Demo: MmWave Lens MIMO

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Abstract—In fifth-generation (5G) communication, the RF lens antenna is introduced with advantages of high antenna gain and low hardware cost in analog/digital hybrid beamforming technology. In this paper, we design and manufacture the appropriate RF lens antenna for mmWave communication identified in simulation analysis and present a real-time mmWave lens MIMO testbed. Furthermore, in conventional phase-shift MIMO, beam-squint, a problem caused by the wideband of mmWave communication, is estimated with the fabricated RF lens antenna.

Index Terms—mmWave testbed, lens antenna, lens MIMO, beam-squint.

I. INTRODUCTION

With the realization of 5G wireless communications requiring wide bandwidth and high spectral efficiency, the understanding of the millimeter wavelengths (6-300 GHz) of electromagnetic waves and the advanced multiple-input and multiple-output (MIMO) technology has become essential. In the mmWave MIMO system, a lens antenna array structure incorporating an RF lens is proposed to achieve high antenna gain with low hardware cost [1]. The narrow beamwidth of the lens antenna can preserve the reduced RF chain operation, making it possible to reduce the power consumption and interference between the streams.

High antenna gain and directivity can be achieved using the lens due to its properties, but challenges such as the low beam scanning angle exist because of the physical limitations of the lens. Therefore, we analyze the issues related to lens antenna design to obtain the desired performance in a realistic environment. Then, we consider the physical characteristics, such as lens structure, shape, material, and $f/D$ ratio, and carry out an analysis on the effect of the lens antenna design on the communication performance. As a result, we describe the relationship between the characteristics and performance of the lens antenna and find the suitable design conditions for desired communication performance.

In addition, when we use a wide frequency band, conventional analog beamforming is significantly affected by the beam-squint phenomenon. In a phased array antenna, the beam-squint means that the transmission angle and direction of the analog beamforming of the antenna are changed depending on the operating frequency [2]. A hybrid beamforming system combining a lens antenna has been proposed to reduce the system cost, but the beam-squint problem in ultra-wideband systems has not been considered extensively. Therefore, in the case of wideband mmWave communication, it is essential to analyze the beam-squint of the RF lens and compare it with the phased array antenna system in the wideband.

Then, the actual lens antenna is fabricated and a link-level experiment is demonstrated to show the results and verify our analysis. Finally, we analyze the overall performance in a realistic communication environment using the software-defined radio (SDR) platform. As a result, this paper demonstrates that the lens antenna design and beam-squint problem affect communication performance in an mmWave MIMO system.

II. SYSTEM MODEL

A. Hardware Layout

The communication system consists of the LabVIEW system design software and PXIe (SDR). As shown in Fig. ??, the Tx node as a base station and the Rx node as a user are separated by 5 meters. The Tx consists of the IF-LO module, I/Q-generator, and Tx NI upconverter as NI PXIe-3620, NI PXIe-3610, and NI mmRH-3642, respectively. The Rx consists of the IF-LO module, I/Q-digitizer, decoder, multiple-access channel (MAC), and Rx downconverter as NI PXIe-3620, PXIE-3630, PXIe-7976R, PXIe 7976R, and mmRH-3652, respectively. The fabricated lens antenna is used in both the Tx and Rx. In the backplane of the RF lens antenna, a 2 by 2 patch antenna exists.

B. Lens Antenna and Beam-squint

![Fig. 1. Relation between PD, AD, HPBW and DBPQ](image)

There are parameters to consider in the manufacture of the RF lens antenna, which is passive beamforming equipment. As the material has high permittivity, high permittivity causes high propagation loss in the lens that decreases the beam gain. Because scanning angle and beam gain are trade-off relation over permittivity of a material, using a material having a high permittivity to improve scanning angle causes severe beam gain degradation. If we want to increase the scanning angle in a fixed material, designing a lens antenna with a low $f/D$ ratio should be considered. In this demonstration, the lens shape is designed by applying a hyperbolic lens, and the lens antenna
Fig. 2. (a) Indoor mmwave software defined radio (SDR) testbed with a fabricated RF lens for beam-squint. (b) fabricated RF lens antenna with polyethene; below figure is 2 by 2 patch antenna inside lens structure.

can be fabricated using polyethylene with a \( f/D \) ratio of 0.7. Experiments with this lens antenna system resulted in beam gains of up to 21.8 dB.

Furthermore, the beam-squint phenomena described in the earlier sections are empirically demonstrated to assess performance degradation due to beam-squint in the indoor link-level testbed. In particular, the angle distortion (AD) and power difference (PD) of the lens antenna caused by the wideband, 27.5-29.5 GHz, is evaluated. To assess the BQ phenomenon, we introduce several parameters. First is the AD, which means a difference of azimuth angle of peak power on operating frequency and azimuth angle of peak power on the center frequency (CF). However, It is not possible to judge a hazard only by the angle distortion generated by the beam-squint. The most influential parameters are half power beamwidth (HPBW) and PD. So we need to require the establishment of a new key performance indicator (KPI) as degraded power over beams squint (DPBQ).

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DPBQ \ [\%] = \left( \frac{Gain(CF) - PD}{sinc(0.6238 \frac{AD}{HPBW})} \right) \times 100
\]  

Fig. 1 describes three parameters used in Eq. 1. First, PD means the difference between peak antenna gain on each operating frequency and peak antenna gain on the center frequency. Second is the HPBW of the beam on each frequency band. Beamwidth is the main factor that can affect degradation DPBQ and is affected by the array size. Larger array size makes the beam narrower and being critical degradation. As a result, Table I illustrates the AD, PD and DPBQ from beam-squint.

C. Link-level Analysis

To test the performance of the lens antenna as a component of a transmission system, in Fig. 3 the link-level performance is evaluated using the mmWave transceiver system SDR platform with an up/downlink frequency of 28.5 GHz and 800 MHz bandwidth. A single data stream is transmitted and received via the modulation and coding scheme (MCS) (i.e., 64-quadrature amplitude modulation (QAM) and 5/6 coding rate). The results show that the prototyped lens antenna can achieve a maximum throughput of 2.6 Gbps. Note that this high throughput was achieved by a single stream. This is attributed to not only the large bandwidth of the channel but also the high directivity and gain of the lens antenna. Due to this high directivity and gain of the lens antenna, one can deduce that the RF lens-embedded MIMO architecture is a good potential choice for mmWave communication, which has both low cost and good performance.

III. CONCLUSION

In this paper, we presented the mmWave SDR testbed system with the RF lens-embedded MIMO architecture. Through the fabricated lens based on the guideline from simulation analysis, we verified the feasibility of mmWave lens MIMO communication and showed that the beam-squint phenomenon is insignificant in lens-embedded MIMO architecture.

ACKNOWLEDGMENT

This work was supported by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIP) (No. 2016-11-1719), (No. 2018-0-00170).

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