Smart and multibeam diversity antenna arrays with high-bandwidth analog signal processing

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I. INTRODUCTION

This talk will present an overview of the work done at the University of Colorado at Boulder in the area of smart and multibeam antennas, specifically as related to the following projects, funded by the NSF Wireless Initiative:

1. *Multibeam lens antenna arrays and reconfigurable antennas for wireless communications with diversity*. Design and characterization of a 10-GHz multibeam array with two different diversities – polarization and angle – will be presented. A new method of using random reconfiguration of a simple antenna to increase capacity will be discussed. This work was done in collaboration with the University of Wisconsin (Profs. Hagness, Van Veen and Sayeed).

2. *Analog processing that enables principal component analysis (PCA) and independent component analysis (ICA) for broadband signals*. The design and performance of a dynamic holographic processor integrated with RF and baseband electronics is discussed. The processor is capable of blind signal separation (ICA), otherwise not possible by state-of-the-art DSP for signals with bandwidths above a few kHz. This work was done in collaboration with Prof. Anderson, Department of Physics and JILA, University of Colorado.

A schematic of a discrete lens array (DLA) is shown in Figure1 and is here discussed in receive mode, although the lens is reciprocal and can also be used in a transmitter. The unit element of the lens array consists of two antennas, interconnected with a delay line [1]. The length of the delay varies across the array such that an incident plane wave is focused onto a focal point in the near field on the feed side of the array in Figure 1. The transmission lines are of different electrical length for each element: the larger delay at the central element with respect to the external ones mimics an optical lens, thicker in the center and thinner in the periphery. Together with the electrical lengths of the lines, the positions of the array elements on the feed side also determine the focusing properties of the lens. This allows for a design with up to two perfect focal points lying on a focal arc or with a cone of best focus. The two degrees of freedom are the positions of the elements on the feed side and the electrical lengths of the transmission lines connecting the two sides. The main design constraint is the equality of the path length from the feed to each element on the radiating side of the lens. Plane waves incident from different directions are focused onto different points on the focal surface, where receiving antennas and circuitry are placed to sample the image, which is a discrete Fourier transform of the incoming wavefront. Multiple receivers correspond to multiple antenna radiation pattern beams, enabling beam steering and beam forming with no microwave phase shifters.

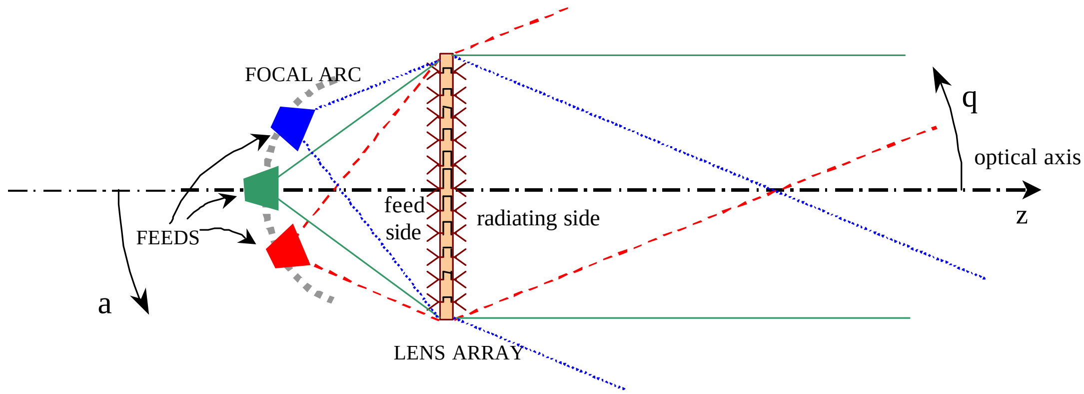


Figure 1. Sketch of a discrete lens array.

The lens array is planar and lightweight, fabricated using standard printed circuit technology. A standard *N*-element antenna array followed by a feed network is replaced by a discrete lens array in which *N* array element pairs perform a Fourier transform operation on the incoming wave front, and *M*<*N* receivers are placed on a focal surface sampling this image. The lens array can include integrated amplifiers in each element, and different lenses have been demonstrated for spatially-fed transmit-receive arrays at X [2] and Ka bands [3]. In active discrete lenses with distributed amplifiers, in transmission the effective radiated power (ERP) is increased with accompanied increase in reliability and efficiency, while in reception the dynamic range is improved as the low-noise amplifier (LNA) noises add incoherently, while the signal adds coherently. The lens array as the front end of a system performs spatial separation of the input waves, which enables simplified subsequent processing. The front-end processing benefits when using a discrete lens in an adaptive array, as applied to interference and multipath propagation, were investigated in [4,5].

II. MULTIBEAM DIVERSITY ANTENNA ARRAYS

The benefits of different types of diversity in wireless communications have been known since the first mobile radio systems. Spatial, polarization, angle, or frequency diversity have been used or proposed to improve signal to noise ratio, bit error rate, channel capacity and power savings in a mobile link. Here we examine the use of more than one type of diversity in the same front-end antenna array – in specific, polarization and angle diversity. Referring to Fig.1, in a multipath environment, the line-of site wave is focused onto one receiver on the focal arc (surface), while the reflected waves are focused onto different receivers, resulting in angle diversity.

A DLA was designed at 10-GHz [6] with a broad scan angle from –45 degrees to +45 degrees, and the measured multibeam radiation patterns are shown in Fig.2. The DLA was then inserted in a controlled multipath environment and the measured improvements are shown in Fig.3. The presentation will discuss loss budgets for a lens array and show how de-focusing and integrated feed-array design can improve performance.

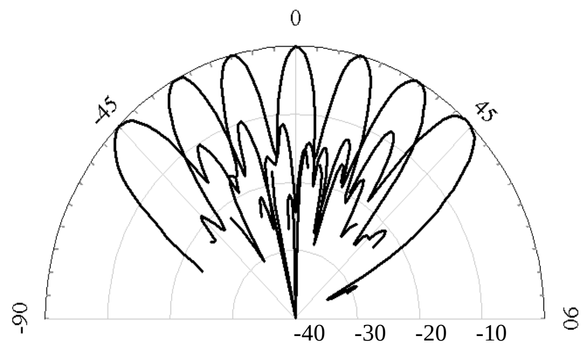
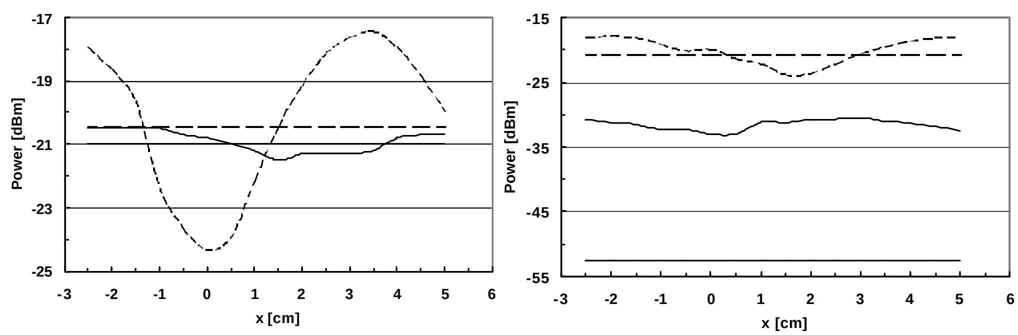


Figure 2. Measured multibeam patterns of a 10-GHz DLA optimized for wide scan angles. The peak power varied by +-1dB, and the beamwidth by a few degrees over the 90-degree scan range.



(a) (b)

Figure 3. Measured received co-polarized power in the presence of controlled multipath without lens in link (dashed line) and with the lens added at the front end of the receiver (solid line). The receiver is positioned for a beam at 0 degrees (a) and 15 degrees (b). The straight lines show the reference power levels received with no reflector (no multipath) in the link, for 500mW input power to the transmitting horn antenna in a line-of-sight setup.

III. SMART ANTENNA ARRAYS WITH BROADBAND ELECTRO-OPTICAL PROCESSING

This project deals with an optical signal processing approach to the challenging problem of blind source separation in a multiple signal space. To detect and separate N signal sources, an antenna array with at least N elements is required. If the N signals are completely unknown, N measured linear combinations of the signals at the N antenna outputs are the only information available for determining the N signals and N^2 elements of the mixing matrix. This seems an impossible problem, however if one has minimal knowledge about the statistics of the signal, the original signals can be retrieved using higher order correlations of the measured signals. This algorithm is referred to in the literature as Independent Component Analysis (ICA) [7], and digital implementations are barely able to implement it for narrowband voice signals at best. Digital implementations of ICA are appropriate for use in areas where real-time processing is not required, and has to date been applied in image enhancement, analysis of astronomical data, electroencephalogram processing, and stock market trend analysis. In this work, we have implemented ICA for a 10-GHz smart antenna array and for two unknown signals. The adaptive processing of the received signals is performed by dynamic holographic optical circuitry, enabling orders of magnitude higher bandwidth than what is currently possibly electronically.

The first step in the ICA algorithm is principal component analysis (PCA) [7], which results in dynamically separated signals ordered by relative strength. A prototype two-channel system is designed to fit in a standard-size briefcase and consume less than 50 W of power, Fig.4a. The inputs to the system are modulated waves with a carrier in X-band, and the output is an electronic demodulated signal. The heart of the system is a holographic optical processor, implemented in a free-space prototype integrated on a glass coin the size of a US quarter, Fig.4b. The output beam of this circuit dynamically chooses the stronger of the two signals and separates the signals by over 20dB. This adaptive receiver system can be used, for example, to mitigate multipath interference effects, and can separate one received signal from another even though their power spectra may entirely overlap. The system is also useful for jammer suppression in hostile signal environments.

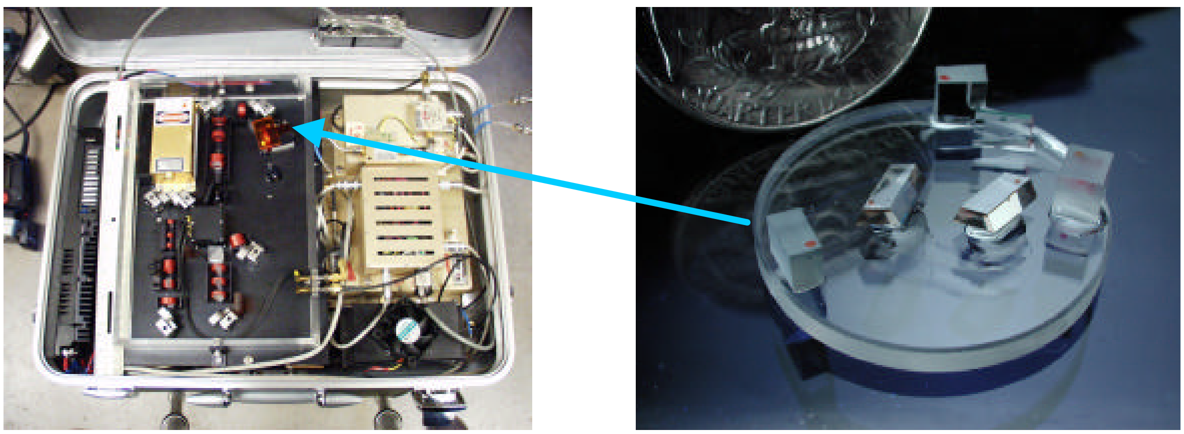


Figure 4. Photographs of integrated PCA smart antenna array processor in standard-size briefcase (left) and the optical processor integrated on a glass coin the size of a US quarter (right).

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