Wireless Transmission of Electromagnetic Energy Based on a Time Reversal Approach for Indoor Applications

R. Ibrahim[1,2], **B. Allard**[1], **A. Breard**[1], **J. Huillery**[1], **C. Vollaire**[1], **D. Voyer**[1], **and Y. Zaatar**[2]

[1]Université de Lyon, Ampere (CNRS UMR 5005, École Centrale de Lyon, INSA-Lyon, UCBL)
Écully Cedex F-69134, France

[2]LPA, Lebanese University Faculty of Sciences 2, Campus Fanar, Jdeidet BP 90656, Lebanon

Abstract— An original approach based on a time reversal technique is proposed to fabricate a wireless transmission of electromagnetic energy for indoor applications. Experiments performed in a low-Q cavity of human size with a carrier frequency around 2.45 GHz show that the energy efficiency is greater than the one obtained with a continuous wave approach.

1. INTRODUCTION

Most of the recent developments in wireless transmission of electromagnetic energy are concentrated on systems designed to harvest the electromagnetic energy disseminated by common wireless systems such as Wi-Fi networks. However, the intermittent and unpredictable nature of these ambient sources makes energy harvesting critical for some applications [1]. In scenarios where the energy is transmitted intentionally, systems using continuous waves (CW) are not necessarily the most efficient. We investigated an alternative approach based on time reversal (TR) which was found to be promising for indoor applications. TR using electromagnetic waves was first demonstrated a decade ago [2, 3]. The implementation of this technique in indoor environment needs two stages. In a first stage called *learning stage*, a low energy pulse is transmitted through an antenna. At another place in the room, the receiver antenna records a signal constituted by a succession of many delayed pulses, more or less attenuated and related to the reflections in the medium. In a second stage called *time reversal stage*, a high energy signal built from the TR of the signal recorded during the learning stage is transmitted through one of the antennas. It follows that the time reversed waves focus spatially and temporally on the receiver antenna. These properties are particularly attractive for energy recovery. Moreover, the energy efficiency increases when the medium becomes more and more complex what makes this approach suitable for indoor applications. The paper is organized as follow: Section 2 details are given concerning the experiments performed inside a low-Q cavity. Section 3 a comparison of the energy performance is made between wireless transmissions based on the TR and CW approaches.

2. EXPERIMENTAL SETUP

2.1. Equipment

The experiment consists of transmitting electromagnetic waves between two antennas placed inside a low-Q cavity of human size ($2.45\,\text{m} \times 2.45\,\text{m} \times 2.45\,\text{m}$) that is supposed to reproduce indoor conditions in terms of both losses and lifespan of waves in the medium. Two obstacles have been positioned between them to avoid a direct path (Figure 1). Even though, resonance related to cavity modes can be observed. This phenomena is illustrated in Figure 2 by the measurement of the transmission parameter between both antennas using a vector network analyzer.In order to perform TR, specific characteristics are required for the antennas. First large band antennas are necessary since nanosecond pulses with a frequency carrier of 2.45 GHz are handled. Second the radiation pattern of the antennas has to be omni-directional in order to investigate reflections in all the directions inside the room. Our choice focused on tap monopoles [4] since these antennas exhibit suitable properties and are easy to manufacture. A waveform generator Tektronix AWG7122C is used to transmit the different signals. This generator is particularly useful in the time reversal stage during which the manipulated signals have a complex shape. Note that the sampling frequency was set to 12 GHz, which is large enough compared to the limit defined by Shanon's theorem. The maximum output voltage of the generator is 1 V peak to peak (pk-pk) but this is not enough to transmit measurable signals because of the losses inside the room. Consequently, an amplifier with a gain value of 20 dB has been added in the transmission line. In reception, the signals are recorded using a digital oscilloscope Tektronix DPO70604C with sufficient capabilities: signals with 50000 samples can be recorded with a sampling frequency up to 25 GHz and an analogical bandwidth of 6 GHz.

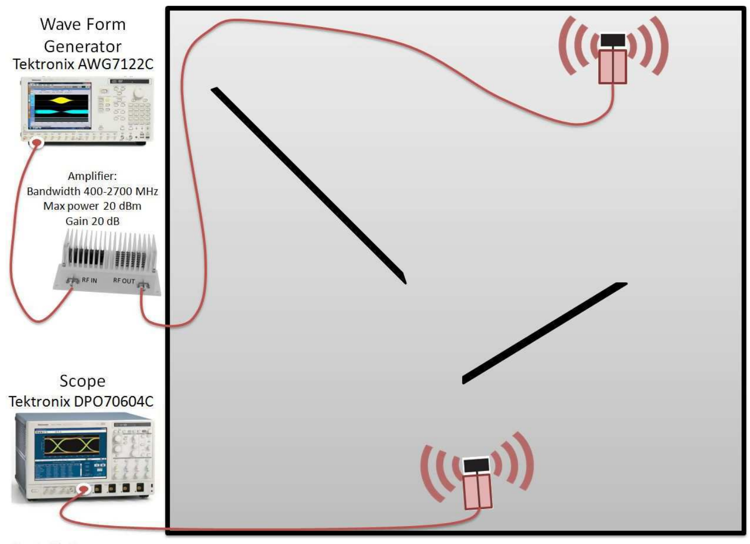

Figure 1: Top view of the cavity with the position of tap antennas and possible obstacles.

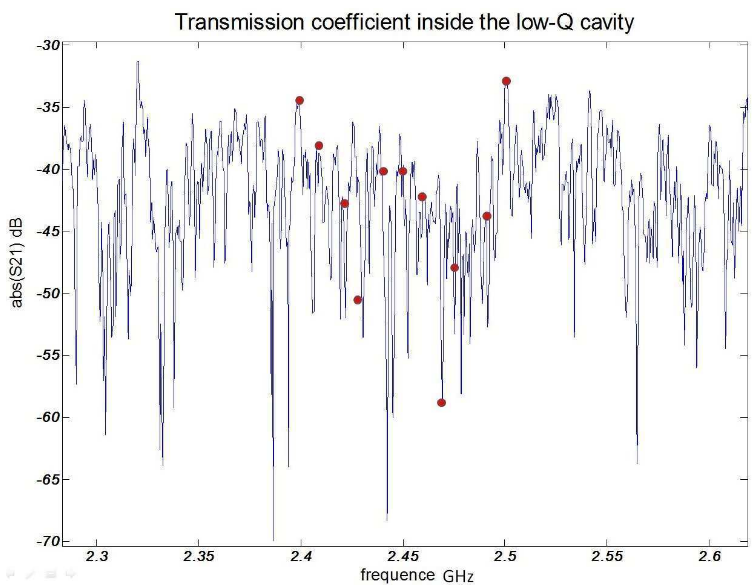

Figure 2: Response of the low-Q cavity between 2.3 GHz and 2.6 GHz. The red points mark the value of the frequency carriers chosen for the experiments see Section 3.

2.2. Time Reversal Procedure

As it is mentioned in the introduction, the TR technique is implemented following two steps (Figure 3):

- *Learning stage*

  A 10 ns pulse with a carrier frequency of 2.45 GHz and an amplitude of 10 V pk-pk is transmitted through the first antenna. A hamming window has been applied such that the frequency bandwidth of the signal is 400 MHz. This signal is called $x(t)$.

  In reception, a complex signal $y(t)$ with a time length of approximately 2 µs and a maximum amplitude of 20 mV pk-pk is recorded using the digital oscilloscope. This signal is constituted of successions of delayed and attenuated reflections inside the room that provide information on the complexity of the medium.

- *Time reversal stage*

  Numerical processing is applied on the signal $y(t)$ using Matlab. First a frequency filtering is performed with a Butterworth's bandpass filter to eliminate the noise outside the bandwidth

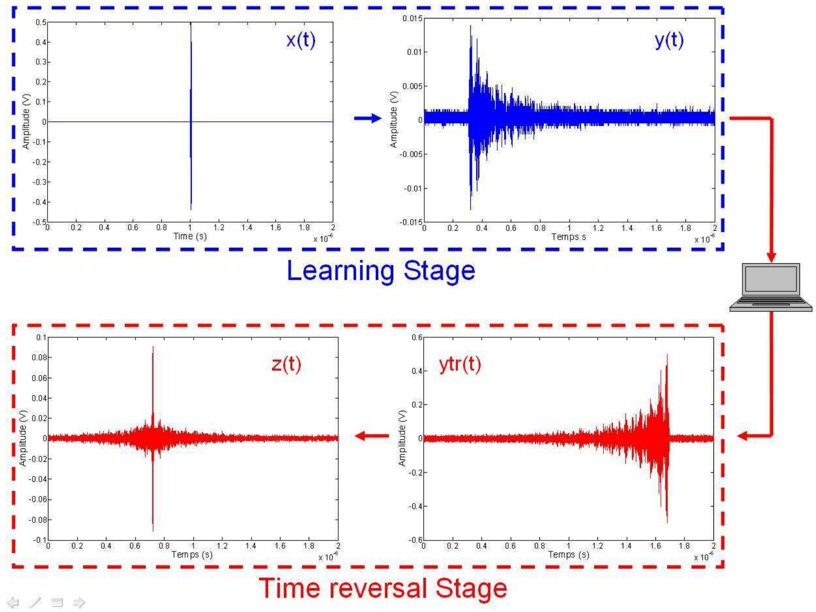

Figure 3: Steps of time reversal scheme with signal waveforms.

from 1.5 GHz to 3.5 GHz. Then the time reversal is applied. At this step, the reversed signal $y_{tr}(t)$ is transmitted from the second antenna so that the reversed waves propagate through the same path as in the learning stage but in the reverse direction. These waves are expected to converge in phase on the first antenna and build a constructive signal. But for some practical reasons, we use the same configuration as during the learning stage. The reversed signal is transmitted through the first antenna to the second. This is possible because of the reciprocity in the medium. Reciprocity implies that the received signal is the same whatever $y_{tr}(t)$ is transmitted by the first antenna or by the second one. Note that the signal $y_{tr}(t)$ generated by the waveform generator is normalized to 1 V pk-pk and the maximum amplitude of the reversed signal at the output of the amplifier is 10 V pk-pk like in the learning stage.

In reception one observes a signal $z(t)$ in which a 10 ns pulse with an amplitude of 200 mV pk-pk is recovered, this amplitude is approximatively 10 times the one measured during the learning stage.

2.3. Continuous Wave Procedure

Experiments have also been performed with common wireless transmission using CW. In that case, a sinusoidal signal with an amplitude V_1' pk-pk (the voltage considered here is the one at the output of the amplifier for about 10 V) and a frequency carrier from 2.4 GHz to 2.5 GHz with a step of 0.1 GHz is transmitted by the first antenna. In reception, one measures a sinusoidal signal with an amplitude V_2 pk-pk at the frequency carrier considered.

2.4. Energy Performance Definition

The efficiency of the TR scheme has to be defined. In the experimental setup detailed in Section 2.2, the signals transmitted during the learning and time reversal stages are normalized to the same amplitude. However if one is concerned about energy performance, the learning stage should be performed using a very low energetic signal $x(t)$. Indeed, this step consists of collecting information about the medium and the amplitude of the signal is chosen based on signal to noise ratio considerations. This is why the energy of $x(t)$ is ignored in the energy performance evaluation. On the contrary, the energy E_z of the pulse recovered in reception during the time reversal stage is related to the energy $E_{y_{tr}}$ of the reversed signal $y_{tr}(t)$. However the amplifier has to be taken into account. The transmitted energy is the one carried by the signal ${y_{tr}}'$ generated at the output of the amplifier. E_z should be calculated at a time interval where the signal is focused supposed to be equal to the period of time for the signal emitted in learning stage, separately from $E_{y'_{tr}}$ that must be calculated including all the signal emitted at interval of 2 µs. Thus, the energy performance for the TR is defined by:

$$\eta_{TR} = \frac{E_z}{E_{y_{tr}'}} = \frac{\int\limits_{10\ ns} z(t)^2\, dt}{\int\limits_{2\ \mu s} y_{tr}'(t)^2\, dt} \tag{1}$$

The computation of η_{TR} is realized using Matlab. Concerning the evaluation of E_z, the recovered pulse is localized in the signal $z(t)$ and the energy is computed inside a window of 10 ns that includes the pulse. Concerning the evaluation of $E_{y_{tr}'}$, one should measure the signal y_{tr}' at the output of the amplifier. But for practical reasons, we made the computations from the signal y_{tr} built during the time reversal stage (Section 2.2). The signal y_{tr}' can approximatively be synthetized multiplying y_{tr} by a factor of 10 in order to take into account the amplification gain of 20 dB. The gain of the amplifier varies between 18 and 20 dB over the bandwidth of y_{tr}. A more precise approach consists of using the frequency response of the amplifier to compute the energy in y_{tr}'. This operation has been implemented using the discrete Fourier transform (Matlab) and the frequency response of the amplifier measured with a Vectorial Network Analyzer.

Since periodic signals are considered, the energy performance η_{CW} can be computed from power considerations, P_1 and P_2 considered as the power related for signal transmitted and received as described in Section 2.3:

$$\eta_{CW} = \frac{P_2}{P_1'} = \frac{V_2^2/8}{V_1'^2/8} = \frac{V_2^2}{V_1'^2} \tag{2}$$

3. EXPERIMENTAL RESULTS

In order to evaluate the strength of the wireless transmission, experiments for CW and TR have been performed for different sets of carrier frequency ranging from 2.4 GHz to 2.5 GHz see Figure 2.

3.1. Energy Performance for TR and CW Wireless Transmissions

Figure 4 shows the voltage measured in reception for TR and CW transmissions for different carriers frequency. In the case of TR, both the learning and time reversal maximum value of the received signal are reported. it is observed that the received amplitude after time reversal stage is 6 to 10 times higher from that of the learning stage.

In the case of CW transmission, one can observe that the voltage recovery strongly varies with the frequency. This behavior is due to the resonance of the cavity reported in Figure 2. In the case of TR transmission, the voltage recovery is nearly unsensitive to the effect. This is particularly striking during the learning stage and a little bit less during the time reversal stage. This result is due to the spectral properties of the signals at hand: a 10 ns pulse with a hamming window being characterized by a bandwidth of 400 MHz, a large range of frequency is investigated inside the cavity and the effects of the resonances are attenuated.

Results in term of energy performance are reported in Table 1. It appears that the absolute value of the energy performance is very weak for both CW and TR wireless transmissions. This is due to the losses inside the low-Q cavity and to the presence of obstacles between the antennas.

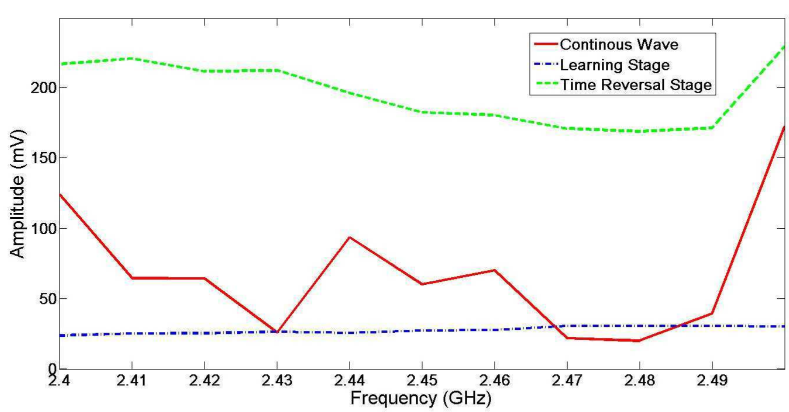

Figure 4: Voltage recovery (pk-pk) for CW and TR with different frequency carriers.

Table 1: Energy performance for CW and TR at different frequency carriers.

Frequency (GHz)	2.4	2.41	2.42	2.43	2.44	2.45	2.46	2.47	2.48	2.49	2.5
η_{TR} ($\times 10^{-4}$)	2.8	3.0	2.7	2.7	2.3	2.3	2.5	2.3	2.4	2.4	2.4
η_{CW} ($\times 10^{-4}$)	2.2	0.6	0.6	0.1	1.3	0.5	0.7	0.07	0.06	0.2	4.2
η_{TR}/η_{CW}	1.2	5.0	4.5	28.3	1.8	4.5	3.5	34.0	42.1	10.8	0.6

The efficiency depends strongly on the frequency in the case of CW transmission; this result is in agreement with the previous analysis concerning the voltage recovery. The comparison between CW and TR transmissions shows that TR transmission is generally more efficient that CW transmission: the gain in energy performance η_{TR}/η_{CW} is 4.5 at the frequency carrier of 2.45 GHz. It reaches 42.1 at the frequency carrier of 2.48 GHz. CW transmission can sometimes be more efficient: as it can be observed at the carrier frequency of 2.50 GHz. In this case the gain in energy performance is 0.6. The mean value of the gain in energy performance η_{TR}/η_{CW} calculated for the 11 frequency points reported in Table 1 is 12.4.

4. CONCLUSION

In this paper, it has been demonstrated that TR is a promising technique for wireless transmission of energy using electromagnetic waves for indoor applications. Experiments made inside of low-Q cavity of human size showed that the energy performance is in average about 10 times more efficient than for wireless transmission using CW. In this later case, there is a sensitivity with respect to the carrier frequency. The extreme situations observed for CW transmission are related to resonances inside the cavity. For future research, the spatial dimensions will have to be taken into account. A strong voltage recovery at one place inside the cavity leads to a low recovery at some other places inside the cavity due to the presence of nodes and anti-nodes. Concerning TR, the behavior is dramatically different. In addition with the temporal focusing, a spatial focusing is expected with a focal spot theoretically limited to a size of about one wavelength.

REFERENCES

1. Krikidis, I., S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng, and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," *IEEE Communications Magazine, Green Communications and Computing Networks Series*, Vol. 52, No. 11, 104–110, 2014.
2. Lerosey, G., J. De Rosny, A. Tourin, A. Derode, G. Montaldo, and M. Fink, "Time reversal of electromagnetic waves," *Physical Review Letters*, Vol. 92, No. 19, 193904, 2004.
3. Lerosey, G., J. De Rosny, A. Tourin, A. Derode, and M. Fink, "Time reversal of wideband microwaves," *Applied Physics Letters*, Vol. 88, 2006.
4. Johnson, J. M. and Y. Rahmat-Samii, "The tap monopole," *IEEE Transactions on Antennas and Propagation*, Vol. 45, No. 1, 187–188, 1997.