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Towards reconfigurable and cognitive communications/Vers des communications reconfigurables et cognitives

Time reversal telecommunications in complex environments

Arnaud Tourin *, Geoffroy Lerosey, Julien de Rosny, Arnaud Derode, Mathias Fink

Laboratoire ondes et acoustique – UMR 7587, ESPCI – université Paris VII, 10, rue Vauquelin, 75005 Paris, France

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Abstract

The time reversal technique is well known in acoustics and has lead to remarkable applications in ultrasound and underwater acoustics. Here we propose to apply it to MIMO (Multiple Input – Multiple Output) UWB (Ultra Wide Band) communication: in a first 'training' step, the intended user transmits an electromagnetic pulse that propagates in a medium, where it undergoes multiple reflections. The resulting signals are recorded at the base station by one or more antennas, time reversed and used to precode the transmitted symbols. The resulting sequences are sent back by the antennas. The time-reversed wave retraces its former paths and leads to a focus of the message in space and time at the receiver. The equalization step is thus simplified since TR compensates for the reverberation caused by the channel. Furthermore, TR takes advantage of the multipaths to increase the signal strength at the receiver and to improve spatial focusing. ***To cite this article: A. Tourin et al., C. R. Physique 7 (2006).***

Résumé

Télécommunications par retournement temporel dans des environnements complexes. Nous présentons une méthode de communication qui allie les avantages des techniques MIMO (Multiple Input – Multiple Output) et UWB (Ultra Wide Band). Cette méthode repose sur le principe de focalisation par retournement temporel, déjà éprouvé en acoustique et récemment transposé aux ondes électromagnétiques. Une impulsion « test » est émise dans une cavité réverbérante par une antenne placée à l'endroit où l'on souhaite transmettre un message. L'onde résultante est enregistrée par une ou plusieurs antennes, retournée temporellement, « enrichie » du message à transmettre, et renvoyée dans le milieu. Elle revit alors les étapes antérieures de sa propagation et reconverge sur sa source en y formant un message intelligible. Outre que cette technique simplifie l'étape d'égalisation puisqu'elle compense les réverbérations du milieu, elle profite des chemins multiples pour focaliser le message sur l'utilisateur, ce qui assure l'optimisation de la puissance reçue, la sécurité de la transmission et permet la communication simultanée avec plusieurs utilisateurs proches les uns des autres. ***Pour citer cet article : A. Tourin et al., C. R. Physique 7 (2006).***

Keywords: Time reversal; Multiple scattering; Reverberation; MIMO; UWB

Mots-clés : Retournement temporel ; Diffusion multiple ; Réverbération ; MIMO ; UWB

* Corresponding author.
E-mail address: arnaud.tourin@espci.fr (A. Tourin).

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1. Introduction

The world of telecommunications is confronted with two main challenges. Firstly the Internet has created the demand for very high information transfer rates. Secondly the development of cell phones and other wireless devices require ubiquitous connectivity for a dense population of users. Merging the responses to these two challenges is at stake. Two ways seem particularly promising. The first one consists in exploiting multiple antenna arrays at both transmitter and receiver to beat fading thanks to *diversity* gain and potentially to increase the Shannon Capacity [1, 2]. The general idea of sending multiple signals between multiantenna arrays is known as MIMO (Multiple Input–Multiple Output). The second way is to use Ultra Wide Band (UWB) transmitters and receivers, which is the natural solution to accomodate for large data rates. After recalling the fundamentals of MIMO and UWB, we present here a way of merging these two techniques.

2. The MIMO (Multiple Input – Multiple Output) and UWB (Ultra Wide Band) approaches

The maximum error-free data rate supported by a communication channel is called its 'Capacity' [3]. In 1996, Foschini [4] realized that the key to increase the Capacity was to form a channel using increased spatial dimensions. To that goal multi-antenna arrays have been proposed to exploit the independent channels of propagation created by scattering off heterogeneities. The basic idea consists in sending a different bitstream from each antenna of the transmitting array. In a medium with sufficiently rich scattering, the signals recorded at the different receiving antennas are decorrelated. If the number of receiving antenna is larger than the one in the transmitting array, the bitstreams can then be decoded. At best the data rate is multiplied by the number of transmitting antenna. Foschini has proposed the first coding/decoding algorithm to exploit this idea, the so-called 'Blast' (Bell Labs Layered Space–Time) algorithm [5]. However, this method has some limitations. First, it is a kind of iterative inverse filtering method which is of high-complexity (time consuming). Furthermore, it is by essence a narrowband technique: it must assume that the channel transfer function is flat over the band of interest. More recently, broadband approaches such as Blast-OFDM [6] (OFDM stands for 'Orthogonal Frequency-Division Multiplexing') have nevertheless been proposed to combine large bandwidths and MIMO techniques but the receiver architecture is complex.

UWB has become another suitable candidate for high-data rates, especially for short range communications. However, when using UWB transmitters, channels with large delay spread arise which is considered as disadvantageous for wireless communications, since it produces huge ISI (Interference Inter-Symbol) and makes the equalization step at the receiver more complicated (here the term equalization stands for any signal processing operation that minimizes ISI at the receiver; it usually relies on matched or inverse filtering methods [7]).

3. Time-reversal communication at the ultrasound scale

To merge the advantages of these two approaches, we propose here a method which exploits multipath effects as well as a wide spectrum. This method is based on the principle of time reversal focusing. In the past years the laboratoire 'Ondes et Acoustique' has developed for ultrasound a focusing technique which exploits the time reversal invariance of the wave equation [8] (http://www.loa.espci.fr). This technique is also widely studied in underwater acoustics [9]. It is well known that the acoustic wave equation in a non-dissipative heterogeneous medium is invariant under a time-reversal operation. Indeed, it only contains a second-order time-derivative operator. Therefore, for every burst of sound $p(\mathrm{r}, t)$ diverging from a source (and possibly reflected, refracted or scattered off any heterogeneous medium), in theory there exists a wave $p(\mathrm{r}, -t)$ that precisely retraces all the forward complex paths in the reverse order and converges in synchrony at the original source as if time were running backwards. This idea gives the basis of time-reversal acoustics. Ideally, in order to perfectly synthesize the time-reversed field, the acoustic field should be sampled in the forward step at every point of a closed surface surrounding the medium, what is called a time-reversal cavity, and retransmitted through the medium in a time-reversed chronology. The wave would then travel back to its source and recover its original shape with a focal spot size of half-wavelength, only limited by diffraction [10]. In practice, the transmitted signals are recorded at a finite-size transducer array—called a time-reversal mirror (TRM)—, then time-reversed and transmitted back. Due to this limitation, when this experiment is performed in free space (typically in water) the wave converges back to the initial source position with a spatial resolution directly related to the TRM aperture. However, if the propagation medium is full of scatterers, the finite array aperture can be compensated.

Indeed, some spatial frequencies that would be lost in free space during the forward propagation step are redirected towards the TRM thanks to scattering off the heterogeneities [11]. In this case, the propagation medium acts as an 'acoustic lens'. If the angular aperture of this lens is large enough to intercept the whole incoming wavefront, the spatial focusing obtained by time-reversal can go far beyond the diffraction limit in free space, an effect which is referred to as 'hyperfocusing'. At best, the classical half-wavelength spot size is retrieved.

Following these first results, we tested a communication scheme based on time reversal with ultrasound in a water tank [12]. A multichannel ultrasonic time-reversal antenna was used to transmit a random series of bits simultaneously to different receivers which were only a few wavelengths apart. Whereas the transmission was free of error when multiple scattering occurred in the propagation medium, the error rate was huge in a homogeneous medium due to spatial cross-talking between receivers. The advantages of this technique are manifold: firstly, it makes communications in channels with large delay spread more feasible since reverberation is compensated. In that respect TR is a kind of 'pre-equalizer'. Secondly reverberation is not only compensated but taken advantage of to improve focusing at the intended receiver. Thus security of transmission and signal-to-noise ratio are optimized. Furthermore hyperfocusing gives the possibility of addressing simultaneously several users, which increases the global data rate. In this sense TR is a 'diversity technique' which exploits the capacity increase in a spatially and frequency selective medium.

4. Time-reversal communication with electromagnetic waves

4.1. A first 'SISO-narrowband' prototype

The extension of TR techniques to wireless communications thus seems particularly promising. From a practical point of view the main difficulty to transpose the time-reversal technique developed for ultrasound directly to the electromagnetic case lies in the much higher sampling frequencies that are needed to digitize radio frequency signals. One way to overcome this limitation is to work only with quasimonochromatic signals and to make a phase conjugation using the so-called three-wave or four-wave mixing in a nonlinear material in order to naturally produce the analogic phase-conjugated wave [13]. In our case, the goal was to propose a truly broadband time reversal experiment for an electromagnetic signal

$$s(t) = m_I(t)\cos(2\pi f_0 t) + m_Q(t)\sin(2\pi f_0 t)$$

with f_0 the carrier frequency, $m_I(t)$ and $m_Q(t)$ the 'baseband' signals. The point is to synthesize the signal

$$s(-t) = m_I(-t)\cos(2\pi f_0 t) - m_Q(-t)\sin(2\pi f_0 t)$$

Our idea was to transpose all time-reversal operations on the baseband signals [14]. Thus, the sampling frequency can be much lower than f_0.

The experimental setup is the following (Figs. 1 and 2): Two omnidirectional antennas working around $f_0 =$ 2.45 GHz (Fig. 1(d)), and attached to them two transceiver circuit boards (Fig. 2), are used. On the transmit side, the transceivers permit one to encode the inphase (cos) and quadrature (sin) components of a baseband signal (labeled I and Q, respectively) onto a 2.45 GHz wave carrier that can be radiated by the transmit antenna. On the receive side, the circuit board demodulates the radio frequency signal back to the baseband. The experiment takes place in a strongly reverberant cavity. Using an arbitrary waveform generator, a short pulse (central frequency 3 MHz, bandwidth $B = 2$ MHz @ -6 dB) is delivered to the I analog input (Fig. 2(a)) of the transmit board. No signal is delivered to the Q analog input (Fig. 2(b)). The mixer upconverts this signal to the GHz band and delivers $e(t) = m_I(t)\cos(2\pi f_0 t)$. Then the waveform $e(t)$ is transmitted by antenna A.

The signal received at antenna B is demodulated to produce the I and Q signals. Due to strong reverberation in the cavity, the I and Q modulations are significantly lengthened. They are sampled at 40 MHz, i.e., much less than the carrier frequency, time reversed and then used to modulate the phase-conjugated carrier. The RF backpropagated signal is sent back by antenna B and refocuses at antenna A to recreate a replica of the initial pulse. Using another antenna moved around antenna A, we also verified that the amplitude of the sidelobes around the focal point drops very rapidly (on the scale of the wavelength). This experiment proves the feasibility of electromagnetic TR in a complex medium with only one single antenna. The reason is the following: the -6 dB bandwidth was only $B = 2$ MHz but the characteristic decay time of the cavity was 3.6 µs, which gives a coherence bandwidth of $B_c = 280$ kHz. The ratio $B/B_c = 7$ gives the number of independent frequencies in the bandwidth and thus defines the available frequency

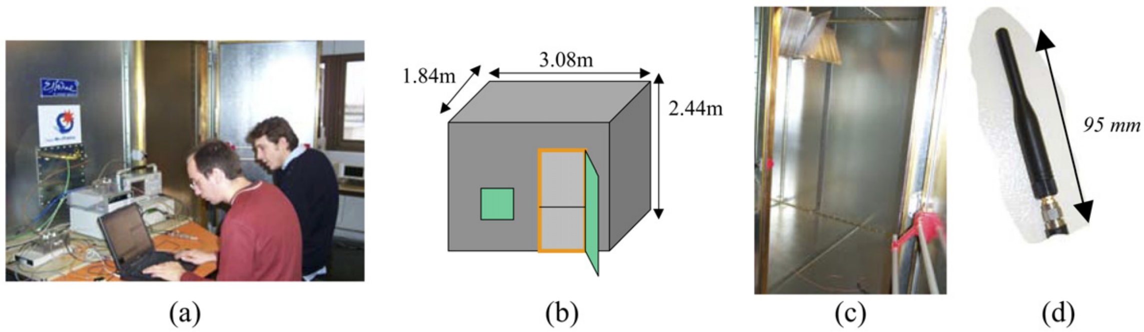

Fig. 1. Experimental setup used for the first time reversal experiment for electromagnetic waves: (a) global view; (b) dimensions of the reverberant cavity; (c) interior of the cavity; (d) antenna.

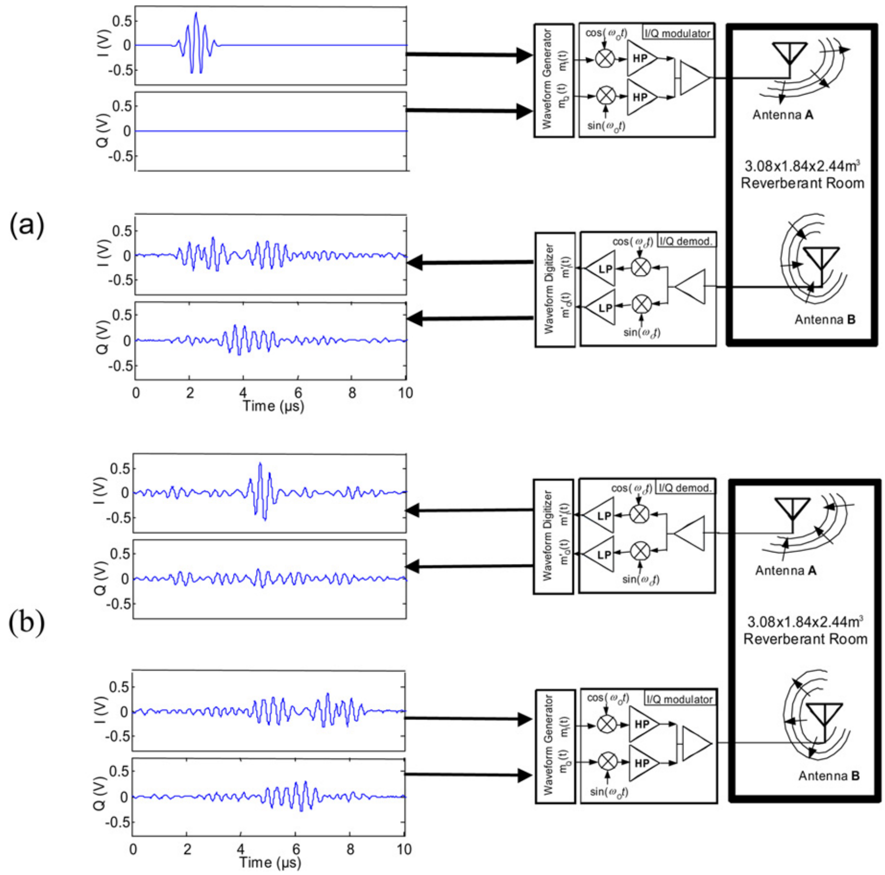

Fig. 2. (a) Training step: a pulse is sent by antenna A in the reverberant cavity. The resulting signal is received at antenna B and demodulated. (b) Time-reversal step: the baseband signals are time reversed, modulated onto the phase-conjugated carrier and transmitted back in the cavity. A replica of the initial pulse is recovered on channel I.

selectivity. This latter is a parameter of major importance for time reversal in random media [12]. Indeed, it determines the ability to focus a wave in both time and space using a TRM limited to 1 antenna only as experimentally shown here. More precisely, the square root of B/B_c governs the ratios 'amplitude at the focusing time over amplitude of the temporal sidelobes' and 'amplitude at the focal point over amplitude of the spatial sidelobes'. Thus the higher the frequency selectivity, the better the focusing.

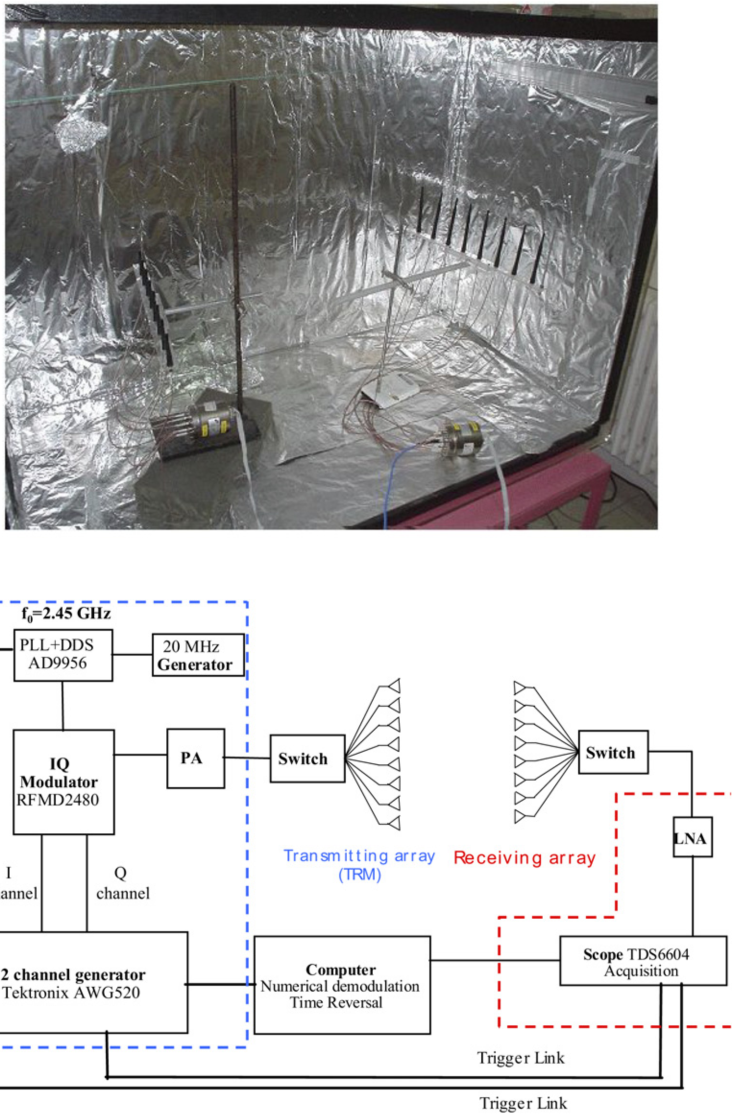

Fig. 3. MIMO TR experimental setup. Top: View of the cavity and the antenna array. Bottom: Block diagram for the TR process. The transmitting array is used in a MRT mode to focus a pulse at one of the receiving antenna. The other antennas in the receiving array are used to quantify spatial focusing.

4.2. A second 'MIMO-Intermediate Band' prototype

In the previous experiment reverberation was necessary to ensure a sufficient delay spread and so to highlight the interest of the TR technique in such a situation. To approach a more realistic situation, we developed a MIMO prototype with a larger bandwidth (200 MHz). As a consequence instead of using a strongly reverberant cavity, we were able to replace it by a homemade cavity with a lower quality factor but sufficient to ensure a higher frequency selectivity than in the first experiment.

A 10-ns long Gaussian-shape signal is synthesized from a Tektronix AWG520 and fed into the I input of a modulator RFMD 2480 which uses it to modulate a carrier at 2.45 GHz. Thanks to a multiplexer, the resulting RF signal $e(t)$ is successively sent from each antenna #i in the transmitting array and the corresponding response $h_{ij0} \otimes e(t)$ is measured at the 'target' antenna #j_0 (an antenna chosen in the receiving array), with h_{ij0} the impulse response. Due to reciprocity, the recorded signals are the same as those which would be received at each transmitting antenna if

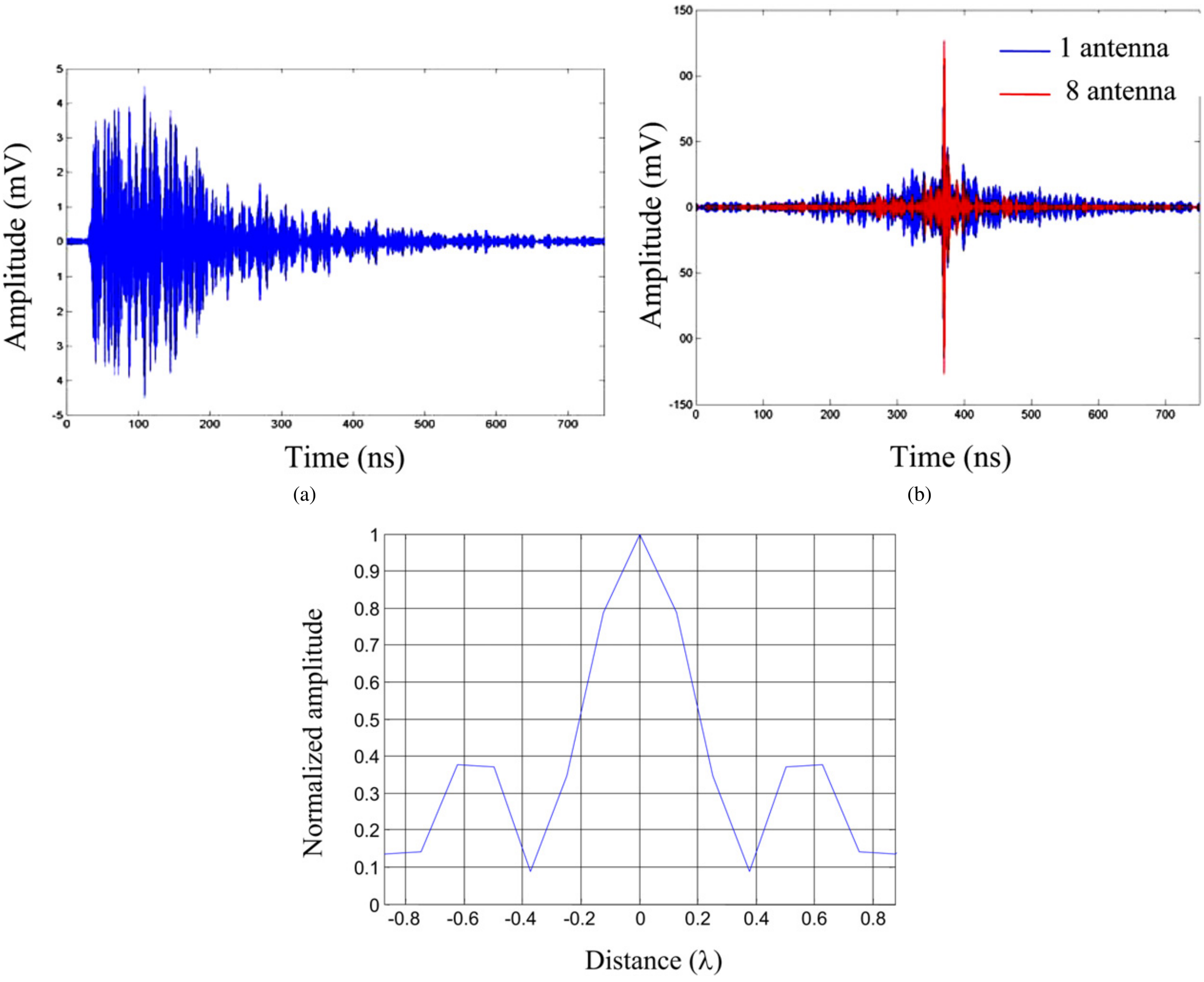

Fig. 4. (a) Typical impulse response measured in the cavity. (b) Time compression at the target antenna with 1 and 8 antenna in the TRM. (c) Focusing spot.

the target antenna transmitted $e(t)$, i.e., $h_{j0i}(t) \otimes e(t)$. As can be seen in Fig. 4(a), they typically last a few hundred nanoseconds. The rms-delay spread averaged over all possible transmitter/receiver pair equals 160 ns, which gives a frequency selectivity of 16. These signals $h_{j0i}(t) \otimes e(t)$ are sampled thanks to a digital scope TDS6604 with a sampling frequency of 20 Gs/s and numerically demodulated. The corresponding I and Q signals are time-reversed and used to modulate the phase-conjugated carrier wave. The resulting RF signals $h_{j0i}(-t) \otimes e(-t)$ are sent from each transmitting antenna and the resulting signals $h_{j0i}(-t) \otimes e(-t) \otimes h_{ik}(t)$ are measured at each receiving antenna #k thanks to a multiplexer. Finally at each receiver the signals measured for each transmitting antenna are summed to give

$$s_k(t) = \sum_{i=1}^{N} h_{j0i}(-t) \otimes h_{ik}(t) \otimes e(-t)$$

with N the number of antennas in the TRM. $s_{j0}(t)$ measures the signal recreated at the target antenna when using a N-antenna TRM (Fig. 4(b)) whereas the focal spot is quantified by $f(k) = \max_t(s_k(t))$ (Fig. 4(c)). A short pulse is recovered at the target antenna. As to the focusing spot, its width is one wavelength which proves that the diffraction limit is reached. To fit the focusing spot we developed a theory which takes into account both polarization and coupling between antenna [15].

Using this setup we began to implement MIMO-Mu (Multi-user) communication schemes. In such a situation, each receiving antenna is attached to a different user. Once the 8 sets of TR signals have been built following the procedure previously described, they are used to encode the different bit series to be transmitted to the 8 receiving antenna. Each message being focused at the intended user with a precision of one wavelength, spatial cross-talking is minimized.

5. Conclusion

In this article we have introduced the concept of TR techniques in the context of broadband wireless communications. It has become a subject of great interest for the last three years [16,17]. TR provides a low-complexity solution to compensate for large delay spreads which typically arise when large bandwidths are used as in UWB. In that sense TR is a pre-equalizer. Usually one way to proceed with equalization is to implement a matched filter at the receiver. The TR technique moves the *matched filter* from the receiver to the radio channel, which simplifies the architecture of the receiver. Furthermore TR optimizes the power at the intended receiver which is particularly interesting taking into account the drastic power limitations in UWB. Finally TR takes advantage of multipathing to ensure spatial focusing at the receiver. Thus it also guarantees the security of transmission and offers an interesting solution for multiuser communications. Of course, this technique must now be studied in the context of non-stationary channels of communication.

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