Discrete Lens Array Modeling and Design for Optimum MIMO Communications at mm-wave

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***Abstract*—Millimeter-wave wireless systems are emerging as a promising technology for meeting the exploding capacity requirements of communications networks. In particular, Multiple-Input Multiple-Output (MIMO) systems have been explored as a method of increasing the capacity of line-of-sight links, as an attractive alternative to fiber-based wired backhaul. A key limiting factor for conventional mm-wave MIMO has been achieving optimal performance, which requires a critically-spaced antenna array and high transceiver complexity. Efforts to reduce the complexity, e.g. with a few widely spaced antennas, lead to significantly decreased performance. Continuous Aperture Phased MIMO (CAP-MIMO) is a hybrid digital-analog transceiver architecture that uses a high-resolution Discrete Lens Array (DLA) for analog spatial beamforming. The DLA enables direct access to the communicating modes, resulting in an optimal MIMO system with dramatically low transceiver complexity. This paper discusses the design, fabrication, and analysis of a prototype DLA-based CAP-MIMO system, using both analytical and measurement results.**

I. Introduction

Millimeter-wave communications systems, operating from 3-300 GHz [1], offer unique opportunities for meeting the increasing demands on wireless communications systems. In addition to large bandwidths, the small-wavelengths allow for high-dimensional Multiple-Input Multiple-Output (MIMO) operation with relatively compact arrays.

A linear aperture of length L is capable of exciting $n = 2L/\lambda$ orthogonal spatial modes, or beams. In a line-of-sight (LoS) system with link length R, $p = L^2/R\lambda$ communications modes couple strongly from TX to RX, where $p \ll n$ [2]. For 2D square apertures, $n_{2D} = n^2$ and $p_{2D} = p^2$. Conventional LoS MIMO systems use arrays with p antenna elements, as in [3], [4] and [5], but the wide spacing required to orthogonalize the channel modes results in reduced array gain, increased interference, and compromised security due to grating lobes. Critically-spaced MIMO systems can, in principle through digital beamforming, achieve optimal communications. However the n RF chains required to individually drive each array element results in $O(n)$ transceiver complexity. Alternatively, analog beamforming enables direct access to the p communications modes, reducing the transceiver complexity to $O(p)$.

II. CAP-MIMO

A recently proposed hybrid analog-digital transceiver architecture, Continuous Aperture Phased (CAP) MIMO [2], achieves optimum beam communications with dramatically low system complexity by using a high-resolution discrete lens array (DLA) for analog beamforming. DLAs, also known as microwave lenses, e.g. [7] and [8], can excite the spatial modes of an aperture by placing an array of feed elements on the DLA's focal surface. In contrast to digital beamforming, activating a subset of the modes only requires activating the corresponding feeds, significantly reducing the required number of RF chains. Additionally, there have been several examples of lenses operating in the mm-wave regime, i.e. [9] and [10]. Previously, CAP-MIMO has been theoretically demonstrated using an ideal Discrete Fourier Transform (DFT) as the DLA, however creating a real CAP-MIMO system requires a physically implementable DLA design. In particular, a high resolution, low loss DLA based on the Miniaturized Element Frequency Selective Surface (MEFSS) [11], provides an attractive means of implementing CAP-MIMO.

III. DLA Modelling and Theoretical Analysis

For theoretical and computational analysis, we must develop a model of the DLA and the DLA-based CAP-MIMO system. As a transmitter, the DLA can be modeled as a $n \times n$ matrix, $\mathbf{U}_{dla}$, mapping the signal on the feeds to the signal on the critically-sampled representation of the DLA aperture. Similarly, $\mathbf{U}_{dla}^T$ models the DLA as a receiver. $\mathbf{U}_{dla}$ can be combined with a full-rank, deterministic, aperture-domain, LoS channel matrix, $\mathbf{H}$, to model a composite, beamspace channel between the feeds of the DLAs, $\mathbf{H}_b = \mathbf{U}_{dla}^T \mathbf{H} \mathbf{U}_{dla}$. $\mathbf{H}_b$ models a complete CAP-MIMO system, and is sparse with p dominant rows/columns, $p \ll n$. Eigen-mode transmission, i.e transmission on the eigen-modes of $\mathbf{H}$ for critically-spaced MIMO and $\mathbf{H}_b$ for CAP-MIMO, is optimal when operating under additive white Gaussian noise, and transforms the problem into parallel Gaussian channels, where the optimal solution is known to be waterfilling power allocation [12].

The results presented are based on a prototype system consisting of two 40cm square apertures separated by a 2.667m link length operating at 10 GHz. These specifications were chosen based on the available measurement equipment and space, and result in $n = 676$ spatial modes and $p = 4$ communications modes. The theoretical capacity curves presented in Fig. 1 compare the p dimensional DLA-and-DFT-based CAP-MIMO systems, critically-spaced MIMO, conventional MIMO with widely spaced antennas, and a single-mode continuous aperture dish system. These curves demonstrate that the DLA very closely matches the performance of the ideal DFT, and that the reduced complexity CAP-MIMO is able to closely match the performance of the full complexity critically-spaced MIMO system. Additionally, the results demonstrate the considerable capacity gains made by CAP-MIMO when compared to conventional LoS communications systems with comparably low complexity.

IV. DLA-Based CAP-MIMO Prototype

A prototype CAP-MIMO system was constructed using the DLA design procedure in [11] and the specifications given in the previous section to experimentally verify the concept. Each prototype DLA is held in a support structure with an adjustable feed antenna support arm. Using a vector network analyzer, the prototype $p \times p$ $\mathbf{H}_b$ was measured. Fig. 2 presents a comparison between the theoretical channel and the measured channel, with the power of each channel normalized to be equal to the theoretical channel power. These curves show excellent agreement between the theoretical and measured capacity. Most importantly the agreement shows that the measured channel has multiple dominant eigenvalues, indicating MIMO operation is possible, as predicted by the theory.

V. Conclusions

The DLA has been theoretically and experimentally shown to be a viable analog beamformer for CAP-MIMO. The computational DLA model allows us to show that the DLA-based CAP-MIMO is capable of achieving near-optimal communications while drastically reducing the required number of RF chains, and the experimental results support this conclusion. Furthermore, the DLA-based CAP-MIMO system is able to achieve significant capacity gains over conventional systems with comparable transceiver complexity.

These initial results also open several avenues for further research. More accurate modeling of the DLA will provide additional insight into the implementation of CAP-MIMO, especially when optimizing the DLA for off-broadside operation, which will be key while exploring point-to multipoint operation. Furthermore, statistical channel modeling, as in [13], will be necessary to extend CAP-MIMO to multipath propagation environments. Finally, prototype construction will continue with systems operating at higher frequencies, starting with a prototype operating in the 30-40 GHz range.

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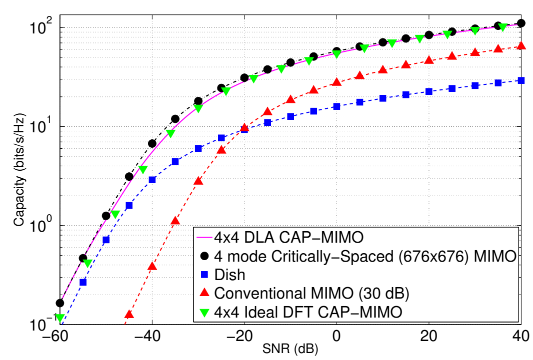

Fig. 1. Theoretical capacity comparison.

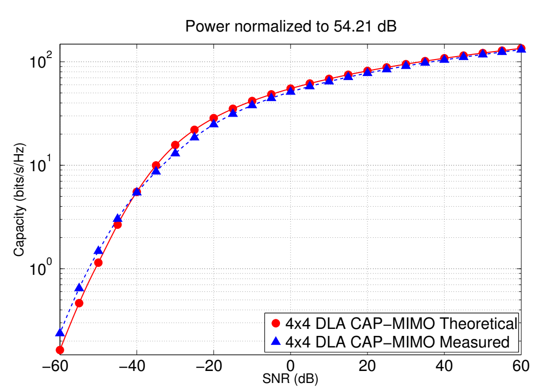

Fig. 2. Normalized measured vs theoretical capacity comparison.