Predicted Time Reversal Performance in Wireless Communications Using Channel Measurements

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ABSTRACT

Using broadband radio wireless measurements in an indoor environment we demonstrate the remarkable space-time focusing properties of signal transmission with time reversal.

I. INTRODUCTION

In a basic time reversal (TR) communications experiment, the intended receiver first broadcasts a short pilot pulse. The transmitter estimates the channel impulse response and then sends the time reversed version of it back into the channel. The emitted "time reversed" waves back propagate in the channel by retracing their paths and focus in space and time at the source, the intended receiver.

In a channel with rich scattering, multipathing or multiple scattering is exploited by TR [1] to focus broadband signals tightly in space and time. Moreover, the effective channel obtained through TR is hardened or statistically stable [2]. Spatial focusing means that the spatial profile of the power peaks at the intended receiver and decays rapidly away from the receiver. Temporal focusing means that the channel impulse response at the receiver has a very short effective length. Channel hardening is the phenomenon of tightening of the distribution function of the effective channel impulse response. TR works well in systems where the delay spread of the channel times the bandwidth of the system is large [3], [2]. In this paper we demonstrate TR with an Ultra-Wideband system in an indoor environment.

The use of TR has three main benefits in communications. Temporal focusing significantly shortens the effective length of the channel. For example, the complexity of a MLSE equalizer is exponential in the length of the channel. TR reduces therefore the complexity of the equalization task.

A more important advantage of the TR technique is *spatial focusing* [1], [2]. Spatial focusing results in very low co-channel interference in a multi-cell system. This results in a very efficient use of bandwidth in the overall system.

Another advantage of using TR is the hardening of the effective channel, which means that TR results in a high diversity gain. The statistics of the time reversed channel are different from the actual channel. Specifically, the time reversed channel has a much smaller variance than the physical channel itself [2].

Fink and his coworkers [1], [3] (and references therein) have conducted an extensive number of experiments with TR using ultrasound and have shown large gains in spatial focusing in the presence of rich scattering. Also, TR methods have been used for underwater acoustic and ultrasound communications [4], [5], [6], [3]. TR experiments using radio waves rather than acoustic waves have not yet been done. Here, we shall perform an initial demonstration of the effects of TR methods applied to radio wireless measurements taken from an indoor environment in the band 2-8GHz. Based on these measurements, we predict the performance of TR in such a setting. We demonstrate temporal and spatial focusing for a SISO link and evaluate channel hardening in terms of the empirical distribution of the received signal strength. Our prediction of the TR performance is exact if there is no channel measurement error at the transmitter and any imperfections in the transmit and the receive chain of the system are not too severe.

In Section II we explain how data from static channel measurements can be used to predict the performance of a TR system, and we define suitable performance measures. In Section III we describe how the measurements were made. In Section IV we discuss the results and summarize our conclusions in Section V.

II. TR FORMULATION

Consider a transmitter-receiver pair. In TR the transmitter uses the time reversed complex conjugate of the channel impulse response as the transmit prefilter. Denote the channel impulse response by $h(\mathbf{r_0},\tau)$, where $\mathbf{r}_0$ is the receiver location and τ is the delay variable. If the transmitter uses $h^*(\mathbf{r_0},-\tau)$ as the prefilter, the effective channel to any location $\mathbf{r}$ is thus given by the *time reversed field*:

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

where $*$ denotes convolution with respect to delay. Note that a convolution with a time-reversed signal is equivalent to a correlation.

In order to study the effects of TR we measure the channel impulse response between the transmitter and a receiver. We repeat the measurement by holding the transmitter fixed and changing the position of the receiver over a square grid. We take one corner of the grid as the reference receiver (the

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intended receiver) and use its impulse response as the transmit prefilter $h^*(\mathbf{r_0}, -\tau)$. The time reversed field at any point on the square grid can now be computed based on the channel measurements and by using Eqn. 1. This is equivalent to having the transmitter perform the prefiltering with the TR filter.

The power of the signal as a function of both space and delay is computed and investigated. As a metric for spatial focusing we define the following quantity:

$$\kappa(\mathbf{r}) \triangleq \max_{\tau} |\mathbf{s}(\mathbf{r}, \tau)|^{\mathbf{2}} \tag{2}$$

This quantity represents the power of the strongest tap at a receiver located at $\mathbf{r}$. We expect $\kappa(\mathbf{r})$ to peak at $\mathbf{r}_0$ and to decay rapidly with increasing distance from the origin.

III. MEASUREMENT SETUP

Measurements were conducted by Intel Corporation at off-peak hours to ensure channel stationarity. The environment is an office space ($40m \times 60m$) with many cubicles. Measurements span the bandwidth 2-8 GHz with 3.75 MHz frequency resolution. From the data we estimate that the coherence bandwidth of the channel is 20 MHz. Antennas are vertically polarized. The virtual grid on which the receiver is moved has a distance of $\lambda_0/4$ where λ_0 is the wave length of the mid frequency of the measurements (5 GHz).

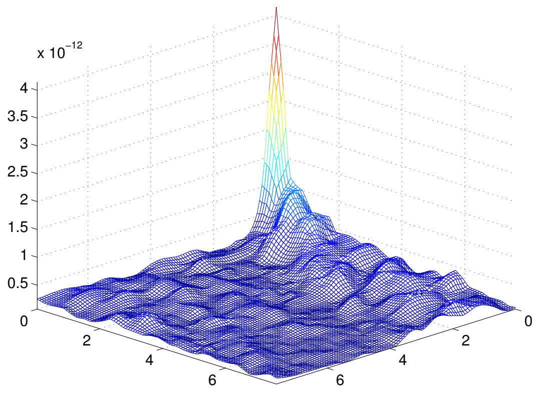
The receiver antenna is moved to a different location with a precise robotic positioner. At each antenna position, the channel is measured using a vector network analyser. The measurements are corrected to compensate for the system components (including cable, gain stages, and antennas). The height of the transmit antenna is about 2.5m and that of the receive antenna is 1m above the floor. The channel impulse response was computed by taking the inverse DFT of measurement data.

IV. EXPERIMENTAL RESULTS

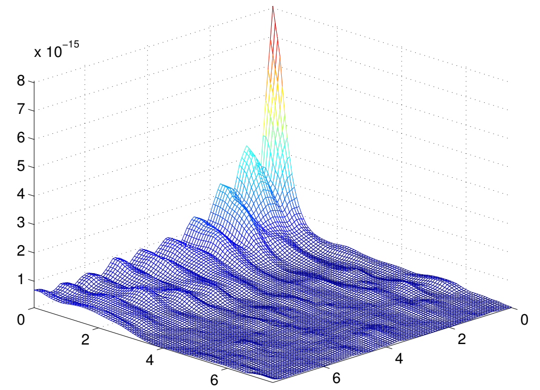
We evaluated $\kappa(\mathbf{r})$ for 11 different scenarios. Here we present two cases. Case I is an essentially line-of-sight scenario with a separation of 3m. Case II has a separation of 11m and is a typical non-line-of-sight situation. The results for the two cases discussed here have the worst focusing but they are very similar to all the other scenarios.

In the 3-D figures, the square grid spans a region of $7\lambda_0 \times 7\lambda_0$. A 3D plot of $\kappa(\mathbf{r})$ of the two cases is shown in Fig. 1. We see that spatial focusing works fine in both scenarios. In neither of them, however, is the peak isotropic; both peaks have one direction in which they fall off faster, and another, in which the decay is slower. The structure of the peak carries some information about the geometry of the environment, i.e., about directions which show faster and those which show slower decorrelation in space.

We also observe that the signal power level is at least $10dB$ lower at a distance of $7\lambda_0$ than its value at the receiver. This demonstrates the spatial decorrelation very well. We can conclude that channel impulse responses show inherent quasi-orthogonality in space, which can be used for interference suppression. In Fig. 2 we demonstrate the compression of the received pulse in the time domain. Displayed are the channel impulse response magnitude for the LOS scenario (a), the respective time-reversed, i.e., compressed impulse response magnitude (b), the impulse response for the NLOS scenario (c), and the compressed one for this case (d). The effective length of the channel is significantly shortened. Still, for the LOS-case, some strong side lobes remain visible. The impulse response of the NLOS channel is much better compressed in time. There will be some intersymbol interference in the time compressed field and one will have to equalize the received signal. However, the time compressed channel has a significantly shorter effective length and is thus less expensive to equalize.



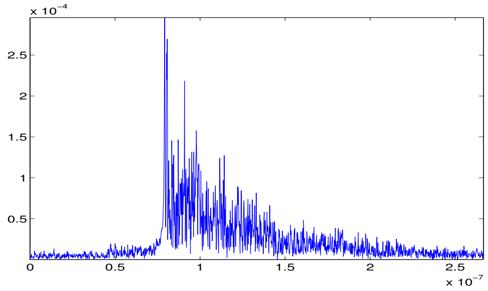
(a) Case I



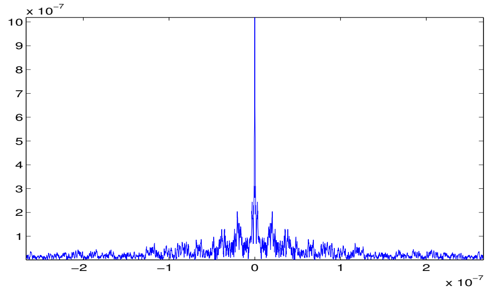
(b) Case II

Fig. 1. Spatial Focusing $\kappa(\mathbf{r})$. One shot spatial field realizations for a) the line-of-sight b) the non-line-of-sight scenario.

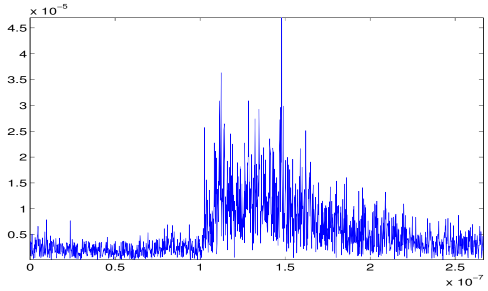
In Fig. 3 we investigate the hardening of the channel. We consider the distribution of the strongest tap of the channel impulse response and of time-reversed field. The dashed curve represents the distribution of the zero-th tap of the channel impulse response, and the solid curve represents that of the compressed signal. In the figure we see that the time reversed field is much less random (i.e., has more diversity) than the



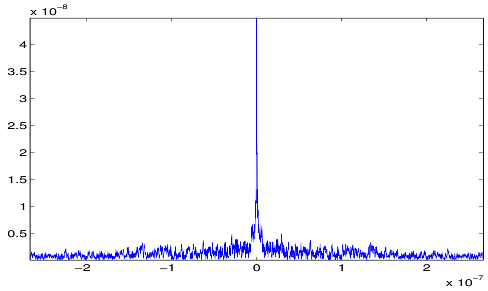
(a) Case I



(b) Case I



(c) Case II



(d) Case II

Fig. 2. Magnitude of channel impulse responses (a and c) and the time compressed impulse response (b and d)

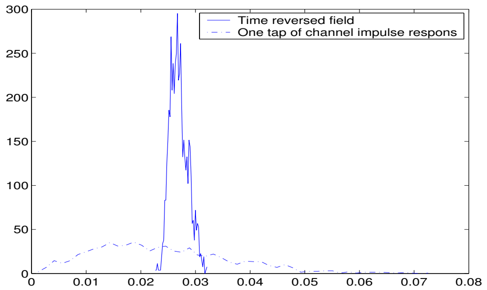


Fig. 3. Distribution of $s(\mathbf{r},0)$ (solid) and that of $h(\mathbf{r},0)$

channel response itself.

V. CONCLUSIONS

Using the indoor measurements discussed above, TR results in strong spatial focusing and time compression. At about 7 wavelengths from the target the signal power reduces by at least $10dB$ from its value at the target. The channel impulse response is well shortened at the target as well. Channel hardening or diversity gain is also observed. In a practical setting the results may degrade if the transmitter does not know the channel perfectly or if the transmitter circuitry has nonlinearities. Our calculations with the indoor radio wireless measurements obtained by Intel suggest that the benefits of TR, which have been observed in ultrasound and underwater sound TR experiments, could also be gained in wireless communications.

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