# Optimum wireless communication through unknown obscuring environments using the time-reversal principle: theory and experiments

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## 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 optimize communication efficiency in such environments. The method applies to communication between a transmitting array and 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 time-reversal and eigen analysis. The highest eigen value is the best possible transmission efficiency and its corresponding eigen vector represents the transmitting excitation at the transmitting elements to achieve maximum efficiency. The nature of this method makes it possible to operate and optimize in unknown, random, and cluttered environments. 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],[4], show relevant numerical examples, and illustrate the experimental verification.

## A method of optimizing communications

Let us consider communication between a *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 $\mathbf{K}$.

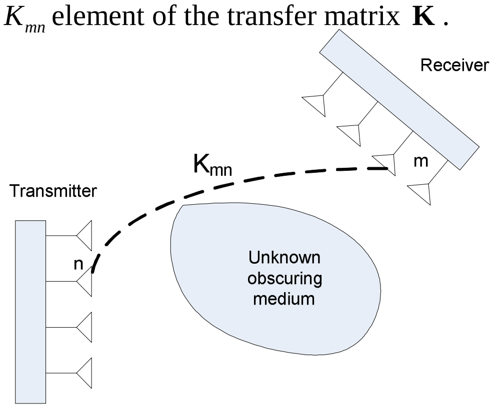



Fig. 1: $K_{mn}$ is the transfer function between the m$^{th}$ element of the receiver and the n$^{th}$ element of the transmitter. $K_{mn}$ is measured and therefore known, even though the medium is unknown.

After measuring and constructing the $M \times N$ matrix $\mathbf{K}$, we form an $N \times N$ matrix $\mathbf{T}$

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

where $\tilde{\mathbf{K}}^*$ is the conjugate of the transpose of $\mathbf{K}$. Then, we calculate the eigenvectors $\mathbf{V}_i$ and eigenvalues $\lambda_i$ 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 communication and showed that the largest eigen value equals to the highest transmission efficiency.

## Numerical calculations and experimental verifications

Consider communication in the geometry shown in Fig. 2. For this geometry, we can calculate the received signals and, thus, estimate the transmission efficiency.

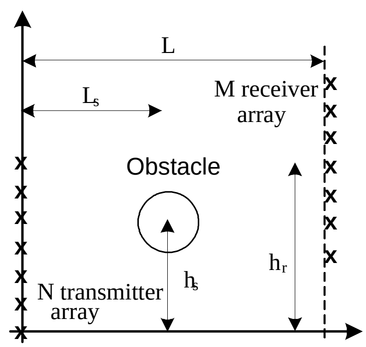



Fig. 2: A spherical obstacle with radius $a$ is located between $N$ transmitter array and $M$ receiver array. The spacing between the elements is $\lambda/2$.

The element of the transfer matrix $K_{mn}$ can be calculated by

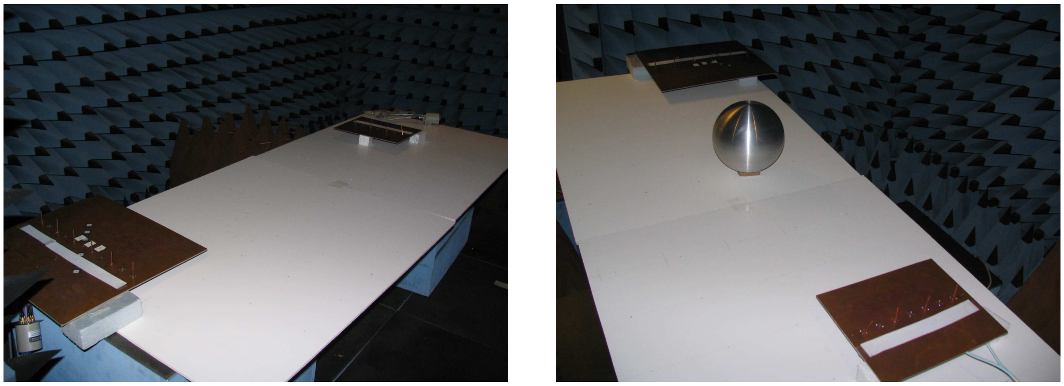
$$K_{mn} = G_o(m,n) + G_s(m,s,n) \tag{3}$$

where

$$G_o(m,n) = \frac{\exp\left(-jkl_{mn}\right)}{4\pi l_{mn}}, \quad G_s(m,s,n) = \sum_{n=0}^{\infty} A_n h_n^{(2)}(k, l_{ms}) P_n(\cos\theta), \text{ and}$$

$$A_n = \frac{-\left(\frac{2n+1}{4\pi}\right)(-jk)\, j_n(ka) h_n^{(2)}\left(kl_{sn}\right)}{h_n^{(2)}\left(ka\right)}$$

For experimental verifications, we construct a 6-element monopole array antenna at the transmitter and we use a 4-element monopole array antenna at the receiver. The communication frequency is 2 GHz. The experiment is performed in an anechoic chamber to reduce multiple scattering and noise from other sources. The picture of the experiment setup is shown in Fig. 3



(a) (b)

Fig. 3: Experimental verifications in anechoic chamber. (a) free space, (b) around conducting sphere

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 calculation, 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. For the free space case, excellent agreement between experimental data and the analytical solution is observed. We notice that using the method explained above, we can achieve an improvement of almost 10 dB. In the conducting sphere cases, there is a good agreement between experimental data and analytical solutions. 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.

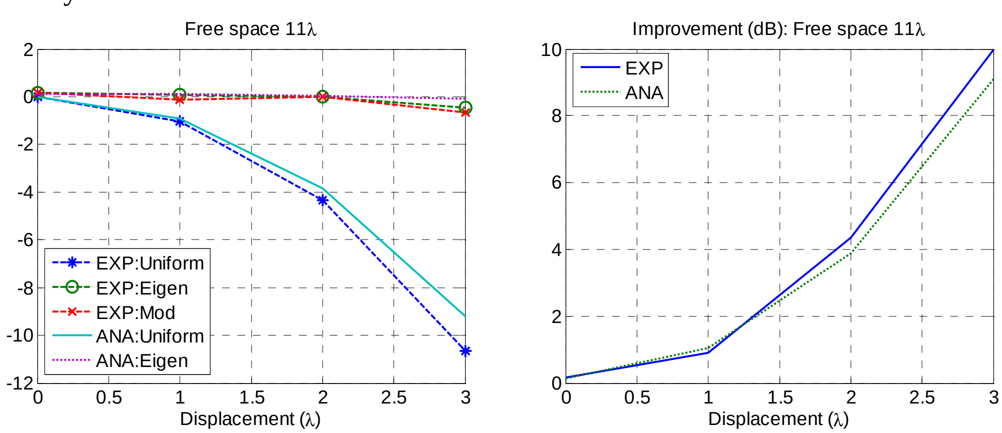



Fig. 4: Communication efficiency comparison: free space case

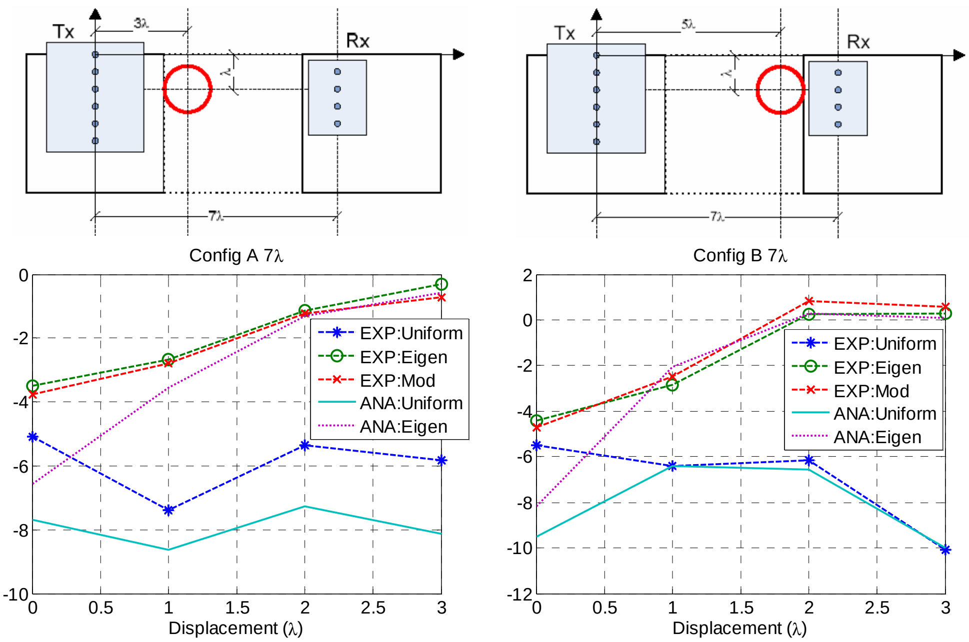



Fig. 5: Communication efficiency comparison: conducting sphere cases

## Conclusions

In this paper, we present a method to maximize the communication efficiency through an unknown, random environment. The method is based on time-reversal and eigen analysis. The performance improvement is verified through experiments. The experiments include communications around obstacles, through an opening, and through a wall. It is shown that the communication efficiency can be greatly improved using this method. Further studies on signal to noise ratio and dispersion are being conducted for practical applications of this theory.

## Acknowledgement

This work is supported by the Office of Naval Research (Grant # N00014-04-1-0074 and Code 321 Grant # N00014-05-1-0843)

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