PROJECT DESCRIPTION

EAGER: A Novel Hybrid Analog-Digital Architecture for Optimum Agile Wireless Communication Using Discrete Lens Arrays

Akbar Sayeed and Nader Behdad

1 Introduction

In this section we outline the reasons why we believe that this project is a good fit for an EAGER project. There are four main reasons that make this project a compelling candidate for an EAGER: 1) it involves interdisciplinary research and is based on new ideas that run counter to conventional wisdom, 2) the performance gains over the state-of-the-art predicted by initial theoretical results are very compelling, 3) the results of the project will open new avenues for research in the timely areas of wireless communication and sensing, 4) the project will have both theoretical and practical impacts, including commercialization opportunities. Thus, while the basic ideas underlying this proposal have a broad scope, we believe that submitting them as a "regular" proposal without first demonstrating the proof-of-concept via this EAGER project is premature. Please also see Sec. 4 for expected outcomes, impact and follow-up research.

1.1 Motivation and Significance

Given the proliferation of wireless devices for communication and sensing, the need for increased power and bandwidth efficiency in emerging technologies is getting ever more pronounced – power efficiency for battery-powered devices and bandwidth efficiency for high-rate devices. Two technological trends offer new synergistic opportunities for addressing these challenges: i) Multi-antenna (MIMO - multiple input, multiple output) transceivers that exploit the spatial dimension in addition to the traditional dimensions of time and frequency, and ii) mm-wave systems (60-100GHz) that provide large bandwidths and high-dimensional MIMO operation with relatively compact arrays. In this 2-year EAGER project, we propose a focussed investigation on a new *hybrid analog-digital MIMO transceiver architecture* that enables a *continuous-aperture phased-array* operation and *optimum beam agility* for dramatic improvements in wireless link capacity and commensurate gains in power and bandwidth efficiency compared to the state-of-the-art. The proposed hybrid MIMO-DLA transceiver leverages a novel metastructure for phased arrays - a high-resolution *discrete lens array (DLA)* - for the analog component and represents a novel integration of digital and analog signal processing that enables *optimum link adaptation* through *software-defined beam agility*.

The goal of this 2-year EAGER project is to demonstrate proof-of-concept of the MIMO-DLA transceiver through an integrated theoretical-experimental research plan that involves validation of key theoretical ideas and prototype development for realistic assessment of the significant performance gains (see Sec. 3). The project draws on complementary expertise of the two-PI team. PI Sayeed is a leading researcher in wireless communications, with particular expertise in MIMO wireless transceivers from communication-theoretic and signal processing perspectives. Co-PI Behdad is a leading expert in the design and fabrication of high-resolution DLAs and metamaterial-based antenna design, including frequency-selective surfaces.

1.2 Intellectual Merit

This EAGER project is inspired by advances at the intersection of MIMO communication theory, physics of wave propagation, and phased-array theory and design for fully exploiting the spatial dimension for optimized wireless communication (see Sec. 1.4). The basic MIMO-DLA theory is motivated by two competing state-of-the-art designs for high-rate mm-wave communication systems: i) traditional systems that employ continuous aperture "dish" antennas that offer high power efficiency but no spatial multiplexing gain, and ii) MIMO systems that use discrete antenna arrays to offer a higher multiplexing gain but suffer from power efficiency. The dramatic performance improvements (see Sec. 2.2) promised by the agile MIMO-DLA transceiver architecture rely on several innovations relative to the state-of-the-art, including:

- Novel integration of analog and digital processing to enable *optimum beam agility*.
- Integration of *coherent beamforming* and *spatial multiplexing* – two traditionally disjoint modes of communication.
- *Source-channel matching* for adapting the spatial *signal* statistics to the spatial *channel* characteristics for capacity maximization.
- *High-resolution DLA-based front-end design* that approximates a *continuous-aperture phased-MIMO* operation for precise control of spatial beam patterns and significantly reduced grating lobes.

Our integrated theoretical-experimental research plan, described in Sec. 3, has two main objectives: 1) Development of basic theory for MIMO-DLA transceiver design in line-of-sight (LoS) channels; and 2) Prototype development and system measurement analysis to demonstrate the theoretical performance gains promised by the MIMO-DLA technology.

We expect the results of this EAGER project to advance the state-of-the-art of wireless communications on both theoretical and practical fronts. In particular, MIMO-DLA technology is directly applicable to two important broadband applications in the short-term: high-rate (10-100 Gb/s) mm-wave wireless backhaul links and smart basestations for 4G networks and beyond. Theoretically, we expect the results of this project to spur new interdisciplinary research on multiple fronts, including transformative new transceiver architectures for wireless communication and sensing, and new conceptual paradigms for antenna array design (see Sec. 4).

1.3 Broader Impact

The interdisciplinary research in this EAGER project draws on tools from a variety of areas, including wireless communications, communication theory, signal processing, multipath channel modeling, electromagnetic theory, physics of wave propagation, and antenna array design. Thus, the project will provide an invaluable opportunity for multidisciplinary training of graduate and undergraduate students at the cutting-edge of wireless communications and sensing. The PIs will hold seminar series related to this project to facilitate interaction between their students and collaborators. A new graduate student, who will be supported on a Departmental Fellowship in the first year, will be supported as a research assistant on this project in the second year. The PI's plan to incorporate the results and findings of the project in graduate classes that they teach regularly on the topics of *Wireless Communications (ECE 736)* and *Antenna Theory and Design (ECE 841)*. The PI also plans to introduce the basic ideas in this project as a cutting-edge application of Fourier theory in the undergraduate communication courses that he teaches regularly (ECE 436 and ECE 437). The PIs anticipate summer involvement of under-represented undergraduates in the project via the SURE program at the UW. The results and publications from the project will be disseminated via the PI's websites and also via presentations at conferences and other venues.

This project could also lead to commercialization opportunities. In particular, the PIs are in the process of patenting the MIMO-DLA technology through the Wisconsin Alumni Research Foundation (WARF). The WiSeNet Consortium at UW-Madison (http://wisenet.engr.wisc.edu) will also facilitate interaction with industry and technology transfer.

1.4 Project Background and Relationship to the State-of-the-Art

The basic MIMO-DLA transceiver concept is motivated by significant recent interest in mm-wave systems for high-rate (1-100 Gb/s) communication over line-of-sight (LoS) channels (see, e.g., [1–3]). Two competing designs dominate the state-of-the-art: i) traditional systems that employ continuous aperture "dish" antennas that offer high power efficiency but no spatial multiplexing gain[1], and ii) MIMO systems that use discrete antenna arrays to offer a higher multiplexing gain but suffer from power efficiency [1–3].[2]

[1] See, for example, the commercial technology available from BridgeWave Communications; http://www.bridgewave.com.

[2] There is also ongoing work on GHz MIMO at Chalmer's University, Sweden. There is also considerable ongoing academic and industrial research on *circuit design* for GHz communications; e.g., at Berkeley Wireless Research Center and Intel.

The MIMO-DLA transceiver combines the advantages of the two designs by enabling *continuous-aperture phased-MIMO* operation and offers additional capabilities (e.g., beam agility) and performance gains.

The project builds on cutting-edge research on wireless channel modeling and MIMO transceiver design performed in Prof. Sayeed's group (http://dune.ece.wisc.edu) over the last several years [4–9]. In [4], we developed a mathematical framework for revealing the MIMO capacity advantages for transceivers equipped with uniform linear (phased) arrays (ULAs). A key insight is that the performance of a MIMO system critically depends on the *interaction* between two factors: 1) antenna array geometry (e.g, aperture and antenna spacing), and 2) multipath propagation characteristics (e.g., angular spread, richness of multipath). This framework was extended to continuous-aperture phased-arrays in [5] and taken together these works show the optimality of *beamspace* signaling from a communication-theoretic perspective [9] and provide physically intuitive guidelines for optimum array design as a function of the propagation channel characteristics. Most relevant to this project, in an earlier collaboration with Prof. Zoya Popovic (Colorado), we identified a promising *analog front-end realization* of optimal digital beamspace processing via a *discrete lens array* [6].

Our more recent works [7, 8] challenged the conventional wisdom of maximum antenna spacing and demonstrated that the antenna spacing in a ULA should be adapted as a function of the operating SNR (signal to noise ratio) to maximize link capacity, resulting in very significant capacity/SNR gains (proportional to the number of antennas) relative to fixed arrays (see Sec. 2.2). This project is inspired by these promising initial results and insights and involves a new collaboration between PI Sayeed and co-PI Behdad.

The proposed MIMO-DLA architecture is based on a high-resolution DLA to approximate a continuous-aperture phased-MIMO operation that enables optimal array reconfiguration identified in [7, 8] through *software-defined beam agility* and promises further gains through its analog-digital interface. Fig. 1 provides a comparison between a double convex dielectric lens, a conventional microwave lens composed of arrays of receiving and transmitting antennas connected through transmission lines with variables lengths [10–17], and a high-resolution DLA that we plan to use in this work [18]. The high-resolution DLA is composed of a number of spatial phase shifting elements, or pixels, distributed on a flexible membrane. The local transfer function of the spatial phase shifters can be tailored to convert the electric field distribution of an incident electromagnetic (EM) wave at the lens' input aperture to a desired electric field distribution at the output aperture. These high-resolution DLAs have several unique advantages over conventional antenna-based microwave lenses, including: 1) Their spatial phase shifters are ultra-thin and their lateral dimensions can be extremely small, e.g. $0.05\lambda \times 0.05\lambda$ as opposed to $\lambda/2 \times \lambda/2$ in conventional DLAs [18]. This offers a greater flexibility and a higher resolution in designing the aperture phase shift profile of the lens; 2) Due to their small pixel sizes and low profiles, the high-resolution DLAs have superior performance at oblique angles of incidence with field of views of $\pm 70^\circ$; and 3) Unlike conventional microwave lenses, high-resolution DLAs can operate over extremely wide bandwidths with fractional bandwidths exceeding 50%.

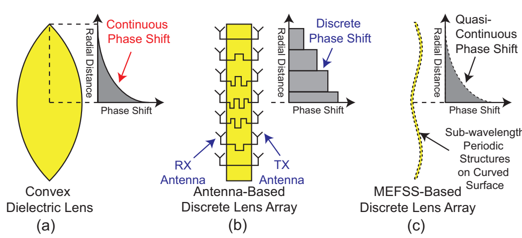


Figure 1: *Comparison between a dielectric lens (a), a traditional microwave lens composed of arrays of receiving and transmitting antennas (b), and the proposed conformal metamaterial-based microwave DLA composed of sub-wavelength periodic structures (c).*

2 The MIMO-DLA Architecture: Technical Overview

2.1 Key Elements of the Hybrid Analog-Digital Transceiver

At the heart of this project is a novel **hybrid analog-digital MIMO-DLA transceiver architecture** illustrated in Fig. 2. The system can support a maximum of n simultaneous data streams – maximum number of analog spatial modes – proportional to the normalized array aperture (electrical length). A given link

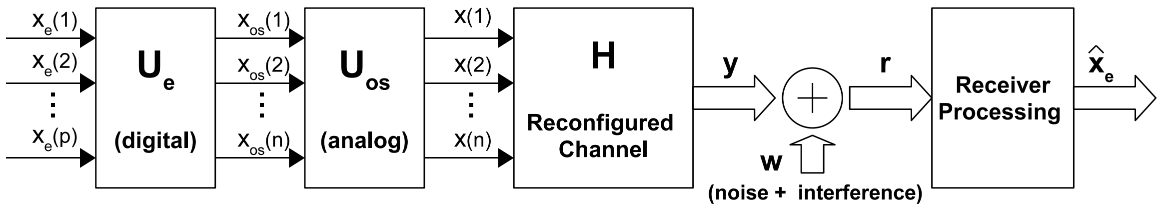


Figure 2: The proposed hybrid analog-digital agile (MIMO-DLA) transceiver architecture.

can support a maximum of $p_{max} \leq n$ data streams - multiplexing gain - depending on its angular spread. The proposed architecture adapts the actual number of data streams, p, $1 \leq p \leq p_{max}$ as a function of the operating SNR, for capacity maximization. Both the analog ($\mathbf{U}_{os}$) and digital ($\mathbf{U}_e$) processors adapt in tandem as a function of p and the operating SNR. For a given p, a *spatial coherence gain* of size $n_c = n/p$ – *the ratio of array's electric dimension to information dimension* – is exploited by the transceiver for dramatic enhancements in capacity and power efficiency. Surprisingly, **three canonical configurations** deliver near-optimum performance over the entire SNR range: **high-SNR - Multiplexing configuration** (MUX, $p = p_{max}$); **medium SNR - Ideal configuration** (IDEAL; $p = \sqrt{p_{max}}$); **low-SNR - Beamforming configuration** (BF; $p = 1$). Different configurations effectively reconfigure the channel for *source-channel matching*: rank of the input (p) is always equal to the rank of the reconfigured channel.

The digital component ($\mathbf{U}_e$) of the transmitter is realized in software via an **oversampled discrete Fourier transform (DFT)**. While the analog component ($\mathbf{U}_{os}$) can be realized in many ways in principle, we have identified a key existing front-end phased array architecture – a **high-resolution DLA** – for initial investigation and prototype development. A DLA (see Figs. 1 and 3) consists of two components: a radiating aperture and feed elements on a focal arc that excite the aperture. The n outputs of the digital processor excite the n feed elements on the *focal arc* of the DLA, which in turn excite the DLA aperture for radiating the transmitted signal (see Figs. 2 and 3). An appropriately designed DLA computes an **analog spatial Fourier transform** from the focal arc to the aperture and plays a key role in effecting the n_c-fold spatial coherence gain.

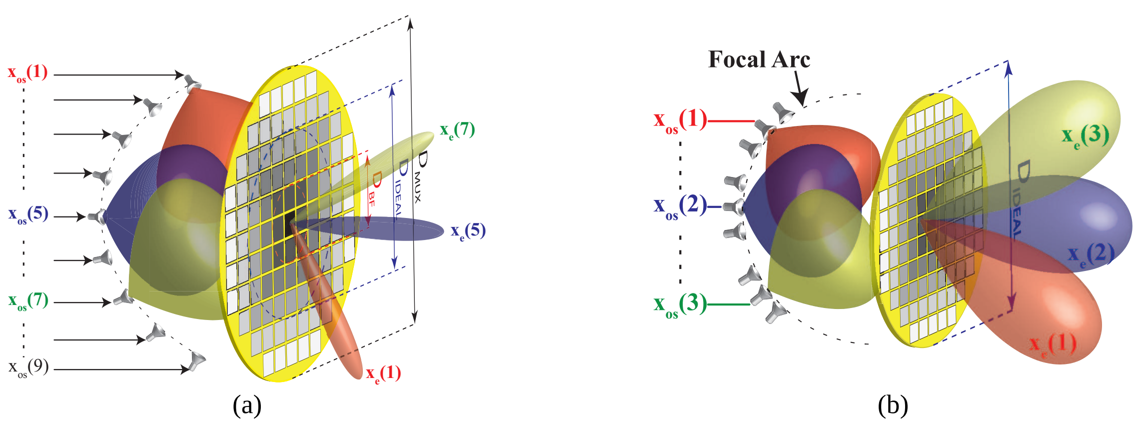
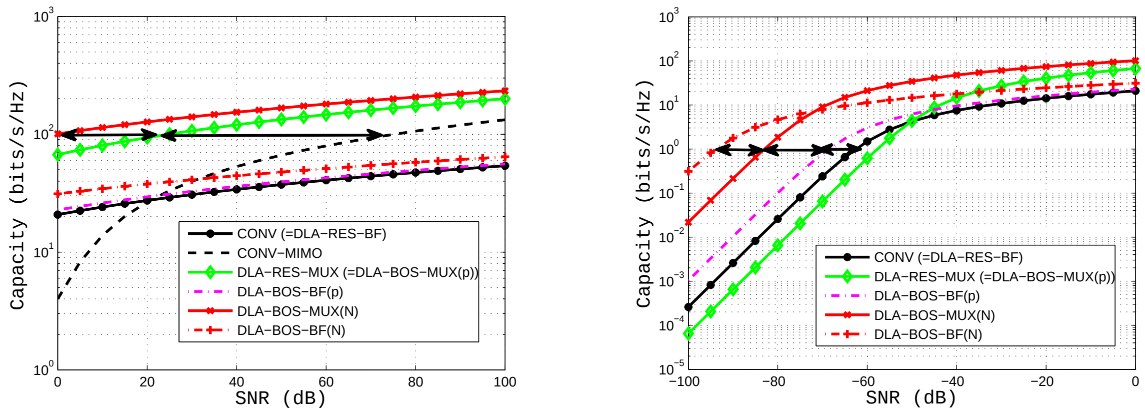


Figure 3: A DLA-based realization of $\mathbf{U}_{os}$. (a) MUX configuration. (b) IDEAL Configuration

Fig. 3 illustrates the DLA operation in two canonical transceiver configurations for $p_{max} = n = 9$. Fig. 3(a) shows a DLA in the MUX configuration, optimum at high SNRs, with a maximum multiplexing gain of $p_{max} = 9$: $p = 9$ independent data streams get mapped (via $\mathbf{U}_e$) to $n = 9$ feeds on the focal arc which in turn excite the *full array aperture*, resulting in $p = 9$ *narrow spatial beams* in the far-field. Fig. 3(b) shows a DLA in the IDEAL configuration, optimum at medium SNRs: $p = \sqrt{p_{max}} = 3$ independent data streams get mapped (via an *oversampled* DFT computed by $\mathbf{U}_e$) to the $n = 9$ elements on the focal arc which now focus the signal energy on a *smaller aperture*, resulting in $p = 3$ *wider beams* in the far-field. In essence, distinct sets of $n_c = 3$ feeds on the focal arc *coherently* excite each of the $p = 3$ data streams in the far-field via *spatial power density shaping*. As a result, the SNR *per data stream* is larger in the IDEAL relative to the MUX configuration by a factor ranging between $n_c = 3$ and $n_c^2 = 9$, leading to commensurate capacity gains. The BF configuration ($p = 1$, not shown) delivers the highest gain at low SNRs with $n_c = 9$.

2.2 Potential Capacity/SNR Gains



(a) High-SNR regime (b) Low-SNR regime

Figure 4: *Theoretical capacity gains due to the proposed hybrid MIMO-DLA transceiver.*

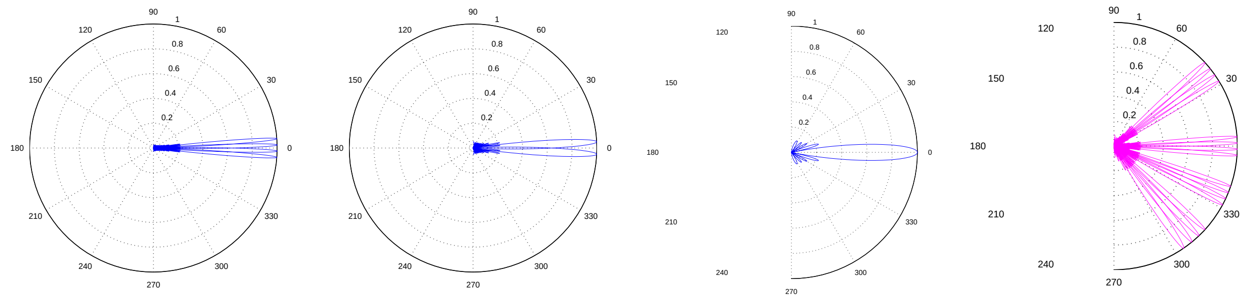
Fig. 4 illustrates the potential capacity/SNR gains of the proposed hybrid MIMO-DLA transceiver over two state-of-the-art conventional (CONV) designs for LoS, long-range microwave links. The comparisons are based on theoretical calculations for a link operating at 60GHz over a distance of 1km, with 1.67m x 1.67m array aperture. The first design - labeled CONV - uses a microwave dish antenna for maximum array gain but transmits a single data stream. The second design - labeled CONV-MIMO - uses MIMO technology (4 discrete antennas a the corners of the aperture) supporting 4 independent data streams but with limited array gain.[3] Between the two, CONV outperforms CONV-MIMO at lower SNRs ($<$ 20 dB) and CONV-MIMO dominates at higher SNRs (see Fig. 4(a)). The proposed agile hybrid MIMO-DLA design (colored lines) combines the advantages of both CONV designs (black lines) and delivers additional gains over the entire SNR range. Different colors depict progressively more advanced versions - the red lines are most advanced. **Two concrete points of comparison:** At high SNRs (Fig. 4(a)), we expect an SNR gain of 40-60dB over CONV-MIMO at a capacity of 100 bits/s/Hz (10 Gigabits/s for a bandwidth of 100 MHz, e.g). At low SNRs (Fig.4(b)), we expect an SNR gain of 8-30dB over CONV at a capacity of 1 bit/s/Hz (100 Megabits/s for a bandwidth of 100 MHz, e.g.).

3 Research Plan

This EAGER project is based on an integrated theoretical-experimental research plan to demonstrate proof-of-concept of the MIMO-DLA transceiver architecture. The research plan is focussed on demonstrating two critical capabilities of the MIMO-DLA architecture in LoS propagation environments. The first capability is **beam agility (BA)** that is at the heart of realizing different MIMO-DLA configurations (see Fig. 3) - the actual beampatterns for $n = 40$ and $p_{max} = 4$ are shown in Fig. 5(a)-(c). The second capability is **point-to-multipoint (P2MP)** operation (in a network of smart basestations in a mesh wireless network, e.g.) in which a MIMO-DLA transmitter can simultaneously send multiple data streams to different spatially distributed receivers, as illustrated in Fig. 5(d). By combining the BA capability with the P2MP capability, the number of beams/data streams associated with a particular receiver can also be optimized.

Our integrated theoretical-experimental research plan has two main objectives:

[3] While the electrical length $n \approx 335$, a maximum multiplexing gain of $p_{max} = 4$ is possible due to the limited angular spread subtended by the arrays, leading to a large $n_c \approx 80$. The operating SNR values in Fig. 4 may be different than those depicted (after accounting for path loss etc.) - *SNR gains* will remain the same.



(a) MUX (b) IDEAL (c) BF (d) multi-point

Figure 5: *(a)-(c): Far-field beampatterns for the three canonical configurations for an array with* $n = 40$ *analog modes and a maximum of* $p_{max} = 4$ *digital modes: (a) MUX,* $p = 4$*. (b) IDEAL,* $p = 2$*. (c) BF,* $p = 1$*. (d) Point-to-multipoint beampatterns.*

1. Development of basic theory for MIMO-DLA transceiver design to enable demonstration of the BA and P2MP capabilities in LoS environments.
2. Prototype development, system measurements and analysis to demonstrate the capacity/SNR gains promised by the MIMO-DLA architecture.

Our technical approach has two corresponding components to achieve the project objectives: i) Basic research and prototype design, and ii) Prototype development, system measurements and data processing. The two components of our technical approach are elaborated below.

3.1 Basic Research and Prototype Design

The basic research and design component is anchored on two key inter-related aspects of the MIMO-DLA transceiver architecture. The first and most challenging aspect is the design of the digital $\mathbf{U}_e$ and analog $\mathbf{U}_{os}$ Fourier transformations (Fig. 2) and *geometric DLA design* – the desired focal arc geometry and aperture phase-profile – to realize $\mathbf{U}_{os}$ and to map the output of the digital transform, $\mathbf{x}_{os}$, onto the focal arc of the DLA. The second complementary aspect is the physical specification and verification of the DLA design.

3.1.1 Characterization of $\mathbf{U}_e$ and $\mathbf{U}_{os}$ and Geometric DLA Design

We have a fairly complete characterization of $\mathbf{U}_e$ and $\mathbf{U}_{os}$ in an *idealized* setting in which all the Fourier relations are exact. This characterization is based on our earlier work [7, 8] and Fig. 5 is generated using this idealized characterization. However, the most significant research challenges relate to the design of these mappings in a real setting: both the analog mapping $\mathbf{U}_{os}$ between the focal arc and aperture and the channel $\mathbf{H}$ coupling the transmitter aperture to the receiver aperture deviate from the idealized Fourier transform relations (due to violation of plane-wave/far-field assumptions). This deviation is well-known in DLA design but has not been investigated in the context of beam agility. Three *geometric design parameters* of the DLA afford the ability to approximate the ideal $\mathbf{U}_e$ and $\mathbf{U}_{os}$: i) the phase-profile on the DLA aperture, ii) the geometry of the focal arc, ii) location of feed points on the focal arc. Thus, the design of $\mathbf{U}_e$ and $\mathbf{U}_{os}$ for an actual physical system is intimately related to DLA design. The aperture phase-profile is the most critical in this regard. Our objective is to design $\mathbf{U}_e$ and $\mathbf{U}_{os}$, as a function of the DLA phase profile, to closely approximate the idealized versions. We plan to execute this design via a combination of analytical investigation based on oversampled DFTs and numerical investigations based on ray-tracing modeling of EM wave propagation between the transmitter and receiver DLAs (to account for the link characteristics) as well as between the aperture and the focal arc. The results of these investigations will yield a modified characterization of $\mathbf{U}_e$ and $\mathbf{U}_{os}$ along with a specification of the three geometric design parameters for the DLA.

3.1.2 DLA Aperture Phase Profile: Physical Design, Verification and Optimization

The high-resolution DLAs that will be used in this work use ultra-miniature spatial phase shifters (or pixels); design of these spatial phase shifters is based on a new class of metamaterial-based frequency selective surfaces composed of non-resonant constituting elements with sub-wavelength unit cell dimensions and periodicities. We refer to this type of FSS as a non-resonant-element frequency selective surface (NREFSS) [19–29]. An appropriately designed band-pass NREFSS can acts as a phase shifting surface (PSS) in its passband, and its constituting elements (unit cells) can be effectively used as the pixels of RF/microwave lenses. Recently, the Co-PI has developed a new class of NREFSSs, where the structure is composed of closely spaced impedance surfaces with reactive surface impedances (capacitive or inductive) separated from one another by ultra-thin dielectric spacers [26]. Additionally, a comprehensive theoretical procedure for synthesizing this type of NREFSSs is also developed and presented in [26]. Using this procedure, we can synthesize NREFSSs with any arbitrary transfer functions (amplitude and phase response) from system level performance indicators such as frequency of operation, bandwidth, phase response, etc.

In a high-resolution DLA, the lens' aperture is populated with numerous spatial phase shifting pixels. The phase shift provided by each pixel gradually changes with respect to its adjacent pixel to achieve the desired aperture phase profile. Each spatial phase shifter is composed of one or more unit cells of an appropriately designed NREFSS. The gradual change in phase shift is provided by changing the center frequency of operation of each NREFSS cell with respect to its neighbor. This way, by appropriately tuning the NREFSS responses, a desired phase shift gradient over the lens' aperture can be synthesized. In this approach, the operational bandwidth of the lens is determined by the range of frequencies over which the magnitude response of all pixels overlap. This, however, is not a practical limitation, since ultra-wide band NREFSS designs can be used, which result in very wideband DLAs with fractional bandwidths as high as 50%. The Co-PI and his student have recently designed, fabricated, and tested a first proof-of-concept prototype of such a high-resolution DLA operating over a wide bandwidth centered at 10 GHz [18].

The above approach will be used to design a DLA according to the aperture-phase profile specified in Sec. 3.1.1. This design will then enable a full EM simulation, verification and optimization of the geometric DLA design specified. The resulting detailed DLA specifications, including aperture phase profile, focal arc geometry, feed element locations and characteristics, will guide prototype development.

3.2 Prototype Development, System Measurements and Data Processing

To facilitate experimental investigation, we plan to design and develop a DLA-based prototype of the proposed hybrid MIMO-DLA transceiver architecture with the following specifications:

- 10 GHz carrier frequency and approximately 10 feet link length with LoS propagation.
- two 40cm x 40cm (aperture) DLAs, one for the transmitter and one for the receiver.
- 10 feed antennas each at the transmitter and the receiver for exciting the focal arc of the DLAs.

The prototype represents a scaled-down version of the set up in Sec. 2.2 with the goal of demonstrating the capacity/SNR gains in Fig. 4. Once the prototype is built, we plan to make phase-coherent measurements coupling the 10 feed elements on the focal arc of the transmitter DLA to the 10 feed elements on the focal arc of the receiver DLA. These measurements will, in effect, characterize the MIMO channel coupling the transmitter and receiver (in the horizontal plane). The measurements will then be appropriately processed, by including the effect of the digital Fourier mapping $\mathbf{U}_e$, to assess the capacity/SNR gains promised by the different MIMO-DLA configurations.

3.3 Project Timeline

This 2-year EAGER project is anchored around the following tentative timeline for various activities:

- Year 1: Basic MIMO-DLA theory development; Detailed prototype transceiver design; Full EM simulation and verification of the DLA design.
- Year 2: Hardware prototype development, system measurements and data processing; evaluation of the capacity/SNR gains delivered by the prototype; Refinements in the MIMO-DLA theory.

4 Expected Project Outcomes, Impact and Outlook

This EAGER project is focussed on basic theory and prototype development for demonstrating proof-of-concept of the proposed agile hybrid MIMO-DLA transceiver architecture. We expect the results of the project to have a broad impact on the theory and practice of wireless communication and sensing, particularly in terms of new front-end architectures and their optimal exploitation. We next outline the expected outcomes, impact and research outlook of this EAGER project.

4.1 Expected Outcomes

We expect three specific outcomes from this project relating to the basic theory, practical realization and feasibility of the proposed hybrid MIMO-DLA transceiver architecture:

- Theoretical understanding of the two critical MIMO-DLA capabilities in LoS channels: BA and P2MP. In particular, the basic theory will outline a framework for complete MIMO-DLA transceiver design that incorporates the non-idealities introduced by the DLA and link propagation.
- MIMO-DLA prototype development for evaluating the theoretical MIMO-DLA transceiver design.
- Phase-coherent system measurements and data processing to provide a realistic assessment of the potential capacity/SNR gains promised by the MIMO-DLA theory.

4.2 Expected Impact

The basic principles underlying the proposed agile MIMO-DLA transceiver architecture have a broad theoretical and application scope: communication at all spatial scales, ranging from short-range to long-range; the whole gamut of propagation conditions, ranging from line-of-sight (LoS) to rich multipath; point-to-point or network operation; and operation over all feasible frequencies and bandwidths. In particular, we expect the results of the project to spur new interdisciplinary research, spanning communication theory, signal processing, physics of propagation, antenna theory and design. Such efforts would significantly enhance and broaden applications of phased arrays in communications and sensing. By virtue of its inherent agility the proposed MIMO-DLA transceiver architecture has the potential of transformative improvements in high data-rate communication links in both space (LoS) and terrestrial (LoS and/or multipath) environments, under various topology, available spectrum, transceiver size and power constraints. In particular, we are exploring the commercialization potential of MIMO-DLA technology in two important broadband applications: long-range (1km) high-rate (10-100 Gbps) wireless backhaul links and smart base stations.

4.3 Research Outlook

We believe that the basic theoretical concepts underlying this focussed EAGER project have a much wider and pervasive potential for exploiting the full-dimensionality of communication and sensing in time, frequency and space via the new hybrid analog-digital agile transceiver architecture. This is prompted by the fact that multi-dimensional Fourier transforms are the at heart of wireless communication and sensing, dictated by the physics of propagation [30]. We expect the results of this EAGER project to enable follow-up research on multiple important fronts: i) extension of the theory in the spatial dimension to account for multipath propagation, impact of channel state information, and receiver optimization; ii) extension of the MIMO-DLA transceiver concept to include the temporal and spectral dimensions; and iii) wireless sensing applications, in particular exploitation of multipath for enhanced sensing. Finally, we believe that the results of this project will also provide new theoretical and conceptual insights for exploiting novel properties of other metamaterials and metastructures, including frequency-selective surfaces, for new phased antenna array designs in communication and sensing applications.

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