OPTIMUM WIRELESS COMMUNICATION THROUGH UNKNOWN OBSCURING ENVIRONMENTS USING THE TIME-REVERSAL PRINCIPLE: THEORY AND EXPERIMENTS

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1. INTRODUCTION

Wireless communication in unknown and cluttered environments is an important problem which has several practical applications, such as communication in urban areas and disaster areas. This paper presents a method to maximize power transfer efficiency for communication in such environments. The method applies to communication between a transmitting array and a receiving array where the transmitting array sends out a *probe* signal, and at the receiving array, the transfer matrix can be constructed. From this measurement, we perform the time-reversal and eigen analysis. The highest eigenvalue is the best possible transmission efficiency and its corresponding eigenvector represents the transmitting excitation at the transmitting elements to achieve maximum efficiency. The nature of this method makes it possible to operate in unknown, random, and cluttered environments because the maximization is based on the measured signals. Also, this method allows for the adjustment of the system due to the change of the channel, which makes this method adaptive and robust. The time-reversal technique was introduced by Fink[1]. Then, Prada and Fink[2] illustrated the idea of time-reversal imaging to obtain selective focusing. Here, we present the theory of time-reversal communication[3]. We show relevant numerical examples and illustrate experimental verifications in a simple geometry. We further illustrate the effectiveness of this method in laboratory/office environments and in through-the-wall situations. We also investigate the effectiveness of this method in wide-band communication.

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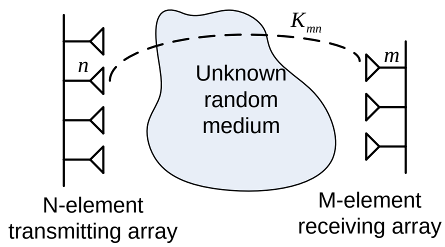


Figure 1. K_{mn} is the transfer function between the mth element of the receiver and the nth element of the transmitter. K_{mn} is measured and therefore known, even though the medium is unknown.

2. THEORY

Let us consider communication between an N-element transmitting array and M-element receiving array in an unknown environment as shown in Fig 1. When a signal is transmitted from the n^{th} element of the transmitter and received by the m^{th} element of the receiver, we can fill in the K_{mn} element of the transfer matrix $\mathbf{K}$. After measuring and constructing the $M \times N$ matrix $\mathbf{K}$, we form an $N \times N$ matrix $\mathbf{T}$ by

$$\mathbf{T} = \tilde{\mathbf{K}}^{*}\mathbf{K} \tag{1}$$

where $\tilde{\mathbf{K}}^{*}$ is the conjugate of the transpose of $\mathbf{K}$. Then, we calculate the eigenvectors $\mathbf{V}_i$ and eigenvalues λ_i from

$$\mathbf{T}\mathbf{V}_i = \lambda_i \mathbf{V}_i \tag{2}$$

The largest eigenvalue $\lambda_{\max}$ is equal to the highest transmission efficiency. Its corresponding eigenvector $\mathbf{V}_{\max}$ is to be used as the excitation at the transmitting array.

The physical meaning of $\mathbf{T}$ can be explained as follows. Assume that the transmitting array sends out a signal $\mathbf{V}_t$, then the received signal at the receiving array will be $\mathbf{V}_r = \mathbf{K}\mathbf{V}_t$. If we time-reverse this signal, which is equivalent to the complex conjugate in the frequency domain, we get $\mathbf{V}_r^*$. We then send this signal back to the transmitter. However, the transfer function from the receivers to the transmitters is $\tilde{\mathbf{K}}$. Therefore, we receive $\tilde{\mathbf{K}}\mathbf{V}_r^*$ at the transmitters. If we time-reverse this signal again, we get $\left(\tilde{\mathbf{K}}\mathbf{V}_r^*\right)^* = \tilde{\mathbf{K}}^*\mathbf{V}_r = \tilde{\mathbf{K}}^*\tilde{\mathbf{K}}\mathbf{V}_t = \mathbf{T}\mathbf{V}_t$. Prada and Fink[2] explained this method and applied it to selective focusing for imaging. We applied this to a communication problem. A quantitative measurement of the communication performance is the transmission efficiency η given by

$$\eta = \tilde{\mathbf{V}}_r^*\mathbf{V}_r \big/ \tilde{\mathbf{V}}_t^*\mathbf{V}_t = \tilde{\mathbf{V}}_t^*\tilde{\mathbf{K}}^*\mathbf{K}\mathbf{V}_t \big/ \tilde{\mathbf{V}}_t^*\mathbf{V}_t = \lambda \tag{3}$$

The maximum efficiency can be achieved by the largest eigenvalue $\lambda_{\max}$.

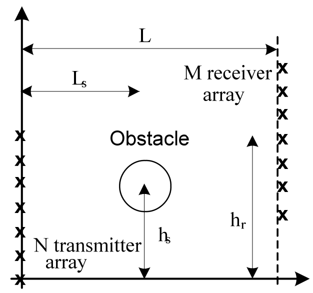


Figure 2. A spherical obstacle with radius a is located between N transmitter array and M receiver array. The spacing between the elements is $\lambda / 2$.

3. NUMBERICAL CALCULATIONS AND EXPERIMENTS

Consider communication in the geometry shown in Fig. 2. For this geometry, we can calculate the received signals and estimate the transmission efficiency. The element of the transfer matrix K_{mn} can be calculated by

$$K_{mn} = G_o(m,n) + G_s(m,s,n) \tag{4}$$

where $G_o\left(m,n\right) = \exp\left(-jkl_{mn}\right)\big/4\pi l_{mn}$, $G_s(m,s,n) = \sum_{n=0}^{\infty} A_n h_n^{(2)}(k, l_{ms}) P_n(\cos\theta)$, $A_n = -\left(2n+1/4\pi\right)\left(-jk\right) j_n(ka) h_n^{(2)}\left(kl_{sn}\right)\big/h_n^{(2)}\left(ka\right)$ where $h_\nu^{(2)}\left(x\right)$, $j_n\left(x\right)$ are the spherical Bessel functions which relate to the ordinary Bessel functions by $h_\nu^{(2)}\left(x\right) = \sqrt{\pi/2x} H_{\nu+1/2}^{(2)}(x)$, and $j_n\left(x\right) = \sqrt{\pi/2x} J_{n+1/2}(x)$. $G_o\left(m,n\right)$ is the Green's function of the free space propagation and $G_s(m,s,n)$ is the result from the scattering from the conducting sphere. Experimental set up for verification is shown in Fig. 3.

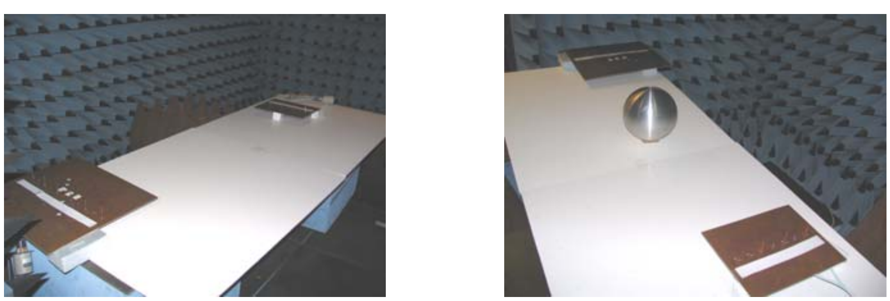


Figure 3. Experimental verifications in the anechoic chamber. Left: free space, Right: around conducting sphere.

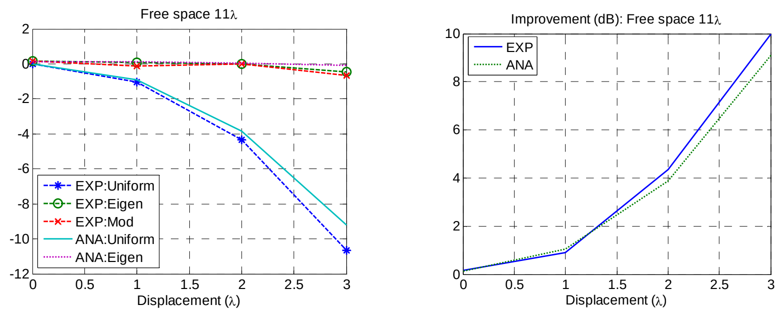


Figure 4. Communication efficiency comparison in the free space case. Left: analytical solution vs experimental data, Right: the improvement of the efficiency comparison.

The communication efficiency is shown as a function of the displacement of the receiving array from the aligned position. The communication efficiency shown is normalized to the free space case in the aligned position. The comparisons show *uniform* as the case where each element of the transmitting antenna radiates the same energy, and *eigen* as the maximum achievable efficiency based on calculations, i.e. $\lambda_{\max}$. The *modify* represents the communication efficiency when the transmitting antenna is excited according to the time-reversal and eigen analysis ($\mathbf{V}_{\max}$).

The results are shown in Fig. 4 for free space and Fig. 5 for the conducting sphere. *ANA* denotes analytical solution and *EXP* indicates experimental data. In both the free space and the conducting sphere cases, excellent agreement between experimental data and the analytical solution is observed. Thus, this shows that the method improves the communication efficiency even in the situation where the line of sight of communication has been obstructed and the improvement is as expected from the analytical solution.

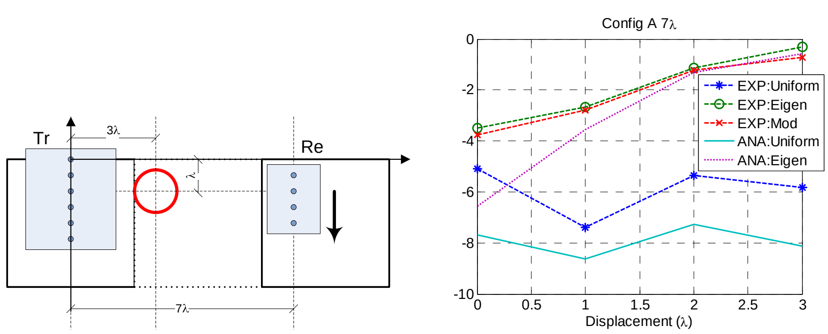


Figure 5. Communication efficiency comparison in conducting sphere cases. Left: schematic of the experimental setup, Right: the efficiency comparison.

Figure 6. Experimental setup in the office/laboratory environment.

We also perform experiments in the laboratory/office environments as shown in Fig. 6. Here, we construct four-element dipole antenna arrays operating at 1 GHz at both the transmitter and the receiver. We test the algorithm in the office/laboratory environments where there are desks, shelves, and experimental apparatus. By moving the transmitter and the receiver in several configurations, we measure the received power when fixing the total transmitting power so that we can quantify the power transmission efficiency. The results in Table 1 show that using the time-reverse eigen value method, we can achieve more efficiency than uniform amplitude scheme.

Table 1. Experimental data for the office/laboratory environment

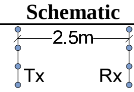
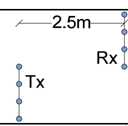
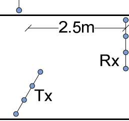
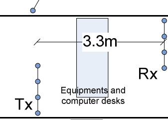
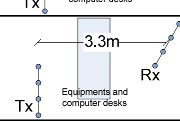
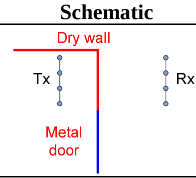
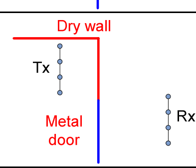
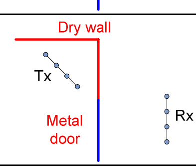
Configuration	Schematic	Efficiency
Aligned		Uniform: 9.3155 Eigen: 10.0225 Modify: 9.6140
Off set		Uniform: 1.8277 Eigen: 6.2069 Modify: 6.3309
Off set with angle		Uniform: 0.3483 Eigen: 1.6683 Modify: 1.2130
Through obstacles – off set		Uniform: 0.3217 Eigen: 0.8358 Modify: 0.6413
Through obstacles – off set with angle		Uniform: 0.3831 Eigen: 0.7055 Modify: 0.5114

Figure 7. Experimental setup in the through-the-wall situation. Left: transmitting unit, Right: receiving unit.

Similarly, we perform the experiment in the through-the-wall situation where the transmitting array and the receiving array are separated by a dry wall. The experimental set up for this situation is shown in Fig. 7. The results of the experiments are listed in Table 2. The eigen method shows significant improvement in the case where the transmitters and the receivers are off-set with angle. In this particular case, the energy from the transmitters is not focused at the receivers in the uniform case. Therefore, the efficiency decreases dramatically. However, when using the eigen method, we can focus the energy more efficiently which results in substantial improvement shown in efficiency numbers.

Table 2. Experimental data for the through-the-wall situation

Configuration	Schematic	Efficiency
Aligned		Uniform: 1.2082 Eigen: 14113 Modify: 1.356
Off set		Uniform: 1.3822 Eigen: 1.6459 Modify: 1.4668
Off set with angle		Uniform: 0.1223 Eigen: 0.8095 Modify: 0.8754

We also perform numerical calculations for a wide-band signal with a bandwidth of 20% of the center frequency when the signal is communicated through an obstructing sphere as shown in Fig. 2. The transmission efficiency as a function of frequency is plotted in Fig. 8. Here, *Eigen-cf* denotes the method where the eigen analysis is performed based on the center frequency data and the eigenvector is used in every frequency. *Eigen* is the calculation where the eigen analysis is performed at every frequency. The results show that the transmission efficiency drops off slowly as the frequency is away from the center frequency, indicating that the wide band communication is possible.

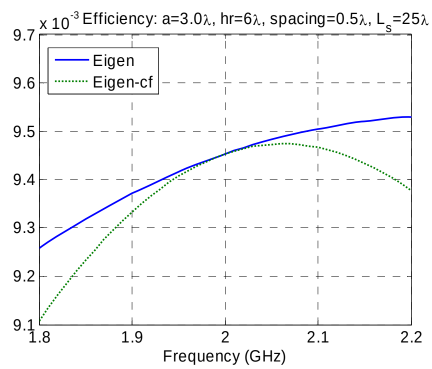


Figure 8. Wide-band calculations.

4. CONCLUSION

In this paper, we present a method to maximize the communication power transfer efficiency through an unknown, random environment. The method is based on time-reversal and eigen analysis. The performance improvement is calculated in a simple case of an obstructing conducting sphere and is verified through experiments. The experiments also include communication in the office/laboratory environments and through-the-wall situations. It is shown that the communication efficiency can be greatly improved using this method. Also, we study the efficiency of this method in the wide-band signals and show that the efficiency slowly drops off away from the center frequency indicating that it is possible to apply this method to a wide-band communication without losing much efficiency. Further studies on signal to noise ratio and dispersion are being conducted for practical applications of this theory.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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