# Bandwidth Limitations of Phase-Conjugate Arrays Used for Multipath Focusing

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**Abstract**

This work explores the bandwidth limitations of phase-conjugate arrays used as a multiple access technique in an indoor, multipath rich environment. A single, phase-conjugating array with two sets of complex coefficients was used to create separate communications channels to receivers located approximately one half wavelength apart and operating at the same frequency. Results are presented showing the variation in the multipath enhanced spatial focusing across the bandwidth of the signals. Our results indicate that with a four-element transmit array, the isolation between the two channels was measured to be about 10 dB over a bandwidth of 15 MHz.

## Introduction

Traditionally, multipath propagation is thought to have an adverse effect on the reliability and capacity of a wireless channel. However, recent research has focused on using multipath to enhance the radio channel. For example, it has been shown that if multiple transmit and receive antennas are used, multipath propagation can be exploited to realize multiple simultaneous information channels [1, 2, 3]. In our work we have used a phase-conjugating array to simultaneously spatially focus power at two different but closely located receivers in an indoor, multipath environment. Further, we quantify the frequency bandwidth over which this spatial focusing occurs and the isolation and usable bandwidth that can be achieved.

Phase-conjugate techniques have long been used in electromagnetics at both radio and optical frequencies. Phase-conjugate electromagnetic antenna arrays were developed in the early 1960s [4, 5, 6], and have been used extensively as retroreflective arrays. The use of radio frequency retroreflecting arrays in multipath environments has recently begun to receive attention. Karode [8] discussed the use of phase-conjugate arrays as multipath sensors, and Tuovinen, et al [9] showed that radio links using a phase-conjugate array resulted in significantly less fading caused by multipath propagation. Further, in [10] we have shown that phase-conjugate techniques benefit from multipath scattering to create an improvement in spatial focusing in an indoor environment.

The size of the multipath focused spot is significantly smaller than what is predicted by the Rayleigh criterion (i.e. cross-range focusing) and the depth of focus (i.e. range focusing). The Rayleigh criterion states that the minimum resolution is limited by $\frac{0.6\lambda}{NA}$ where $\lambda$ is the RF wavelength, and $NA$ is the numerical aperture. In free space $NA = sin(\theta)$, where $\theta$ is the half-angle subtended by the antenna array as viewed from the target antenna, as shown in Figure 1(a). Thus, it can be seen from Figure 1(b) that an increase in scatterers in the environment should allow an increase in the effective numerical aperture of the antenna array. However, the minimum size of the focused spot remains of order one half wavelength or greater.

## Experiment

A cluttered laboratory setting, as shown in Figure 2, was used for the phase conjugate array measurements. A four element antenna array consisting of 9 dBi panel antennas was used to focus power at two target antennas. A 2 dBi discone was used as a target

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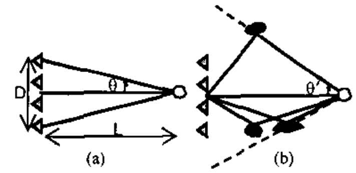


Figure 1: The numerical aperture of an antenna array, (a), and the enhancement of the numerical aperture of an antenna array due to the salutary use of multipath, (b).

antenna and moved to various locations in a cross-range direction to the array. To increase the effects of multipath, a large metal plate was placed about 1 meter in front of the antenna array. Power splitters and matched length cables were used to feed each array antenna element with matched magnitude and phases as shown in Figure 3. A vector modulator was used with each element to provide magnitude and phase offsets between antennas. The modulator multiplies an RF signal by a complex exponential, $Ae^{j\theta}$. The modulators are capable of attenuations, $A$, of 0 to 70 dB and phase shifts, $\theta$ of 0 to 360 degrees with an accuracy of $\pm$ 0.2 dB and $\pm$ 5 degrees and higher granularity.

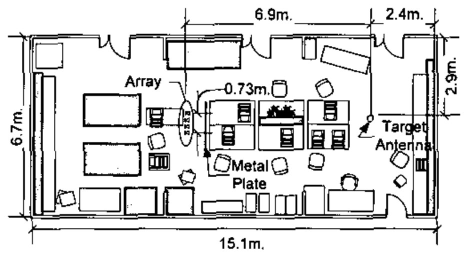


Figure 2: Schematic of laboratory in which experiments were performed. The clutter and metal plate obstructing the line of sight path encourage multipath propagation.

A vector network analyzer, shown in Figure 3, was used to measure the magnitude and phase of the frequency response between the antenna array and target antenna. To compute the phase-conjugate settings, the network analyzer measured the magnitude and phase of the channel between each antenna element and the desired target location at a single frequency of 2.45 GHz. Each antenna was measured individually by setting all but a single vector modulator to maximum attenuation. After measuring, the computed gain and conjugate phase complex coefficient was loaded into each vector modulator. The network analyzer was then used to measure the communications channel.

To quantify the potential bandwidth of spatial focusing, measurements of the received power were made in a range of frequencies about the focus frequency and at several locations in the cross-range direction about the target antenna location. The results of these measurements are shown in Figure 4. As can be seen from the figure, a definite focusing of power is present at the target location and frequency. Also, the spatial half power bandwidth is consistently about 5 cm for a band of frequencies about the focus frequency. This indicates the multipath focusing phenomenon is valid for a range of frequencies, not just the focus frequency, despite the constant phase shift with frequency provided by the vector modulators. It is also interesting to note that the best focusing occurs at a frequency other than the focus frequency.

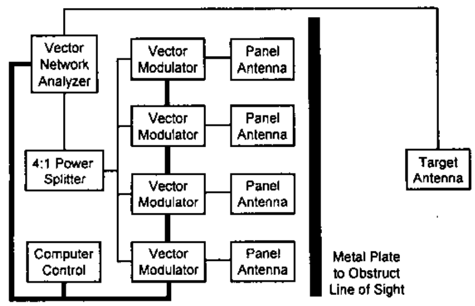


Figure 3: Setup of apparatus for experiment. All cables were matched lengths.

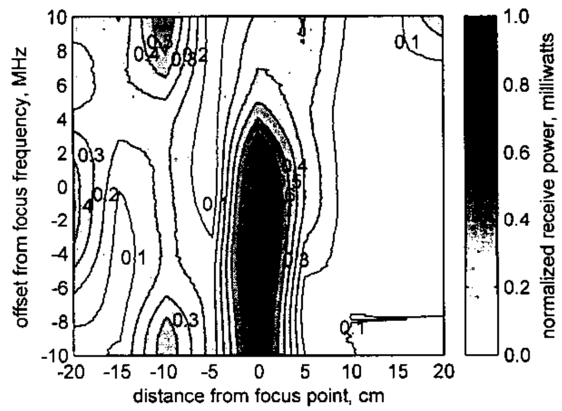


Figure 4: Focusing effect in the cross-range direction by multipath focusing for band of frequencies about focus frequency used to compute conjugate-phase coefficients.

To measure the isolation the focusing seen in Figure 4 could provide to two nearby antennas, phase-conjugate coefficients were computed using measurements for two target locations separated by 5 cm in the cross-range direction. Four frequency responses were then measured using the target 1 and target 2 phase-conjugate coefficients with the target antenna at locations 1 and 2. These four cases allow the comparison of the isolation that would be provided if 8 vector modulators were used to simultaneously create different communications channels to the two target locations. The channel response measurements are shown in Figure 5. From the figure, it is clear that 10 dB or more of isolation is present between the two target antenna locations over a bandwidth of about 15 MHz centered at the calibration frequency. This appears to be consistent with Figure 4, which showed the isolation measured at location 1. This isolation could be improved by adding additional elements to the phase-conjugate antenna array.

In conclusion, we have shown that phase-conjugate techniques can provide a spatial focusing of power in a multipath environment across a band of frequencies. The isolation between two target locations spaced slightly less than one-half wavelength apart was found to be more than 10 dB over a frequency range of about 15 MHz at 2.45 GHz. Thus, two independent information channels have been demonstrated between a

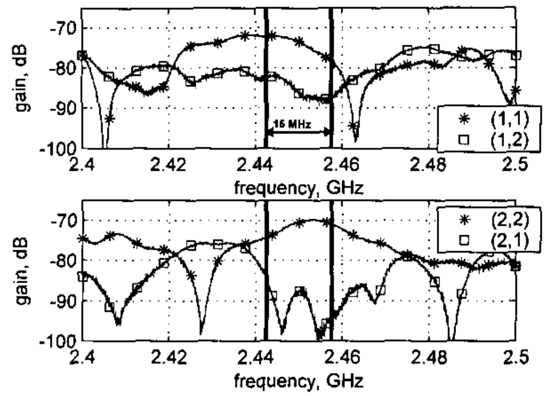


Figure 5: Measured channel responses for different target locations. The legend indicates the measured target location and the intended target location.

phase-conjugate array and closely-spaced target antennas, and the bandwidths of these channels are sufficient to support data rates of practical interest.


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## References


[1] G. J. Foschini and J. J. Gans, "On limits of wireless communication in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, pp. 311-335, Mar. 1998.

[2] E. Telatar, "Capacity of multi-antenna gaussian channels," *Eur. Trans. Telecommun.*, vol. 10, no. 6, pp. 585-595, 1999.

[3] A. L. Moustakas, H. U. Baranger, L. Balents, A. M. Sengupta, and S. H. Simon, "Communication Through a Diffusive Medium: Coherence and Capacity," *Science*, vol. 287, no. 5451, pp. 287-290, 14 January 2000.

[4] L. C. Van Atta, "Electromagnetic Reflector," *U.S. Patent*, No. 2,908,002, Oct. 6, 1959.

[5] C. Y. Pon, "Retrodirective array using the heterodyne technique," *IEEE Trans. Ant. & Prop.*, vol. AP-12, pp. 176-180, March 1964.

[6] R. Y. Miyamoto and T. Itoh, "Retrodirective arrays for wireless communications," *IEEE Microwave Mag.*, vol. 3, no. 1, pp. 71-79, Mar. 2002.

[7] A. Yariv and D. M. Pepper, "Amplified reflection, phase conjugation, and oscillation in degenerate four-wave mixing," *Opt. Lett.*, vol. 1, no. 1, pp. 16-18, July 1977.

[8] S. L. Karode and V. F. Fusco, "Use of an active retrodirective antenna as a multipath sensor," *IEEE Microwave and Guided Wave Letters*, vol. 7, pp. 399-401, Dec. 1997.

[9] J. Tuovinen, G. S. Shiroma, W. E. Forsyth, and W. A. Shiroma, "Multipath Communications Using a Phase-Conjugate Array," *IEEE MTT-S Digest*, p. 1681-1684, 2003.

[10] B. E. Henty and D. D. Stancil, "Multipath Enabled Super-Resolution for RF/Microwave Communication Using Phase-Conjugate Arrays", *Phys. Rev. Lett.* (submitted for publication).