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Analysis of Time-Reversal-Based Propagation for Spatial focusing and Multiplexing

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Abstract – Time-Reversal (TR) technique is well-known for its ability of focusing waves. A common claim, based on this focusing ability, supports that TR technique may allow spatial multiplexing and secure transmissions. In the present paper, measurements campaigns were performed in a reverberation chamber and in a standard office to assess the viability of TR technique. It is shown that the results obtained do not support the common claim, especially in standard indoor environment where the focusing ability is strongly degraded.

1 INTRODUCTION

For the past few years several works have been presented aiming at evaluating the use of Time-Reversal (TR) propagation technique as an alternative transmission method for telecommunications in standard indoor multipath environments [1-5]. Most of the works assume that the spatial focusing property provided by a TR procedure may enable simultaneous parallel communications between different users like in multiple-input-multiple-output (MIMO) systems and would allow more secure transmissions. Surprisingly, the studies dealing with the use of TR for wireless transmissions are only based on what happens at the focusing instant.

The present paper aims at analyzing the wave propagation using Time-Reversal technique, at different instants and locations. This analysis is performed in two extreme environments: a reverberation chamber (RC) which behaves as a rich scattering channel and was shown to provide an interesting TR gain [6]; and in a standard office where the degree of reverberation reduces only to few echoes.

Section 1 is dedicated to a spatio-temporal analysis of the electric field topographies in a RC. It will focus on the quality of the transmitted signal and on the degree of secure transmission that one may expect from TR technique. Section 2 is dedicated to the case of a standard office, allowing an analysis of the performance that one might expect in a more realistic indoor environment where wireless transmissions are supposed to be performed.

1 Reverberation chamber

We performed a measurement campaign using the SUPELEC's RC (3.08m×1.84m×2.44m) where a (directive) log-periodic antenna and a phase-sensitive optical probe (EFS-105 ENPROBE) have been used (see Fig. 1a). The antenna was placed ensuring the main lobe to be directed towards the stirrer, as shown on Fig. 1a, in order to minimize direct light-of-sight transmissions. The optical probe has been moved manually on a Styrofoam monitor providing 12 cm separated-spatial samples (see Fig. 1b). The y -component of the field has been measured. The RC is used in a lossless configuration, i.e, no losses have been introduced in the chamber leading to time delay spread of about 10 μ s. The stirrer has been used in order to provide different realizations of the chamber – for the present work fifty stirrer positions have been used.

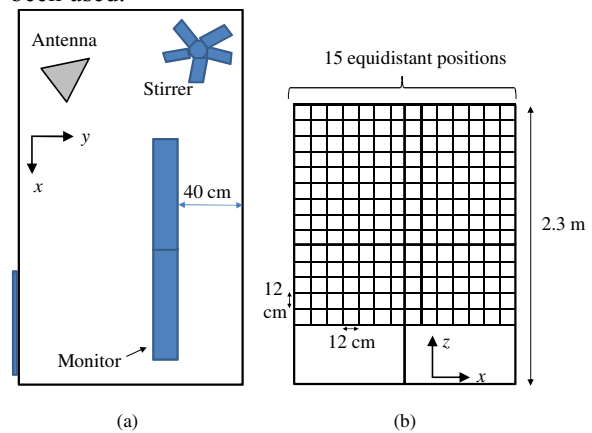


Figure 1: (a) Setup in the reverberation chamber based on sampling different monitor positions. (b) Schematic of the dimensions of the monitor.

The heterogeneous media are well-known to be a proper environment for TR performance in terms of signal-to-noise ratio (SNR) [7]. The use of a reverberating chamber should consequently provide interesting performance in terms of focusing. To

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illustrate and verify this feature, we consider an initial source position, regarded as a target in the time-reversal stage, placed at the center of the monitor. We plot on Fig. 2 the progression of the focusing wave-front, measured on the monitor, at some instants preceding the focusing instant referred as $t=0$. The right shots are related to the field topographies averaged on the fifty stirrer positions; the left shots correspond to the topographies obtained at a given stirrer position. For both cases, a central frequency of 1.5GHz and a Gaussian pulse bandwidth of 500MHz has been used. It can be clearly seen that the spherical convergence of the wave-front, i.e. the focalization, is not perfect in spite of the ensemble mean performed on the stirrer positions. For a given position of the stirrer, the results are even worse: the right part of the wave-front is almost missing. For both cases, the fact that only a single antenna has been used induces that the propagative part of the field cannot be well reconstructed, justifying the inhomogeneous wave-front of the field around the target receiver.

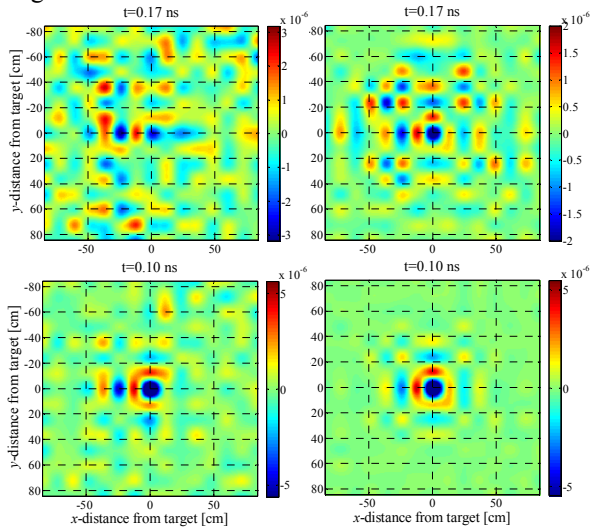


Figure 2: two shots of the y -component of the electric field related to two instants before the focusing time. The cases of a single stirrer position (left column) and the average on the ensemble of fifty stirrer positions (right column) have been reported.

Interestingly, a spatio-temporal analysis of the electric field allows to see clearly how the field propagates towards the center. Fig. 3 shows how the electric field y -component spreads along the z -axis as a function of time. The black line on the figure brings out that the wave propagates at the light speed, and that the signal may not be received only at the target. This spatio-temporal view may temper the common claim that TR may be regarded as a technique allowing secure transmissions [5].

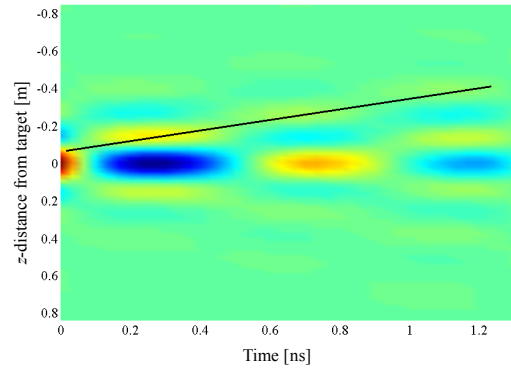


Figure 3: a spatio-temporal analysis of the field along the z -axis. The black line exhibits the wave field propagation at the light speed.

We are interested also in analyzing the spread of the focusing spot. The target being kept at the middle of the monitor, we analyze the amplitude of the y -electric-field component along the z -axis. The ensemble average on the number of stirrer positions has been considered and is plotted on Fig. 4. Theoretically, the time-reversed field repartition corresponds, on average, to the correlation functions between two transfer functions. We can show that these latter correspond to the spatial-correlations ρ_t and ρ_r presented in [8]. The y -component being analyzed along the z -axis, only the transverse correlation function ρ_t must be considered. In the present case, this latter must be averaged on the bandwidth Δf , and is defined as,

$$\langle \rho_t(r) \rangle_{\Delta f} = \left\langle 1.5 \left(\frac{\text{sinc}(kr) - \text{sinc}(kr)}{(kr)^2} + \cos(kr)/(kr)^2 \right) \right\rangle_{\Delta f} \quad (1)$$

where $\langle \cdot \rangle_{\Delta f}$ stands for the frequency average on the Δf bandwidth, r is the distance from the target and k is the wave-number defined at the frequency f .

Concerning the experimental results, we observe, on Fig. 4, dissymmetric shapes, in accordance with the imperfect reconstruction of the spherical wave-front observed of the 2D topographies on Fig. 2. The discrepancy with the theoretical model, i.e. with the ρ_t function, is quite satisfactory since the theory is based on a common asymptotic model consisting in modeling the field by an infinite number of plane waves [9], never met in practice. Accordingly, the theoretical model must be regarded as a mean to provide a trend, at least near the target. Indeed, we have reported on the figure, the maximum value of the field along the z -axis obtained and occurring for each stirrer position, allowing a worst-case scenario. Accordingly, at a distance greater than 4λ (λ being the wavelength corresponding to the central frequency), a worst-case attenuation of 25 dB is

observed experimentally whereas the theoretical model predicts 45 dB. Consequently, from an applicative point of view, the results presented herein do not support the claim that using TR technique would allow spatial multiplexed transmissions for MIMO systems. Indeed, for a typical antenna-array receiver where each antenna is separated from a distance $\lambda/4$, a “spatial isolation” cannot be achieved.

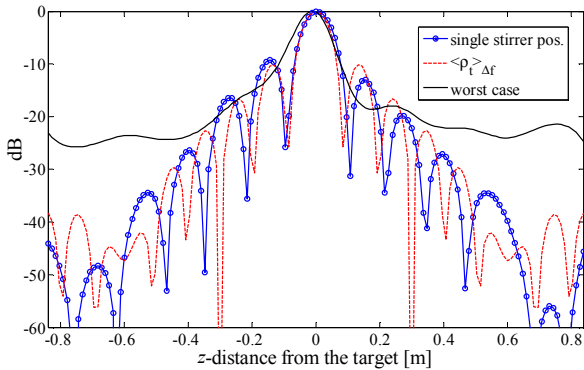


Figure 4: Field spread along the x -axis. The cases of a single stirrer position, of the theoretical case given by (1) and the worst case corresponding to the maximum level obtained for each stirrer position.

To observe the variations in time of the signal near the focused point, we plot on Fig. 5 the waveforms obtained at 12 cm and 24 cm from the target. We can clearly see that the transmitted symbol can be received around at instants related to the separating distance. Taking the target case as a reference, an attenuation of 20 dB and 25 dB is found at 12 cm and 24 cm. Accordingly, recalling that the power range of a typical wireless receiver is around -110dBm, the transmissions cannot be regarded as secure, since the signal can be received at other positions with a non-negligible level.

The reverberation chamber is not however a representative environment of standard indoor places. In order to analyze the TR performance in such places we will consider a more realistic indoor environment in the next section.

3 Standard indoor environment

In order to study the viability of TR technique in real conditions, i.e., in standard environments where wireless transmissions are supposed to take place, we perform a measurement campaign in an office whose dimensions are given on Fig. 6. The walls are made of plasterboard and the ceiling is made of metallic paneling. This environment is very poor in terms of scattering and presents a low time delay spread of about 100 ns.

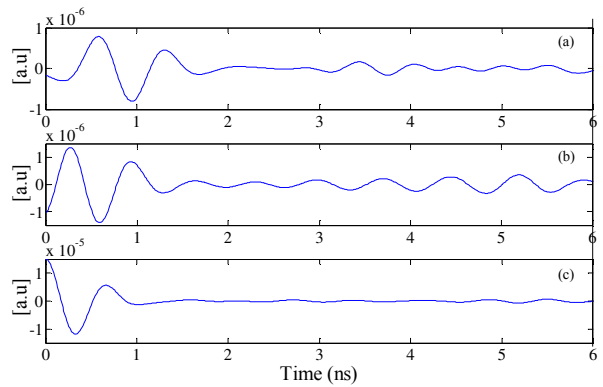


Figure 5: Waveforms of the signal measured at (a) 24 cm, (b) 12 cm, (c) 0 cm, from the target.

For the setup, the main lobe antenna was directed towards the metallic book cases in order to minimize the direct line-of-sight transmissions. Moreover, an x -horizontal polarization has been used and a sampling of 10×14 positions has been performed on the monitor, placed horizontally, leaning on an office. The spatial samples were separated with a distance of 6cm.

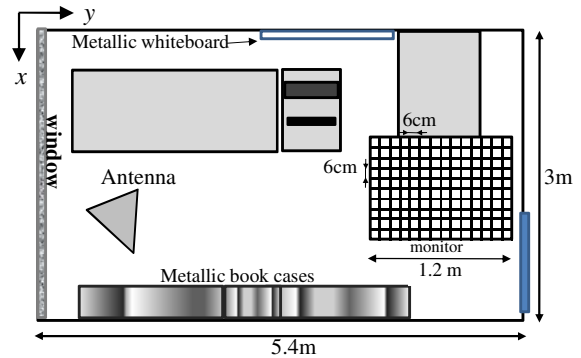


Figure 6: Dimensions of the office used as standard indoor environment. The walls are made of plasterboard and the ceiling is made of metallic paneling.

As previously the target is assumed in the center of the monitor and a 500MHz bandwidth Gaussian pulse with a 1.5GHz central frequency has been used. An analysis of the focalization has been performed and the results are shown on Fig. 7. We can clearly see the absence of spherical convergence, i.e, the absence of focalization. The TR technique being a spatio-temporal matched filter, a maximum is clearly present at the target position and at the focusing instant. We can note that the field spread at the focusing instant has a similar shape than the results presented in [5] on the basis of simulation channel models. However, the interesting point is to see that the wave-front is quite large in the y -direction, even before the focusing time. This implies a possible

reception of the signal in a wide area around the target, before the expected focusing instant.

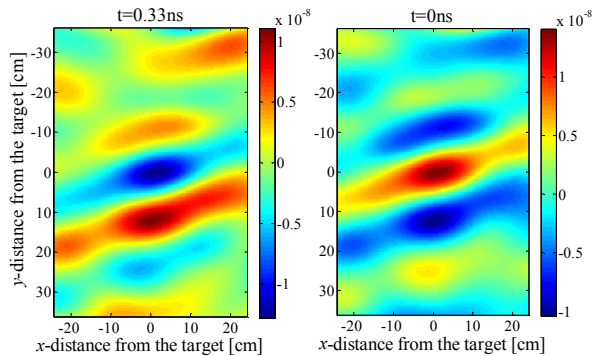


Figure 7: wave-front measured at the focusing instant (right) and 0.33ns before the focusing time (left).

An analysis in time along the y -axis is presented on Fig. 8. Interestingly, we can see a seemingly pseudo-periodic patterns that informs on the few number of plane waves in the room, confirming that the RC case is not quite representative of a standard indoor environments. The focusing areas are consequently related to the structure of the room. The poor number of plane waves induces consequently the appearance of other local maxima in time and in space as observed on Fig 8. This last point questions on the real advantages of TR in standard indoor environments over the existing transmissions techniques.

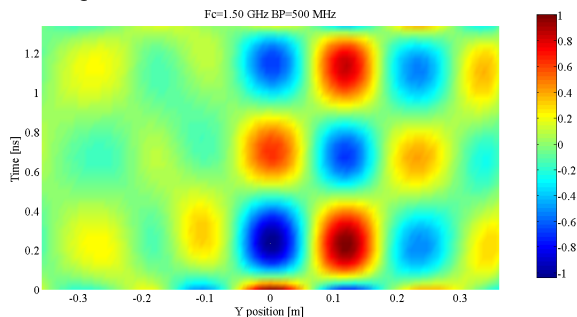


Figure 8: spatio-temporal representation along the y -axis. A maximum field level is observed at the target position, as expected, but also at some neighboring distance.

4 Conclusion

It has been shown in the present study, that the attenuation at the focusing instant cannot be regarded as sufficient on the basis of the power range of a common wireless receiver, to allow spatial multiplexing. Indeed, even in a reverberation chamber, allowing a good TR performance in terms of focusing, a worst-case scenario of 25 dB attenuation is found on an almost one meter distance.

A spatio-temporal analysis shows that the signal propagates as in a free-field environment on the last stage preceding the focusing instant. Accordingly, the signal can be received by any neighboring receiver. Although the signal is attenuated in comparison with the one received on the target, the level cannot be regarded as negligible.

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