Time Reversed Electromagnetic Wave Propagation as a Novel Method of Wireless Power Transfer

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***Abstract*—We investigate the application of time reversed electromagnetic wave propagation to transmit energy to a moving target in a reverberant environment. "Time reversal" is a signal focusing method that exploits the time reversal invariance of the lossless wave equation to focus signals on a small region inside a complex scattering environment. In this work, we explore the properties of time reversed microwave pulses in a low-loss ray-chaotic chamber. We measure the spatial profile of the collapsing wavefront around the target antenna, and demonstrate that time reversal can be used to transfer energy to a receiver in motion. We discuss the results of these experiments, and explore their implications for a wireless power transmission system based on time reversal.**

I. Introduction

Many techniques have been proposed for wireless power transfer (WPT) ranging from magnetic resonance to microwave beaming. While the ability to transmit power practically and efficiently at short to mid-range is well demonstrated in the literature, there is relatively little prior work that retains both high efficiency and practicality at distances beyond a few meters [1].

Traditional methods of long-range WPT have relied on microwave beaming [2]. While efficient, this technique requires precise alignment of transmitter and receiver, and requires a clear line of sight propagation path. Even in those cases where line of sight might be achievable, it is highly impractical due to the danger it introduces to any humans or wildlife that might cross its path. Finding a way to transmit microwave power over long distances in a less concentrated transmission channel would be highly desirable.

Magnetic resonance beacons have been used to extend magnetic resonance coupling to longer distances. While safer than microwave beaming, these beacons still have a relatively limited range [1]. There is also interest in MIMO (Multiple Input Multiple Output) charging devices that allow for combined data and energy transfer using microwaves [3]. Other methods, such as WattUp, apply phase conjugation to the microwave signal [4], but suffer from bandwidth limitations in general [5], [6]. The efficiency and reliability of these techniques has yet to be fully explored in the literature.

In this paper, time reversal is proposed as a potential alternative to the methods described above. The method is especially well suited for ray chaotic environments, which are quite commonly found in settings where WPT technology is desired [7]. The source sends weak signals through many different trajectories in the scattering environment, spread out over an extended time period. All of these signals converge on the target location where they superimpose coherently at one instant to deliver a large burst of power. As a result energy is concentrated only at the location of the intended target, and the limitations of microwave beaming are avoided.

While there exists extensive prior work on electromagnetic time reversal [8]–[11], it remains largely unexplored in the context of WPT. For the technique to be viable, reconstructions must converge in a small region, without interfering with nearby electronics or biological matter. Here we employ a single-channel time reversal mirror to accomplish this task.

The primary advantage of time reversal in the contenxt of WPT is its ability to focus energy on a receiver anywhere in an enclosed space, even at distances well beyond the meter scale [8], [9]. This overcomes the main limitation imposed by technologies relying on magnetic near fields.

The rest of this paper is structured as follows. We begin by describing our experimental equipment and procedures in Section II. In Section III-A, we develop a model for the spatial distribution of energy around the receiver as a function of carrier signal wavelength. We then extend this model to describe the energy delivered to a moving receiver and experimentally demonstrate the collapse of time reversed energy on a moving receiver in Section III-B. In Section IV we describe a practical WPT system based on time reveresal and discuss the limitations of our experiments that should be addressed in future work. We conclude in Section V.

II. Methodology

We have investigated the applicability of time reversal to wireless power transfer (WPT) within an enclosed, reflective cavity (Fig. 1a): a 1.06 m^3 aluminum box with conductive scattering paddles to make the ray trajectories more ergodic. Ray chaos ensures that a propagating pulse will eventually reach every point in the environment. This simultaneously excites many transmission channels and thus improves reconstruction fidelity.

Two monopole antennas inject and extract electromagnetic signals from different points in the enclosure. A transmitting antenna is attached to the cavity wall opposite the receiving antenna. The receiving antenna is attached to a panel that can move vertically with a total range of 70 mm. Motion of the receiving antenna is achieved using an externally-mounted PI MikroMove `M-415.DG` translation stage and the enclosure remains sealed during the translation.

All signals are created and broadcast using a `Tektronix AWG7052` arbitrary waveform generator feeding into an

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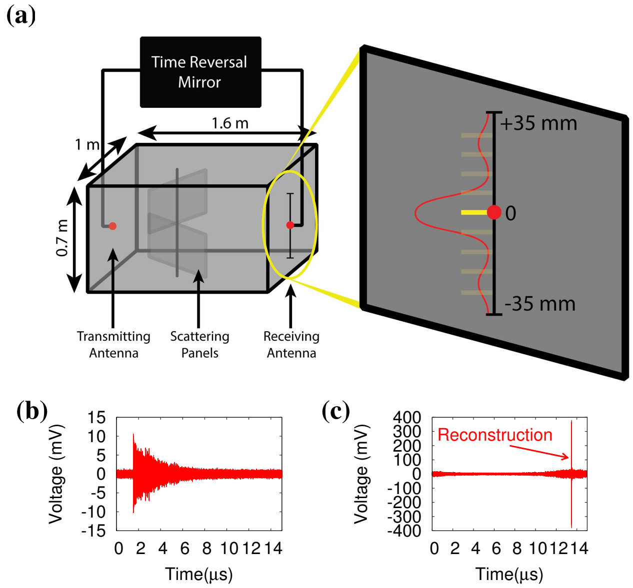

Fig. 1: (a): A ray-chaotic enclosure with two antennas, one of which is attached to a sliding panel that can move freely along the y-axis, as shown in the right inset. A time-reversed sona (b) is broadcast from the transmitting antenna, resulting in a reconstruction at the receiving antenna, shown in (c).

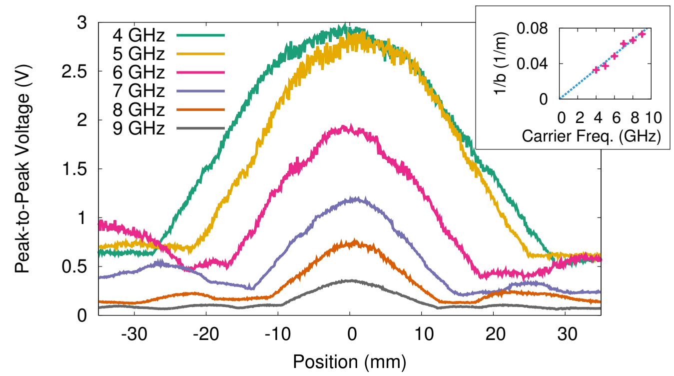

Fig. 2: Spatial profile of peak-to-peak voltage amplitudes of reconstructions at carrier frequencies ranging from 4–9 GHz in 1 GHz steps. The inset shows the inverse of the fit b value versus carrier frequency, showing the expected linear relationship. Note that the reconstruction amplitude varies with frequency as the antenna properties change.

`Agilent E8267D` Vector PSG microwave source. An `Agilent DSO91304A` digital storage oscilloscope is used to record waveforms of interest. MATLAB is used for signal processing, instrument control, and coordination.

The basic time reversal process in this environment proceeds as follows: First, a 50 ns Gaussian pulse (with a carrier frequency of 5 GHz) is injected into the cavity through the transmitting antenna. A complex time-domain signal (referred to as a "sona") is measured at the receiving antenna (Fig. 1b). This sona is the sum of the reflections of the initial pulse, scaled in magnitude due to ray-divergence and loss, and shifted in time due to differing lengths of reflection paths. In the next step, this sona is time reversed and injected into the transmitting antenna. The result is a reconstruction of the initial pulse back at the receiving antenna (Fig. 1c). This process makes use of another robust symmetry, namely the spatial reciprocity of the wave equation.

III. Results

A. Spatial Profiling

The first experiment conducted measures the spatial profile of a reconstruction with the goal of characterizing reconstruction size as a function of carrier signal wavelength. Initially, a reconstruction is focused on the receiving antenna in the middle of its movement range. Without changing the time reversed sona being broadcast, the receiving antenna is systematically translated through its entire range of movement. Samples are taken every 0.2 mm across the entire 70 mm range and the maximum peak-to-peak reconstruction voltage is recorded at each step. We repeated this experiment for carrier frequencies in the range 4–9 GHz and display these results in Fig. 2.

The reconstruction peak-to-peak voltage profile is expected to take the form of a $|sinc(x)|$ function about the antenna [12]. Thus, the following equation is proposed to predict $V(x)$, the maximum peak-to-peak voltage from a given reconstruction, as a function of x, the distance between the reconstruction focal point and the translated receiver:

$$V(x) = a \cdot \left| sinc\left(\frac{x+c}{b}\right)\right| + d\,, \qquad (1)$$

where a is the maximum peak-to-peak reconstruction amplitude, b is the wavelength of the signal divided by 2π, c is the location of the antenna along the x-axis, and d is the noise-level offset voltage.

Since b is proportional to the wavelength (and inversely proportional to frequency), as the carrier frequency is increased, $\frac{1}{b}$ also increases, causing the main lobe of the $|sinc(x)|$ function in Fig. 2 to narrow. This relationship is shown explicitly in the inset of Fig. 2.

Fig. 3 shows Eq. 1 fit to the 5 GHz curve from Fig. 2, including error bars. This fit has a reduced χ^2 of 234 due in part to the rather large background noise level. The error bars are primarily systematic, introduced by the oscilloscope's internal voltage multiplier used in scaling.

B. Moving Reconstructions

The time reversal process assumes that the environment remains fixed between the time-forward and time reversed steps. It also assumes that the source and target remain fixed between these two steps. We performed time reversal on a moving target to better understand how a translating target affects reconstruction strength.

For this experiment, the receiving antenna moved at a constant speed of 0.5 $\frac{mm}{s}$ across the entire 70 mm range

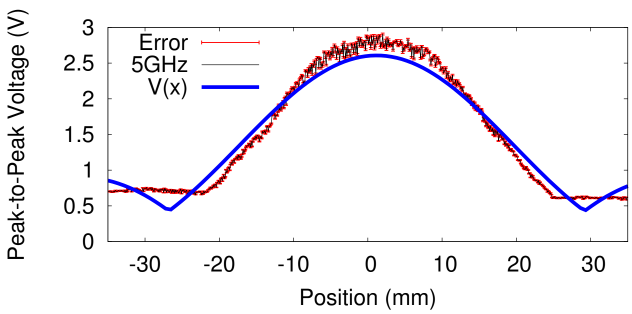

Fig. 3: Measured peak-to-peak voltage amplitude of reconstructions received in the vicinity of a time reversed wave collapse location with a 5 GHz carrier frequency, and a fit to the $|sinc(x)|$ profile from Eq. 1.

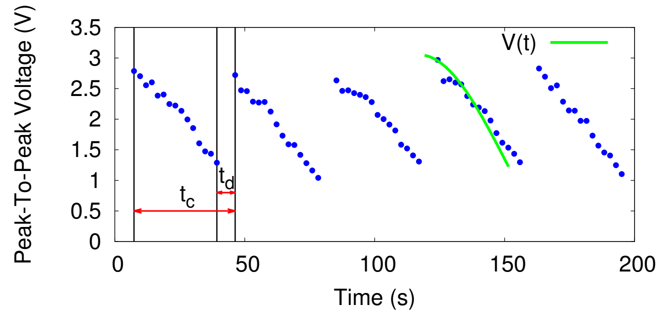

Fig. 4: Peak-to-peak reconstruction voltage measured over time as the target moves along one wall of the enclosure at 0.5 $\frac{mm}{s}$. A new sona signal is acquired every t_c seconds.

provided by the MikroMove. To counteract the degradation of reconstruction strength as the antenna moved, we periodically repeated the interrogation step, effectively re-centering the reconstruction on the antenna. Since the test equipment does not allow broadcast of one sona while collecting another, it was not possible to transmit power during the collection time, leading to a finite "dead time", denoted t_d in Fig. 4. During the broadcast period, the time reversed sona was continually broadcast into the cavity (once every 15 μs) and the peak-to-peak voltage across the receiver was measured once every 2.05 seconds, meaning that the reconstructions are highly under-sampled in this plot. After 15 samples were collected, we initiated the collection of a new sona, processed and rebroadcast it, and began again. We refer to this full process of collecting a new sona and then broadcasting it for a given period time as a full "cycle" of length t_c. The results in Fig. 4 were obtained using a carrier frequency of 5 GHz, t_d of 7 seconds, and t_c of 39.8 seconds.

Based on the results from Section III-A, the peak-to-peak reconstruction voltage measured by the receiver is expected to decay according to the $|sinc(x)|$ function as the receiver moves away from the reconstruction focal point. This $|sinc(x)|$ function will be centered on the position where the sona was last collected, making the reconstruction focus continually lag behind the antenna. Consequently, the maximum reconstruction strength is limited by the time needed to collect, time reverse and re-broadcast an updated sona.

The following equation is proposed as a model for the peak-to-peak voltage of the reconstruction on a moving target as a function of time, assuming a constant velocity $\bar{v}$:

$$V(t) = \begin{cases} 0 & : t \pmod{t_c} \leq t_d \\ a \cdot \left|sinc\left(\frac{\bar{v}t}{b}\right)\right| + d & : t \pmod{t_c} > t_d \end{cases} . \quad (2)$$

In Fig. 4, the green curve represents a fit of Eq. 2 to one full cycle. As in Fig. 3, this function fits the data well using the same parameters.

IV. Discussion

A. A Time Reveresal WPT System

This research represents a first step in the exploration of building a time reversal WPT system. We demonstrate one possible realization of this idea in Fig. 5. However, we leave optimization of performance and efficiency to future work.

The proposed system consists of two basic components. The first is a rectenna that serves as the receiver. Although the system as described in Section II would require an out-of-band feedback channel between the receiver and transmitter, prior work has shown how a transmitter can target receivers entirely in-band [9], [13]. Our system in Fig. 5 builds on these findings. The second is a transmitter that performs the time reversal process. This component is responsible for recording characteristic signals from the receiver(s), time reversing the signals, and re-broadcasting them into the environment.

In a practical system, the rectenna could be integrated into the hardware of a mobile device, or into an external component that plugs into the battery. The transmitter would need to be connected to an external power source, but could otherwise be located anywhere in the room.

Although not a component of the system, another important consideration in this scenario is the environment; a low-loss scattering environment is necessary for time reversal to be effective.

B. Limitations and Future Work

Our experiments were limited primarily by the environment and equipment used in testing. A consumer electronics environment is likely to be much larger than the chamber used in this study, and filled with clutter. Both of these properties would improve the modal density of the environment, creating more transmission channels between source and target, ultimately improving reconstruction quality. On the other hand, such environments would likely create more loss.

In our experiments, we found that approximately 0.44% of energy transmitted through our test cavity was received. Although this initial result is too low to act as the sole source of energy for a device, it may be sufficient to perform long-term trickle charging or to act as a secondary source of energy

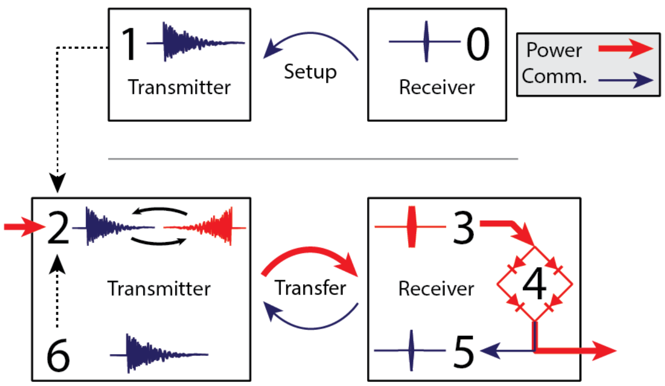

Fig. 5: A notional time reversal WPT system. In the acquistion phase, a new receiver joins the system by broadcasting or emitting a characteristic signal (0). Here, the receiver actively emits a signal, but it is also possible for the transmitter to find a passive target, as shown in [9]. In either case, the next sona that the transmitter collects will contain spatial information unique to the receiver's location (1). In the power transfer cycle, the sona is time reversed (2), amplified, and broadcast back into the environment. The amplified signal reconstructs on the receiver (3) and is converted to usable DC power by the rectifier (4). A small fraction of the signal is used to re-broadcast a new characteristic signal (5) into the environment, which will be collected in the next sona (6). The cycle repeats from (2).

for extending battery life. In order to improve efficiency, the most important area of future work would be developing a better understanding of sources of environmental loss and how to mitigate them. In addition, our experiments used a single channel, but other WPT systems, such as Cota, rely on a large number of channels [14]. Modifying the time reversal system to exploit multiple channels could improve power transmission to levels sufficient for fully powering a device.

In Section III-B, we showed that the ability of a time reversal system to transmit energy to a moving target is dependent on the spatial profile and transmission dead time, t_d. In this work, our equipment limited us to a t_d of 7 seconds, which would be too slow to handle most typical movement, such as walking across a room. The primary bottlenecks here were the communication between the oscilloscope and computer, and the fast Fourier transform (FFT) operations performed in MATLAB on the computer. A practical system could overcome these limitations by combining the two components into a single device, which would remove the communication overhead, and optimizing for the FFT computation in hardware. Once a sona has been recorded (shown in Fig. 1b to be on the order of 10 μs), the theoretical lower bound on processing time would be limited only by the amount of time required to compute an FFT.

V. Conclusion

This paper proposes time reversed electromagnetic wave propagation as a new approach for WPT. Our experiments demonstrate that the spatial profile of reconstruction voltage is very tightly confined to the area surrounding the intended receiving antenna, and roughly follows a $|sinc(x)|$ profile. Further, we successfully demonstrate the ability to focus time reversed signals onto a moving target in a ray-chaotic scattering environment. We believe that, with improvements to the transmitter and receiver, time reversal could provide a viable approach for WPT in certain environments.

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