Super-resolution Focusing and Nulling in Rich Multipath Environments using Time-Reversal Techniques

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Abstract **– Super-resolution focusing and nulling experiments are described based on multipath-enhanced time-reversal techniques. Using these techniques, two independent 2.45 GHz signals focused at locations separated by 5 cm at a distance of 6.7 m are successfully demodulated.**

1 INTRODUCTION

Traditionally, multipath propagation in RF networks is viewed as undesirable, and considerable effort has been expended developing technologies that are robust in such environments. More recently, it has been recognized that multipath can actually be used to enhance the reliability and capacity of wireless networks [1]. A new approach enabling the exploitation of multipath to enhance wireless channels is referred to as *time reversal*.

Time reversal techniques have been used extensively in acoustics [2]. In the basic configuration, a short pulse is transmitted from a beacon location, and the signal from this beacon is recorded at multiple receive sensor locations. If the signals received by each sensor are time-reversed and retransmitted simultaneously, a portion of the signals transmitted from the array will retrace their initial paths, and combine constructively at the location of the original beacon. In this way, the signal can be focused both in space and time at a desired location. In an environment free of obstructions, the focusing will be determined by the effective numerical aperture of the sensor array as viewed from the beacon location. Specifically, the cross-range size of the focused spot in space is given by the Rayleigh criterion $1.5\lambda L/D$, where λ is the wavelength, L is the distance from the beacon to the array, and D is the size of the array aperture. Intuitively, one would expect the presence of obstructing and reflecting objects to impair the focusing. However, as illustrated in Figure 1, if the phases of the scattered rays are set so that constructive interference occurs, the presence of scattering objects can actually improve focusing by increasing the effective numerical aperture!

This has clear implications for communications. For example, Derode and coworkers [2] have shown that a dense array of scattering rods makes it possible to focus acoustic signals in water onto individual transducers that cannot be resolved in the absence of the rods. Using this effect, they showed that it was possible to send five parallel streams of information when the rods were present, while only one could be sent with a clear line-of-sight without the rods.

Until very recently, these effects had not been shown using radio waves, since it was believed that fractional bandwidths larger than could be realized with existing technology would be required. However, Lerosey et al. [3] showed that time reversal focusing of electromagnetic waves is possible using 1 MHz bandwidth signals in a reverberant chamber. Further, using frequency-domain techniques, super-resolution focusing of radio signals in an ordinary indoor environment was demonstrated in our laboratory [4].

In this paper, we review recent work at Carnegie Mellon demonstrating both focusing and nulling of radio signals, and discuss applications to wireless networks.

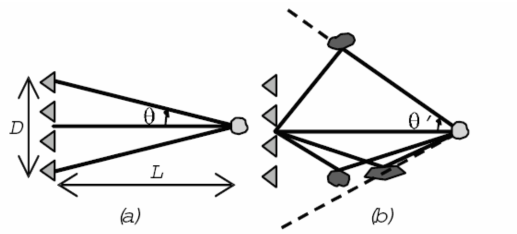

Figure 1. (a) The size of a focused spot from an array depends on the ratio L/D. (b) The effective aperture of the array can be increased using multipath reflections, thereby making the focused spot smaller. (From [4])

2 TIME-REVERSAL FOCUSING

Time-reversal focusing of radio waves is done using the same procedure used with acoustic waves. Specifically, a beacon signal is sent from the target location, and the signals received at one or more antennas comprising a focusing array are recorded. These recorded signals are then time-reversed and retransmitted from the array antenna elements. To verify focusing in space and time, a probe antenna is then moved through the region surrounding the beacon location.

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2.1 Time Domain Experiments

The setup used for time domain experiments is shown in Figure 2. First, the digital signal generator was programmed to transmit a Gaussian pulse with a duration of 100ns and a 3-dB bandwidth at baseband of 8 MHz. The corresponding RF pulse had a center frequency of 2.45 GHz and a 3-dB bandwidth of 16 MHz. The channel response was downconverted and decomposed into I and Q components with a vector signal analyzer. The I and Q signals were then transfered to a computer and time-reversed. The digital signal generator was then programmed to generate a signal with inphase and quadrature components of I(-t), -Q(-t). To investigate the focusing, the receiving probe was then moved longitudinally about the original location. (Note that owing to reciprocity, it is actually not necessary to interchange the location of the transmitter and receiver for the time reversal step.) Figure 3 shows the observed focusing in both space and time.

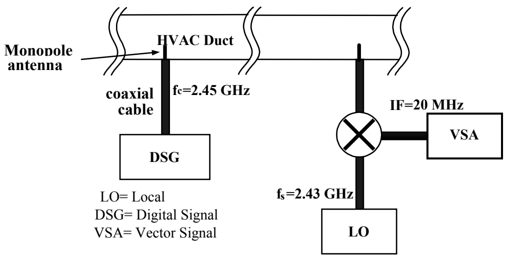

Figure 2. Setup for time domain experiments. The measurements were made in an overmoded waveguide chamber formed by a section of HVAC duct with metal endcaps. (From [5])

Note that the focusing was achieved with only one antenna transmitting a time-reversed signal. This was possible because of the bandwidth of the signal. For the duct cavity, the 50% coherence bandwidth was measured to be 5.7 MHz, so the focusing was achieved with approximately 3 degrees of freedom, even though only one transmit antenna was used.

2.2 Frequency Domain Experiments

In the frequency domain, time-reversal is accomplished by retransmitting the complex conjugate of the received signal at each frequency. This is the principle used for retroreflective arrays [6]. In a free-space environment, the result is the retransmission of a plane wave back into the direction from which it was received. The behavior of retrodirective arrays in multipath environments has also begun to receive attention [7]. In particular, we have demonstrated super-resolution focusing using a four-element array in a cluttered laboratory environment, as shown in Figure 4. The line of sight was blocked by a metal plate as well as by furniture in the room, so the received signal resulted entirely from multipath.

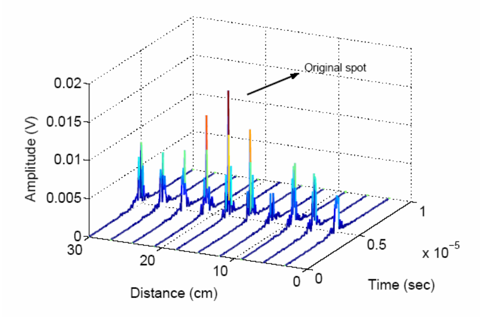

Figure 3. Focusing in space and time measured at positions along the length of the duct. (From [5])

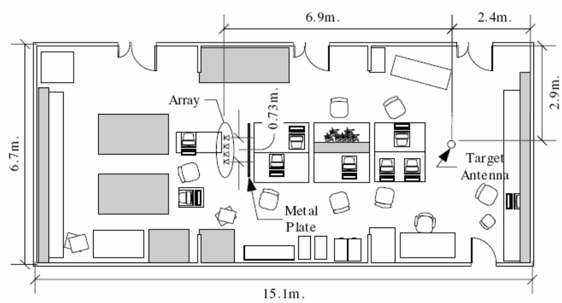

Figure 4. Laboratory environment used to focus RF energy on the target antenna location on the right, using frequency-domain time-reversed signals from the array just to the left of center. (From [4])

The measurements were made by moving the target antenna on a nine-by-nine grid, with 5 cm between grid points. The conjugate amplitudes were set using vector IQ modulators, and the received signal was characterized using a vector network analyzer, as shown in Figure 5. The frequency was 2.45 GHz.

The observed super-resolution focusing can be seen in Figure 6. The null-to-null width in the cross-range direction (vertical in Figure 6) is approximately 12 cm. In contrast, focusing resolution without multipath is determined by the Rayleigh criterion stated earlier. In our experiment, λ = 12.2 cm, L = 6.7 m and D = 0.73 m, giving a null-to-null spacing of 1.73 m, or more than an order of magnitude larger than that observed using multipath-enhanced time-reversal focusing.

In contrast to the time-domain experiments, the frequency-domain experiments described in this section used a single frequency. In this case the degrees of freedom used to achieve focusing came from the use of four antennas. In general, focusing can be further enhanced by simultaneously using degrees of freedom from multiple antennas and bandwidth.

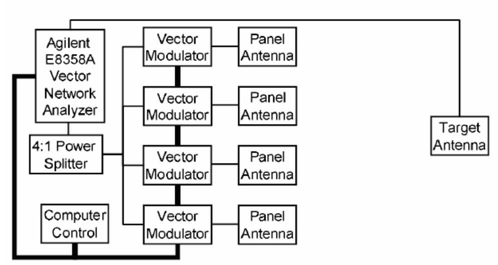

Figure 5. Setup for RF super-resolution focusing experiments in the frequency domain. (From [4])

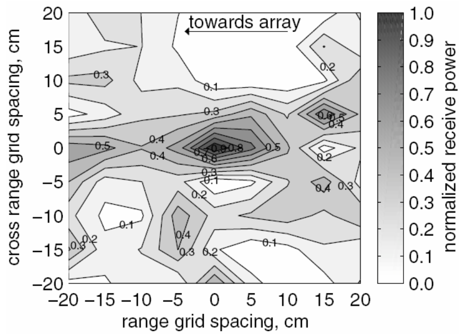

Figure 6. Super-resolution focusing of a 2.45 GHz signal from multipath in the cluttered laboratory environment shown in Figure 4. (From [4])

3 TIME REVERSAL NULLING

It is also possible to modify the time-reversal process to force a null at a target location rather than a focused spot. As before, this can be done in either the time domain, or in the frequency domain.

3.1 Time Domain Experiments

The apparatus and procedure for demonstrating nulling in the time domain is identical to that used for focusing (see Figure 2), except that the time-reversed waveform is altered to cause destructive rather than constructive interference at the target location. One way to do this is to introduce a π phase shift in the time-reversed signal at the point in the waveform at which exactly half of the total pulse energy has been sent. The time-reversed signal is extended in time compared to the original pulse owing to the multipath echoes. After passing back through the channel, this dispersion is reversed, collapsing the energy back into a narrow pulse. However, because of the additional π phase shift between the two "halves" of the signal, the fields from the multiple paths cancel, leading to a null instead of a focus. The resulting signal that is nulled in both space and time is shown in Figure 7.

It should be noted that the phase shift technique used here illustrates the concept, but may not be the optimum way of achieving a null. This is a topic of on-going research.

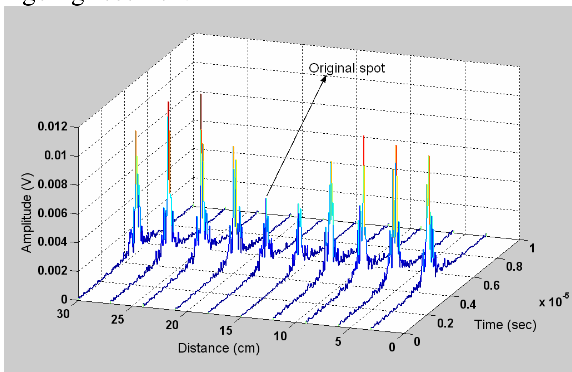

Figure 7. Time reversal nulling in space and time using the setup shown in Figure 2. (From [5])

3.2 Frequency Domain Experiments

Frequency domain nulling experiments were performed using the same setup shown in Figure 4 and Figure 5, except that the retransmitted signals were again altered to achieve destructive rather than constructive interference. First, the amplitudes of the retransmitted signals were determined by the *inverse* of the received signals, and second, a π phase shift was introduced to every other antenna in the panel array.[†] The amplitude renormalization equalized the channel so that each antenna made an equal contribution to the total field at the target location, and the π phase shift on alternating antennas ensured cancellation at the target location. The resulting nulled spot is shown in Figure 8.

As with the time-domain nulling experiment, the procedure described here illustrates the concept, but may not be the optimum algorithm.

4 COMMUNICATIONS APPLICATIONS

The ability to focus and null signals within regions of the order of a wavelength at arbitrary distances from the transmitter has significant implications for communications. For example, separate signals could be sent to multiple closely-spaced locations using the same carrier frequency. This could enable increased capacity to a single user with multiple antennas, or reduced interference between multiple users in close proximity to one another.

To demonstrate this concept, the geometry illustrated in Figure 4 was used but with the more complex RF feed network shown in Figure 9 [4]. In this setup, two distinct RF signals were generated

[†] Also, the metal plate blocking the line-of-sight was placed just to the left of the target antenna instead of just to the right of the panel antenna array. This difference is not significant for the experiment.

with the same carrier frequency: a 1 Mbps frequency shift keying (FSK) signal with 1 MHz frequency deviation, and an analog FM signal with 1 MHz frequency deviation modulated with a 1 MHz sinusoid. These two signals were fed into two separate IQ modulator arrays—each set to focus on a different location separated by 5 cm in the cross-range direction. The vector signal analyzer was used to measure the signal-to-interference ratio (SIR) at each location, and the bit error rate (BER) of the demodulated FSK signal. In the cluttered environment, the SIR at the two locations were 15.5 dB and 11.2 dB. This resulted in BERs of 0.1% and 2.2%, respectively. For comparison, all of the furniture and obstructions were removed from the center of the laboratory, restoring the line-of-sight and minimizing multipath. In this configuration, the SIR at the two antennas was 1.9 dB and 0.2 dB respectively. In this case, the digital signal could only be demodulated for the SIR 1.9 dB location, and then with a relative high error rate of 4.5%.

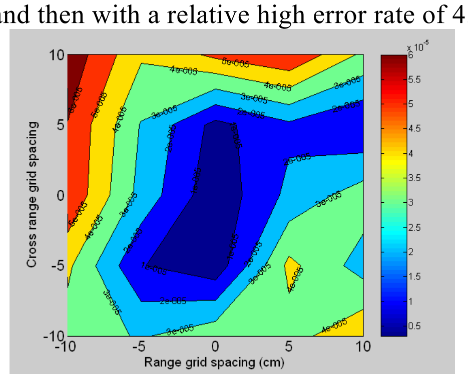

Figure 8. Null created by alternating phases and renormalizing the amplitudes used with the array of Figure 4.

5 CONCLUSIONS

Time-reversal techniques show significant promise for improving the capacity and performance of wireless communications networks operating in rich multipath environments. The enhanced performance results from the ability to focus or null signals within a region on the order of the wavelength in extent—regardless of the distance between the transmit array and the target location of interest.

This super-resolution focusing and nulling has been experimentally demonstrated both in the time domain and the frequency domain, using degrees of freedom arising from the bandwidth used, or the number of antennas in the transmitting array.

The applicability to communications systems has been demonstrated by successfully transmitting separate RF signals on the same frequency to two locations separated by 5 cm at a distance of 6.7 m in an indoor environment with no line-of-sight.

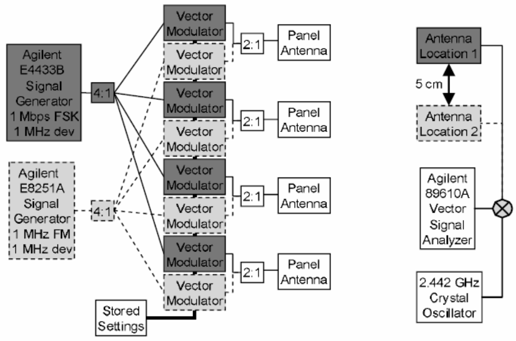

Figure 9. Apparatus used to send separate signals to two separate locations separated by 5 cm, using frequency domain time reversal techniques. (From [4])

Acknowledgments

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