DESIGN APPROACH FOR A TIME REVERSAL TEST BED FOR RADIO CHANNELS

— SPECIAL SESSION ON MIMO PROTOTYPING —

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ABSTRACT

In time reversal, a message signal to be transmitted is first convolved with the time-reversed channel impulse response and then sent to the receiver. The "time-reversed" waves which propagate into the channel retrace their former paths; they eventually lead to a focus of power in space and time at the receiver. Time reversal systems can use antenna arrays in order to enhance the focusing, but they do not necessarily need to. The channel's degrees of freedom are rather excited by using broadband signals, and the focusing can be achieved with single-antenna links.

To the authors' best knowledge, there has been no demonstration of time reversal in wireless radio yet. This paper describes the broad design principles of a system that is designed to demonstrate time reversal in wireless radio channels. The system block diagram, some critical specifications and sources of error are described. Experimental data will be presented, if available in time, at the workshop.

1. INTRODUCTION

In a practical system employing time reversal (TR), an intented receiver sends a training sequence to an intended transmitter which is equipped with one or potentially more than one transmit antenna. The transmitter time-reverses the estimated channel impulse response (CIR) and convolves this signal with any message signal that is then sent to the receiver.

In quasi-static, reciprocal channels this simple precoding scheme yields a concentration of power at only the intended receiver at a particular time. The spatial and temporal focusing that can be achieved by TR has been successfully demonstrated in ultra-sound by Fink [1, 2] and in underwater acoustics [2, 3, 4, 5].

In wireless communications, no demonstration is known to the authors. In this paper, we propose to convert a commerically available broadband MIMO channel sounder into a device that can demonstrate the leverage of TR in low Doppler (quasi time-invariant) channels with about one microsecond delay spread. Our strategy is to keep the upgrade as simple as possible. We rely on the MIMO sounder's capability for channel estimation, and add the features to transfer the CIR estimates back to the transmitter via an external link and to then transmit a precoded message. Hence, we replace the pair of transceivers usually considered in TR experiments by a single transmitter and a single receiver which are connected by some feedback loop. The TR sounder is designed such that this feedback loop can be chosen from a variety of publicly available, wired or wireless, links.

The rationals for this strategy are twofold. For one, the modification of this type of existing and verified system minimizes the amount of additional hardware effort needed and the risk of system performance failure. Secondly, the usage of the same link for channel estimation and TR eliminates any problems with the reciprocity assumptions that possibly occur due to differences in transmit and receiver RF chains of a single transceiver.

The remainder of the paper is organized as follows. In the next section, we give a brief introduction to TR. In the third section, we describe the system's design principles. We proceed to investigate critial specifications and sources of error in the fourth, and conclude in the fifth section.

2. TIME REVERSAL

The transmitter uses the time-reversed complex conjugate of the CIR as the transmit prefilter. We denote the CIR by $h(\mathbf{r}_0, \tau)$, where $\mathbf{r}_0$ is the receiver location and τ is the delay variable. Applying $h^*(\mathbf{r}_0, -\tau)$ as the prefilter, the effective channel to any location $\mathbf{r}$ is thus given by the time-reversed field

$$s(\mathbf{r}, \tau) \triangleq \mathbf{h}^*(\mathbf{r_0}, -\tau) \otimes \mathbf{h}(\mathbf{r}, \tau) \tag{1}$$

where "$\otimes$" denotes convolution.

A convolution with a time-reversed signal is equivalent to a correlation. We see from (1) that the focusing relies on the decorrelation of CIRs in the delay and the spatial domain. A CIR can be considered a random code sequence that is assigned to a transmit-receive pair. The auto- and crosscorrelation properties of this sequence are given by nature. In contrast to CDMA, they come without any additional bandwidth spreading. The decorrelation of the CIRs is obviously best in a rich scattering environment. In addition, high bandwidths unleash the channel's degrees of freedom and aid decorrelation. Physically, one can consider the ubiquitous locations of the scatterers to form a large virtual aperture which enables focusing even with a single antenna down to the diffraction limit. A simple but effective measure for the focusing capability of a TR channel is the delay-spread bandwidth product which roughly gives the number of taps that the CIRs has. For an initial evaluation of the benefits of TR we refer to [6].

3. SOUNDER ARCHITECTURE

The commercially available MIMO sounding unit consists of the following parts. The transmitter contains a signal generating unit (SGTx) and a transmitter RF module (RFTx), the

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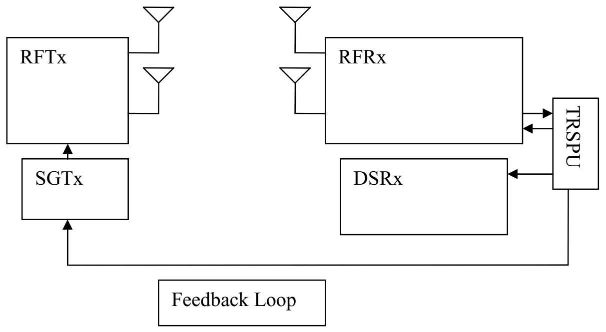

Figure 1: A schematic of the TR sounder.

receiver contains a receiver RF module (RFRx) and a data storage unit (DSRx). The conversion of this sounder into a TR sounder is done by adding components which we call TR signal processing unit (TRSPU) and feedback loop (FL). Fig. 1 shows the architecture of the TR sounder.

The proposed TR scheme operates in three steps; the main function of the TRSPU is the flexible definition and coordination of these steps. In a first step, called channel estimation step (CES), the transmitter transmits a training sequence that the receiver uses to estimate the channel. This estimate is time-reversed in the second step, convolved with the transmit sequences, and sent back to the transmitter via the FL. Then, in a third step called time reversal step (TRS), the transmitter transmits the time-reversed sequence into the channel; the receiver now sees a signal that is focused in space and time. The time focusing can be demonstrated by the compressed CIR at the intended receive antenna; the spatial focusing appears because apart from this one antenna, all other ones will detect signals that look like noise.

In the next subsections we describe the specifications of the TR sounder in more detail.

3.1 MIMO Sounding Unit and Antennas

3.1.1 Bandwidth, Carrier Frequency, and Output Power

The maximum bandwidth of the currently available system is 120 MHz. For a delay spread in the range of up to 1 μs, we can hence expect a time bandwidth product of up to 100. Under normal conditions, we expect delay-spreads which are a factor of 10 lower than that; hence, the systems works with a time bandwidth product of about 10 which still suffices to achieve a reasonable benefit with TR.

The carrier frequency of the system is in the ISM band at 2.4 GHz. Unfortunately, the available transmsission bandwidth is limited to 83 MHz. According to FCC regulations on RF devices [7], the maximum allowed EIRP is 4 W, the maximum transmit power is 1 W. The additional 6 dB can be achieved by a suitable choice of transmit antenna.

A second suitable choice would be the ISM band at 5.8 GHz with an available bandwidth of 150 MHz. However, as the free space attenuation is higher and thus reduces transmission range, we decided to perform the demonstration at the lower carrier frequency.

The output power of the system is limited to 1 W.

3.1.2 Signaling

The sounding signals, and in particular their power and power spectral density distribution, are designed in frequency domain. The signals used for channel estimation have constant maximum amplitude over frequency and their phase is designed to minimize the crest factor and hence maximize average output power. Since all signal processing is performed in frequency domain, instead of estimating and time-reversing the CIR, the transfer function (TF) is complex conjugated in frequency domain.

3.1.3 Antennas and Switching

In our system, the antenna elements in an array of the sounder are switched. In this case the number of channels is essentially limited by the number of available switches and antennas and the maximum measurement time for which the quasi-static channel assumption still holds. For the TR experiments, arrays with 4 and 8 antennas will be employed.

Since TR requires a large angular spread, omnidirectional antennas are most advantageous. However, the range that is reqiured to be large in order to obtain a large delay spread would benefit from high gain antennas. The compromise between these two constraints are basestation type transmit antennas (very narrow vertical and wide horizontal beamwidth, gain about 12dBi) and slightly directional antennas (very wide horizontal and wide vertical beamwidth, gain of 6 to 10 dB).

3.1.4 Synchronization

The synchronization is done by using very stable reference clocks at 10 MHz (e.g. Rubidium standards). The clock signal guarantees long term stability. In each RF unit, the carrier signal is generated independently by low-noise PLLs.

3.2 Feedback Loop

In between the CES and the TRS, the estimated channel data has to be transferred from the receiver to the transmitter. The transferral time must be much shorter than the coherence time of the channel. The data rate of the link becomes hence a critical parameter. A single complex CIR with about 1000 taps and 8 bit resolution has a size of about 16 kbit. Assuming a time invariant channel with Doppler frequency of 1 Hz, a realistic transmission time should not be longer than 0.2 s; consequently, the FL needs a data rate of at least 80 kbit/s per CIR that is transferred.

The following options have been evaluated.

3.2.1 Microwave Link

A microwave link is advantageous in terms of data rate, which is in the order of Mbit/s, and in terms of flexibility. Microwave links can be established whereever the experiment is to be performed. However, TR experiments are likely to be conducted in environments with large delay spreads. Here, the TR sounder will operate at maximum EIRP allowed by the FCC regulations. This limit holds for the microwave link, as well. In areas where the SNR of the TR experiment is low, that of the microwave FL is low, too. The link quality can be improved by using directional antennas mounted on high poles, but this requires difficult adjustments and large efforts in the preparation of the experiment.

3.2.2 *Cellular Systems*

Currently available cellular systems such as GPRS offer great flexibility without the need for heavy experimental equipment. Their main drawback is their comparably low data rate (order of 100 kbit/s for GPRS) and, in particular, the unreliable transmission delay. Since the data rate offered does not provide much overhead compared to the data rate required, the application of current cellular services for the FL appears risky, in particular if the Doppler spread of the channel may at times exceed 1 Hz.

3.2.3 *Wired Network*

The wired network offers tremendous data rates; the main drawback is the inflexibility of its access. However, most TR experiments will be conducted in urban areas, where wired access to the internet can be expected to be in range. A wireless network system (WLAN) such as one based on the IEEE 802.11b standard still offers data rates in the order of Mbits and can be employed to bridge the gap between the experimental device to the next wired network connection.

The final decision about the best link depends on the availability of particular services, on local network traffic, and the Doppler spread of the channel. The sounder itself is equipped with RJ45 connectors and can be hooked up to any of the above-mentioned systems.

3.3 The TRSPU

The role of the TRSPU is to coordinate the three steps on which the operation of the sounder is based. Since it also performs the nessecary signal processing, it is located in between the RF and the data storage unit of the receiver.

3.3.1 *The Different TR Modes*

The tasks of a TR sounder are at least threefold: 1) It must demonstrate spatial and temporal focusing when TR experiments are performed with a) a single, or b) multiple transmit antennas. 2) It must be flexible to allow further research about benefits of TR, i.e. for multiuser (MU) communications. 3) It should be backwards compatible. Since it is based on commerical MIMO technology, MIMO channel measurements should still be possible with a TR sounder. It turns out that 4 different TR modes evolve from these requirements:

1. *MIMO Measurements:*
   For MIMO measurements, the TRS is omitted. The sounder performs a predefined number of channel estimations and no TR transmissions.
2. *SISO-TR:*
   In the CES, the channel estimation is performed n_1 times with a single transmit and a single receive antenna. The received TFs can be averaged to obtain a better estimation of the channel. The TRSPU complex conjugates this TF, multiplies it with the Fourier transform of the used transmit sequences, and sends it via the FL to the transmitter. The transmitter loads this sequence and transmits its Fourier-inverse into the channel. Now, in the TRS, the TRSPU provides a second switching table and the RFRx switches through the antenna array. At the one receive antenna that is used in the CES, the detected CIR is compressed. At all other antennas, a noise-like signal appears. After n_2 transmissions, the CES is repeated. This mode is the simplest and best suited to demonstrate TR.

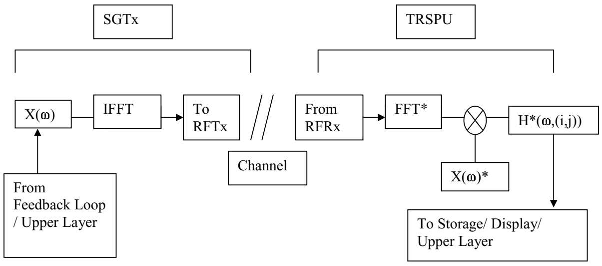

Figure 2: The lower layer of the TRSPU, synchronized with the SGTx.

3. *MU-SIMO-TR:*
   In this mode, MU communication with TR can be demonstrated. The CES is performed with a single transmit antenna and an antenna array at the receiver. Conceptually, it works similar to the SISO-TR mode, except that the TFs of all receive antennas are estimated. The TF estimated at each antenna is multiplied with a message that is to be sent to this antenna; the sum of all these products is fed into the FL and retransmitted in the TR-mode. The channel acts now as a filter; each receive antenna receives only its intended message, and all the other messages as noise.
4. *MISO-TR:*
   In the original underwater acoustic applications, TR is performed with a transmit array. Each transmit antenna focuses its signal on the same receive antenna, so that the focusing is enhanced proportional to the number of transmit antennas. Since in our application, the arrays are switched, the superposition of the signals can only be done by software. Also, the switching requires short-term phase stability at the transmitter.
   This 4th mode is not only the most demanding with respect to synchronization, but also with respect to the data rate on the FL, since as many CIRs must be transferred as there are transmit antennas.

3.3.2 *Double Layered Structure of the TRSPU*

The TRSPU is implemented in a double-layered structure. The lower layer runs synchronized with the SGTx and is as such displayed in Fig. 2. The SGTx receives a sequence from the FL, transforms it into time domain and hands it over to the RFTx. The TRSPU receives the demodulated signal from the RFRx and computes the conjugate of the received CIR via an FFT and division by the sequence used for channel estimation. This layer is run in all modes of the sounder, be it MIMO channel estimation, or one of the two stages of the different TR modes.

The upper layer bascially determines the TR mode, as described in Subsection 3.3.1. Each mode is defined by particular numbers n_1 and n_2 for the duration of the CES and the TRS, and the one (for the MIMO mode) or the two (for all other TR modes) corresponding switching tables that are provided to the RFRx. The upper layer is software-defined. This allows any user to make changes in the setup; in particular, the TR modes can be embedded in more sophisticated high-level transmission schemes, e.g., schemes that adapt the numbers n_1 and n_2 to particular channel conditions.

An example of the SISO-TR mode is shown in Fig. 3. For

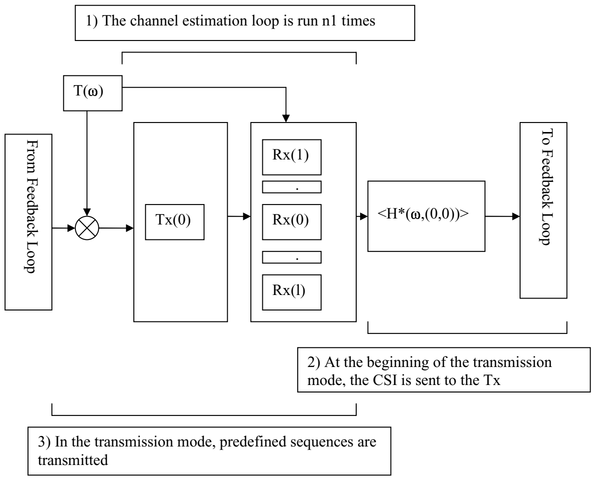

Figure 3: The SISO mode as triggered by the upper layer of the TRSPU.

a given transmit antenna Tx(0) and an intended receive antenna Rx(0), the TF $H(\omega,(0,0))$ is estimated in the first step. In the second step, it is multiplied with the Fourier transform of a transmit sequence and transmitted to the FL. In the third step, the sounder transmits these combined sequences until it again enters the first step.

4. CRITICAL SPECIFICATIONS AND SOURCES OF ERROR

4.1 Range and Power

TR works best in environments with large delay spreads, i.e. over large distances. Consequently, the demands on the link budget are high. The critical parameters are here the pathloss exponent, the maximum and average transmit power determined by hardware and FCC, the bandwidth and the carrier frequency, the antenna gains, the correlation gains, the sounder's sensitivity and the target SNR. Initial computations result in a range of about 600m for the described system with a target SNR of 30 dB in a cluttered environment with a pathloss of $q = 3.5$. This range corresponds to a propagation time of $2\mu s$ which is considered sufficient to create a delay spread of up to $1\mu s$.

4.2 Feedback Loop

The FL is the bottleneck of the sounder. As discussed in Subsection 3.2, the data rate required for the feedback is about 80 kbit times the number of CIRs to be transferred. Depending on the mode, only one CIR, or as many as there are transmit antennas, have to pass the loop.

If links with a data rate in the order of Mbits such as a wired network or a wired network in conjunction with a WLAN are used, the transmission time itself is much shorter than any residuary Doppler of the channel within the observation period. However, other traffic in the network can delay packet transmission. Initial experiments showed that packets of the size of 64 kbit had travel times of about 130 ms on an 11 Mbit WLAN and 20 ms on a local 100 Mbit LAN.

4.3 Phase Noise

TR requires exact phase information at the transmitter. Inaccuracies in the phases occur since a) the channel is not perfectly time variant, b) the LO signals derived by PLLs from the 10 MHz reference have phase noise.

The time variance can be overvome if the data rate of the FL is large enough (Subsection 3.2 and 4.2).

Phase noise destroys the coherent superposition of signals transmitted from multiple antennas. Since it enters both at the transmitter and the receiver, it will reduce the received power by a factor of $\cos({}_{\Delta}\phi_1 + {}_{\Delta}\phi_2)$, where ${}_{\Delta}\phi_i$, $i = 1,2$ are random variables that describe the phase fluctuations of the transmitter's and the receiver's oscillators. For phase errors less than 15°, this yields a performance loss of about 10 % in SNR, which is tolerable. For switched antenna sounders this is less of a problem with respect to TR.

5. CONCLUSIONS

This paper introduces time reversal (TR) as a promising transmission technique for wireless communications. We propose the design of a prototype device that will allow the demonstration of the benefits of TR. This prototype is heavily based on commercially available systems and components, implementation and development costs are kept at a minimum. The core of the device is a commercially available MIMO broadband channel sounder. It can be connected to various types of publicly available networks which serve as a feedback loop. Its key component is the TR signal processing unit, which can operate in several modes and offers flexible handling of the entire device.

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