used to convert the frequency domain measurements to the time domain.

Two sets of measurements with the antennas in copolar and cross-polar mode were completed. However, for our TiR analysis we used the channel results from the cross-polar mode only, which exhibit large delay spread because of the removal of the direct path between the transmitter and receiver antennas.

For the analysis of time reversal technique it is necessary to have an overall knowledge of the measured channels. Thus, the statistical characterization of the measured channels was done by evaluating the average power delay profile (PDP) and the cumulative distribution function (CDF) of the root mean square (rms) delay spread. The rms delay spread, which is defined as the square root of the second central moment of the power delay profile (PDP), is computed using

\[
\tau_{\text{RMS}} = \sqrt{\frac{\sum_k P(\tau_k) \tau_k^2}{\sum_k P(\tau_k) \tau_k^2 - \tau_m^2}} \tag{4}
\]

where \(P(\tau_k)\) is the PDP obtained for each channel, scaled such that the first detectable signal arrives at the receiver at \(\tau = 0\). The calculations consider a threshold level of 50 dB below the peak of the power delay profile. \(k\) is the number of detectable paths, and \(\tau_m\) is the mean excess delay, defined as the first moment of the PDP,

\[
\tau_m = \frac{\sum_k P(\tau_k) \tau_k}{\sum_k P(\tau_k)} \tag{5}
\]

Fig. 2 shows the average PDP of the measured channels obtained by averaging 243 measured PDPs; the first path arrived with a delay of 20 ns, which corresponds to a distance of 6 m between the transmitter and receiver antennas. Fig. 3 shows the CDF of the rms delay spread. Large delay spread is observed, with 90% of the channel realizations exhibiting a delay spread between 57 and 75 ns. This large delay spread is the result of using the antennas in cross polar mode and the laboratory environment with several metallic reflecting surfaces. The given delay

![Fig. 2. Average PDP of the indoor channel.](image)
spread is several times the delay spread that was proposed for NLOS standard UWB channels.

For the data analysis, channel pulse response filtering was applied by using a bandpass filter with a center frequency at 3500 and 4700 MHz of 10 dB bandwidth shaped with a Hamming window. The path loss for the filtered signal was 37 dB. The shadow fading is Gaussian distributed with a very small variance of 0.5 dB, which is the result of the wide bandwidth and the small measurement area. Thus, the selected square area receives almost constant average power.

4. Correlation receiver

The channel sounding is a difficult task and therefore is carried out at the base station of the communication system. One direct method of channel measurement consists in using a digital sampling system. Such system with UWB signals requires fast sampling rate in the order of 2–4 times the signal bandwidth. Because of the large bandwidth, the system noise power increases and high SNR is required for correct channel estimation. Furthermore, the implementation of a digital sampling system is complex and requires high power consumption. With the current technology the high speed digital sampling may be implemented in laboratory instruments [13], however, it is not viable for practical communication applications.

Hence, we propose using a correlation receiver for the channel sounding task. By using a correlation receiver, the signal sampling is done at the correlator output with a period equal to the integration time; additionally, the effects of the additive noise can be alleviated by the signal integration. Fig. 4(a) shows the structure of the receiver.

In the channel sounding process, the user terminal sends multiple short pulses with a known repetition period \( T_p \), which is larger than the delay spread of the channel. Thus, the collision between the spread signals at the receiver is avoided. Assuming perfect synchronization, the correlation receiver starts the integration at the time interval \( \Delta \), equal to the width of the template pulse \( p(t) \). Only one MPC is obtained at the correlator output for each transmitted pulse. The process is repeated for the next nth MPC by just generating the \( p(t) \) at time \( T_p + (n - 1)\Delta \). With this process, \( N \) multipath components with a resolution of \( \Delta \) can be recorded by using \( N \) transmitted pulses from the user’s terminal. Fig. 4(b) shows a sample of the channel pulse response and the output of the correlator (resolved MPCs). Note that the process can be accelerated by using a bank of correlation receivers. If the number of the correlator branches was enough, the MPCs can be extracted by using a single transmitted pulse from the user’s terminal. The output of the correlator can be expressed as

\[
x_{corr}(t) = \sum_{n=1}^{N} a_n A_n \delta(t + (n - 1)\Delta)
\]

where \( N \) is the number, \( \{a_n\} = \pm 1 \) is the polarity and \( \{A_n\} \) is the amplitude of the MPCs. The amplitude needs to be quantized and saved in the memory using a large number of quantization levels, a fact that adds complexity and quantization noise to the base station unit.

In our study of the indoor channel a Gaussian pulse was selected as the template, \( p(t) \), with center spectrum frequency at 3500 and 4700 MHz 10 dB bandwidth. The pulse width is \( \Delta = 0.8 \) ns, therefore the MPCs with a maximum resolution of 0.8 ns are recorded. Only the MPCs up to 30 dB below the strongest power of the MPCs are saved in a memory and used for the TiR signaling. This threshold is chosen in order to guarantee that the noise has not been mistakenly recognized as MPCs. The number of the MPCs (\( N \)) that were obtained using this analysis is distributed between 50 and 300 taps for the 243 measured channels. The average number of taps is around 145.

The correlation receiver that is used in this work considered equal time distance, \( \Delta \), between multipath components. Despite the random delay for each MPC, the proposed receiver can acquire significant energy of the MPCs due to the large delay spread of the signal in the indoor channel. This correlation receiver does not necessitate synchronization with each MPC. In addition due to the pulse multiplication and integration technique, which is used for the estimation of the MPCs, the signal to noise ratio can be alleviated significantly. In the forthcoming analysis, we disregard the noise at the transmitter and the receiver.

5. Time reversal and binary time reversal

In this section, the channel MPCs obtained with the correlation receiver are time reversed and a sequence of template signals with different amplitudes and polarities is generated. Thus, the TiR signal is constructed by a train of pulses with different amplitudes and polarities. The same Gaussian pulse that was used for the correlation receiver is used for the TiR signal generation. This means that one data bit \( d_j \) with value \( \pm 1 \) is expressed by a sequence of weighted templates. The mathematical expression of this TiR signal can be written as

\[
x_{TR}(t) = d_j B \sum_{n=1}^{N} a_{N-n+1} A_{N-n+1} p(t + (n - 1)\Delta)
\]

The total energy of the \( x_{TR}(t) \) is normalized to a constant value in order to make a comparison of the system with and without TiR signaling; \( B \) is the normalization term for the energy. Due to the energy normalization, \( x_{TR}(t) \) has significantly lower amplitude than the single pulse transmission system which has a short duration. For TiR signaling.
the pulse repetition frequency (PRF) is equal to $\Delta$. The TiR signal is transmitted through the channel and the received signal is calculated using (3).

We propose a novel TiR method to reduce the complexity of the TiR signal given in (7). The so-called BTiR scheme accounts for the polarity of the MPCs $\{a_n\} = \pm 1$ but uses a constant amplitude value for all the MPCs, i.e., $A_n = 1$. Thus, only the polarities of the resolvable MPCs are stored in the memory. Hence, the mathematical expression for the BTiR can be written in a simpler form as

$$x_{BTiR}(t) = d_j D \sum_{n=1}^{N} a_{N-n+1} p (t + (n - 1) \Delta) . \quad (8)$$

The normalization term D is varied to carry the same total energy used in TiR (7). The amplitude information of the MPCs which can occupy more memory and need quantization task is removed in this case thus TiR is enabled by the diversity of the polarity of the MPCs. The BTiR signal is generated by switching between two pulse polarities with a rate equal to $\Delta$. After transmitting the $x_{BTiR}(t)$ signal through the propagation channel, the received signal is obtained by applying the convolution process in (3) by using $x_{BTiR}(t)$ instead of $x_{TiR}(t)$.

The proposed BTiR scheme is analogous to a direct sequence spread spectrum (DSSS) scheme, where the binary transmitted data, $d_j$, are expressed by a train of pseudorandom pulses. However, in BTiR the pseudorandom pulses are generated from the propagation channel state information. Contrarily to a DSSS scheme, which needs a de-spreading electronic circuit at the receiver, the de-spreading system for the BTiR scheme is the physical propagation channel. The received signal at the antenna output is a spike signal.

6. Performance analysis

The performance evaluation of the TiR and the BTiR schemes was done in terms of the focusing gain, temporal sidelobes, and spatial focusing. Fig. 5 shows an example of the transmitted TiR signal and the received signal peak power at the user's terminal. In this example, the transmitted signal is composed of 75 symbols “chips”, i.e., a signal length of 60 ns. The received signal is compressed in time, thus the user terminal observes a single MPC (Fig. 5(b)). The temporal sidelobes are noticeably small. Likewise, Fig. 6(a) shows the transmitted BTiR signal made of 75 symbols generated using (8). Compared to

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Fig. 5. (a) Transmitted TiR signal and (b) received signal.

Fig. 6. (a) Transmitted BTiR signal: binary pulse sequence and (b) received signal.

Fig. 5(a), the amplitude of the transmitted signal is constant and, because of the energy normalization, it has lower amplitude than the TiR signal. The received signal power at the user’s terminal is shown in Fig. 6(b). A single MPC at the receiver with very high temporal compression is observed. The peak power is lower than the TiR scheme due to the removal of the amplitude information and energy normalization.

To study the statistical robustness of these methods, the CDF of the peak power is shown in Fig. 7 which was obtained by using the information of the 243 measured channel realizations without TiR, using TiR, and using BTiR.
The CDF of the peak power at the direct, TiR, and BTiR channels, respectively (Fig. 7). As can be seen, the statistical value of FG can be evaluated from the difference between the corresponding CDF of the channel with and without TiR for different probability levels. For instance, the FG is 8 dB for the TiR scheme for a CDF value of 0.5 whereas it is 4 dB for BTiR. This means that BTiR allows for a simplified transmitter structure at the expense of 4 dB peak performance loss compared to the TiR scheme.

Fig. 7. CDF of the peak power at the direct, TiR, and BTiR channels, respectively. The FG of TiR and BTiR, respectively, is also indicated.

The CDF of the peak to sidelobe level ratio is shown in Fig. 8 for the TiR and BTiR schemes. The peak to sidelobe level ratio, for the CDF value of 0.9 is above 8 dB in both cases. This shows the good sidelobe suppression properties of the two schemes. In terms of the sidelobe level, both TiR and BTiR perform similarly.

Fig. 8. CDF of the peak to sidelobe level ratio for the TiR and BTiR schemes.

Finally, the spatial focusing was evaluated for both TiR and BTiR. Fig. 9 shows an example of the spatial focusing obtained for an intended user’s terminal located at the center of the measurement area at coordinates $x = 200$ mm and $y = 275$ mm. One can see that by using the TiR scheme, the peak signal level for the intended user’s terminal is much higher than for the surrounding ones, which shows the efficiency of the TiR with the proposed correlation receiver structure. Using the BTiR scheme, the non-intended users receive larger peak power, between 1 and 2 dB, in comparison to the TiR scheme. However the spatial discrimination is still significant. The small loss of BTiR is an additional cost of the system simplification obtained with BTiR. The spatial focusing of BTiR is comparable with TiR that can be used for secure data transmission.

The given one bit time reversal can be extended for multiple data bits transmission. Inter symbol interference (ISI) is the limiting factor for high data rates, however the data rate can be increased by using orthogonal time division multiplexing at the transmitter by accepting some amounts of ISI [21].

7. Conclusions

This paper describes the realization of TiR for impulse radio UWB communications by using the channel resol-
able multipath components obtained with a correlation receiver. This receiver with equally spaced extracted MPCs makes the channel estimation easier in terms of complexity and implementation. Moreover, a BT1R scheme was proposed, which takes into account the polarity of the channel MPCs only. This reduces the transmitter task to a binary pulse sequence generator with pulse modulated “chips” at the expense of marginal performance degradation. The statistical performance of TiR and BT1R schemes was evaluated in terms of the focusing gain, temporal side lobes, and spatial focusing. We observed that the proposed BT1R technique has 4 dB less focusing gain, the same temporal side lobes, and 1–2 dB less spatial focusing compared to the TiR scheme. However, the proposed BT1R technique allows for a significant simplification of the overall system in which the system can be implemented using a direct-sequence spread spectrum transmitter with the spreading chips selected from the polarity of the resolvable channel multipath components. The physical channel acts as the signal de-spreading electronic circuit. This work contributes to the simplification of the physical implementation of UWB communication systems in highly dispersive indoor environments.

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References


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