# RF Lens-Embedded Antenna Array for mmWave MIMO: Design and Performance

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The authors propose two types of lens antennas, one for static and the other for mobile usage. The lens antennas' sizes are varied to also discuss the lens design. Their performance is evaluated using measurements and simulation data along with link- and system-level analysis. Results show the lens antenna yields high gain, directivity, and improved beam-switching feasibility compared to when a lens is not used.

## Abstract

The requirement of high data rate in 5G calls for utilization of the mmWave frequency band. Researchers seeking to compensate for mmWave's high path loss have proposed that mmWave MIMO systems make use of beamforming. Hybrid beamforming systems demonstrate promising performance in achieving high gain and directivity by using phase shifters. The actual implementation, however, is costly and complex. To reduce such cost and complexity, this article presents actual prototypes of the lens antenna to be used in 5G mmWave beamforming systems. Using a lens as a passive phase shifter enables beamforming without the heavy network of phase shifters, while gain and directivity are achieved by the energy-focusing property of the lens. Proposed in this article are two types of lens antennas, one for static and the other for mobile usage. The lens antennas' sizes are varied to also discuss the lens design. Their performance is evaluated using measurements and simulation data along with link- and system-level analysis. Results show the lens antenna yields high gain, directivity, and improved beam-switching feasibility compared to when a lens is not used.

## Introduction

For fifth generation (5G) wireless systems applications, the specified data rate requirement for low-mobility users is at least 10–50 Gb/s [1], 10 times the Long Term Evolution-Advanced (LTE-A) peak data rate. Clearly, the sub-6 GHz of LTE-A is too crowded for 5G utilization. An intuitive approach to achieve higher data rate would be to utilize the large frequency resources available at the millimeter-wave (mmWave) range (30–300 GHz). The currently operating mmWave-based standard, IEEE 802.15.3.c-2009, has bandwidth of 2–9 GHz, which is 20 times the average bandwidth of LTE-A Pro [2].

One of the most studied aspects of utilizing mmWave is overcoming the high free space path loss, which severely attenuates the signal when confronting blockages or being transmitted across long distances. A previously studied solution to this problem is designing much smaller but more compact massive multiple-input multiple-output (MIMO) using the short wavelength of mmWave compared to what is achievable at the sub-6 GHz frequency range. With more antenna elements, a higher gain is achieved, over-compensating mmWave's path loss. To further increase this array gain, the signal phase for each antenna can be shifted by modules such as phase shifters. This results in an antenna radiation pattern of high directivity and gain. Applying phase shifting to each of the multiple data streams after the baseband to form highly directed beams in multiple directions is called hybrid beamforming. The beamforming gain is, in general, proportional to the antenna array size and dimension, which is an advantage delivered by the compactness of the mmWave massive MIMO.

In prior work, prototypes for beamforming using phase shifters [3, 4] or Butler matrix [5] were presented to demonstrate the feasibility of mmWave beamforming. While the Butler matrix is simple and easy to realize, its limited, low achievable gain and scanning plane make it hard to utilize for actual 5G applications. Regarding phase shifters, in [3], Roh *et al.* presented a 27.9 GHz operating analog beamfomring prototype using 8 × 4 uniform planar arrays (UPAs) at the transceivers with 520 MHz bandwidth orthogonal frequency-division multiplexing (OFDM) settings. In non-line-of-sight (NLoS) outdoor environments, the prototype supported a data rate of more than 500 Mb/s with 8 km/h mobility. In [4], Jang and colleagues also examined the feasibility of 3D hybrid beamforming with phase shifters. The authors proposed an algorithm for beamforming without channel state information (CSI) and tested it using a real-time testbed with software-defined radios (SDRs), and fabricated dual-pole antenna arrays. Under LTE environments, the proposed system gave higher average data rate of 32 Mb/s compared to the conventional LTE system indoors.

The aforementioned studies demonstrated through actual prototypes that beamforming is indeed significant and feasible. However, the crucial drawback of beamforming via phase shifters is that their prototypes' number of RF chains or antenna array size had to be reduced due to the high power consumption and hardware complexity involved in implementing the actual network of analog-to-digital converters (ADCs) and phase shifters. This complexity and power consumption issue should be dealt with to actualize hybrid beamfoming in mmWave massive MIMO systems.

The research in [6–9] incorporated a lens in place of the conventional phase shifters into the beamforming architecture to reduce computational complexity and power consumption. The

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lens acts as a virtual passive phase shifter, focusing the incident electromagnetic wave to a certain region. This lens, when used jointly with antennas, exhibits two significant properties: (i) focused signal power at the front-end achieving high directivity and gain,[1] and (ii) concentrated signal power directed to a sub-region of the antenna array. These properties make the lens a practical tool for implementing the RF front-end in beamforming systems. It not only enables improvements in system performance by increasing gain and directivity via energy focusing, but also reduces signal processing complexity and RF chain cost by allowing only a subset of antenna elements to be activated instead of all.

In this article, we evaluate the feasibility of mmWave lens antennas aimed to be used in hybrid beamforming structures. We use actual lens antenna prototypes that differ in design, and compare them with the case when a lens is not used. The lens antenna is designed differently according to whether it is employed in static or mobile communication links. Regarding low-cost, low-complexity beamforming lens modules, to the best of our knowledge, there is no prior research that analyzes the performance of fabricated mmWave lens modules with different structures and compares it with cases where a lens is not used through link- and system-level evaluations.

We elaborate on the general concept of a lens antenna beamforming system and present the relevant previous research. We describe the details of our proposed lens antenna prototypes, including measurement and link-level evaluation. A system-level simulation of the proposed system is introduced, with an analysis (using 3D ray-tracing) of the antenna's throughput performance in real-life scenarios. We then conclude our article.

## mmWave Hybrid Beamforming with Lens Antennas

### What Is Lens Antenna Hybrid Beamforming?

In general terms, a lens is a refracting device that focuses an incident electromagnetic wave. In wireless communications, a lens can be described as a passive phase shifter that modifies the input signal phase according to its incident point on the lens aperture. Consequently, the lens focuses signal energy to a subset of antennas according to the angle of departure (AoD) or angle of arrival (AoA); this is called the *angle-dependent energy focusing* property [7]. This property contributes to the lens antenna's high gain and directivity since the beam is focused in a certain direction with concentrated signal power.

The targeted mmWave lens hybrid beamforming system to which we ultimately aim to apply our proposed lens antenna is shown in Fig. 1a. While the baseband and transmitter/receiver (T/R) modules' structure follows that of a conventional hybrid beamforming system, for lens antenna beamforming, a lens is positioned in front of the *N* element antenna array to exploit the properties of the lens. The lens and the antenna array, as a whole, are referred to as the *N* element lens antenna. The *angle-dependent energy focusing* property of a lens provides unique benefits to the hybrid beamforming system. First, the system becomes practical and cost-efficient when only a

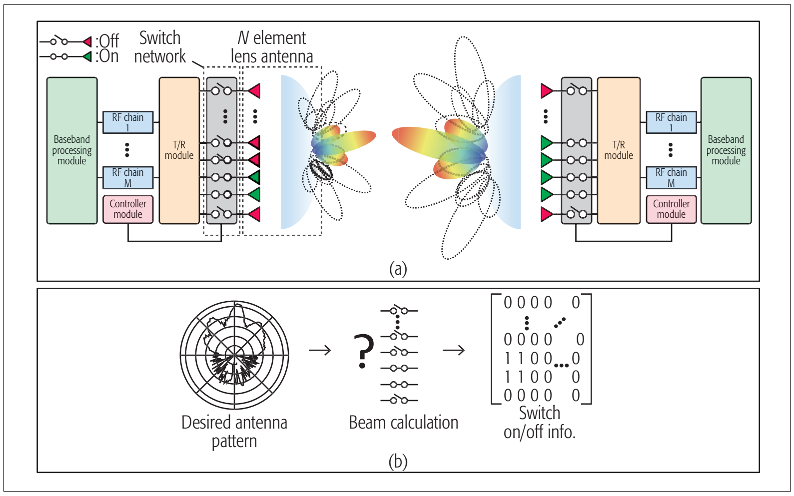



**Figure 1.** a) Proposed mmWave lens hybrid beamforming system; b) a schematic of the controller module used in the proposed mmWave lens hybrid beamforming system.

subset of antennas is selected (antenna selection) for signal processing. Depending on the pre-decided AoD or AoA, a controller calculates which subset of the array elements should be switched on to electronically steer the antennas in a specific direction (Fig. 1b). By replacing the heavy network of phase shifters with the switching network with lens, the signal processing complexity and RF chain cost are significantly reduced. Moreover, the high antenna gain of the lens antenna from directivity compensates for the expected performance degradation of antenna selection, which is the opposite to when a lens is not used [10].

### Feasibility of Lens Antenna Hybrid Beamforming

Several studies focused on the theoretical and measurement-based analysis of actual prototypes of the mmWave lens hybrid beamforming system. In this section, we present previous research on both the theory and measurements of such systems. As for theoretical work, the authors in [6] introduced discrete lens arrays (DLAs) and antenna-selection-based systems to mmWave hybrid beamforming. The lens acts as an approximate spatial Fourier transformer, projecting signals to the beamspace domain, which significantly reduces the number of required RF chains. Multi-path environments and multiuser scenarios were also evaluated [8].

In addition to the theoretical work, several researchers investigated the actual prototyping of mmWave lens hybrid beamforming systems. In [11], researchers configured a lens array multi-beam MIMO testbed with an Rx lens module with a maximum of four RF chains and a single feed open-ended waveguide Tx. For each RF chain, a subset of four feeds was assigned, and with four switches, one of the feeds out of the four was chosen from each RF chain to change the beam. The lens was placed in front of the 16-feed array. Under a multi-user MIMO (MU-MIMO) OFDM system setup, results showed that the prototype was able to separate the mixed signals coming from the two Txs.

The authors in [12] presented a 2D beam steerable lens antenna prototype operating at 71–76 GHz with a 64-element feed antenna

[1] Although the concepts of gain and directivity are correlated, we use the two terms distinctly throughout the article. Gain means the maximum achievable gain of the antenna, and directivity means the capacity of the antenna to generate a sharp beam.

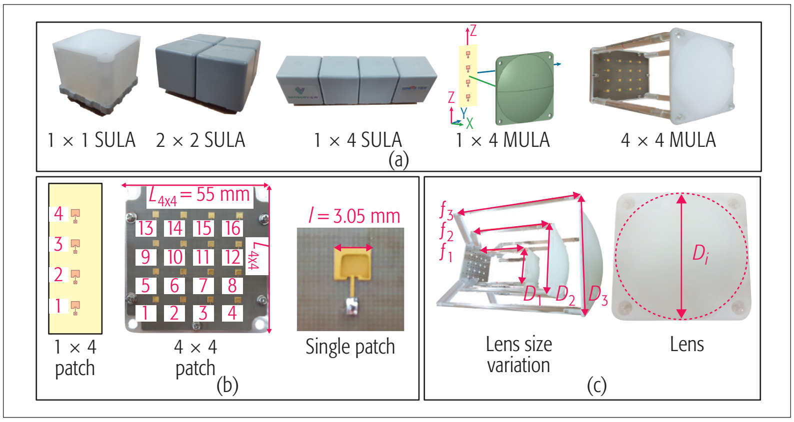



**Figure 2.** SULA and MULA prototypes and fabrication details: a) fabricated prototypes of the SULA and MULA; b) details of the fabricated patch antenna array and the assigned port numbers; c) type of lens and size parameters.

array. Beam steering and switching were implemented by simply selecting one of the 64 antenna elements using RF switches integrated into the module. In a near-field antenna test range, the maximum measured directivity and gain were approximately 36.7 dB and 15 dBi, with a beam steering range of ±4° × ±17°. A link budget analysis showed 700 Mb/s throughput for a transmission length of 55 m.

Previous theoretical research and prototyping studies provide support for the practicality and feasibility of the mmWave lens beamforming system. It is unclear, however, how the actual lens antennas will perform in real environments with real blockages and how the lens antennas' performance will differ based on their design. Moreover, cases in which a lens is not used also have to be evaluated thoroughly to fully understand the usage and properties of a lens antenna in beamforming. Hence, in this article, we evaluate different types and sizes of lens antennas compared to when a lens is not used. We also present their performance through link- and system-level analysis.

## 28 GHz Lens Antenna Prototype: Fabrication and Measurements

### Lens Antenna Prototype

The different types of 28 GHz lens antenna prototypes depend on their design. Certain types can perform better than others in specific circumstances. This article evaluates two types of lens antenna prototypes: static-user lens antenna (SULA) and mobile-user lens antenna (MULA). The SULA is for applications where the user is static, so beam-switching is unnecessary, and all that is needed for high performance is directivity gain. The MULA is for applications where the user is mobile, so both beam switching and high directivity gain should be achieved.

The SULA is cube shaped. In the cube, a 2 × 2 patch array antenna is placed behind the lens with a polyethylene wall surrounding the gap between the lens and the antenna. For higher array gain, a single SULA can be concatenated into arrays of size $N \times N$ or $1 \times N$. The single SULA size is 50 × 50 × 60mm$^3$, small enough for a massive MIMO system. The MULA, in contrast, is not cube shaped, which facilitates beam switching, as the cube walls can limit the beam-switching angle by converging beams in a certain direction. The lens for the MULA is placed in front of the patch array antenna for a certain focal distance $f$, with four thin polycarbonate cylinder pillars placed on each of the corners for fixation of the lens to the patch array antenna. Detailed illustrations are in Fig. 2a.

For both types we use an identical patch antenna, a square of side length $\ell$ = 3.05 mm. For an array of patch antennas the inter-element distance between patches is $\lambda \approx$ 10 mm, where $\lambda$ is the wavelength for 28 GHz. Each patch antenna is a port capable of sending a single beam, enabling beam switching if multiple ports are each sequentially activated. Each port of the 1 × 4 and 4 × 4 MULA is given specific index numbers to facilitate analysis of different scenarios of activated ports mentioned later. The details are depicted in Fig. 2b.

The lens used for both types is a hyperbolic, dielectric lens made from polyethylene (dielectric constant $\varepsilon_r$ = 2.40). The lenses are designed using the well-known principles of classical lenses [13, 14]. While there is no size variation in the lenses for the SULA, three differently sized lenses with diameters $D_1$ = 75 mm, $D_2$ = 115 mm, and $D_3$ = 155 mm are fabricated and evaluated for the MULA (Fig. 2c). For a fixed center frequency of 28 GHz and wavelength $\lambda$, the diameter is defined as $D_i = L_4 \times 4 + 2\alpha_i$ where $\alpha_i = \lambda(2i - 1)$ for $i$ = 1, 2, 3 and $L_4 \times 4$ = 55 mm is the fixed side length of the 4 × 4 patch array antenna. The ratio of focal length to diameter (i.e., $f_i/D_i$), was fixed to 1.2 for all cases. In this article, we have analyzed lens antenna arrays of sizes up to 2 × 2 for the SULA and 4 × 4 for the MULA. However, note that size is not limited and can be modulated to larger arrays depending on required specifications.[2]

## Measurements and Analysis of the 28 GHz Lens Antenna

In this section, the simulated and measured antenna pattern and gain for the SULA and MULA are presented. We compare our lens prototypes to cases in which no lens is used — "no lens."[3] For 1 × 1 SULA, 4 × 4 MULA, and no lens, we present the actual measurements made in an anechoic chamber; the other data presented is simulation data from high frequency electromagnetic field simulation (HFSS). Moreover, the antenna radiation pattern presented in this article is that of the vertical plane since all antennas are set to vertical polarization.

In Fig. 3a we present the radiation pattern at the vertical plane of no lens and the SULAs. Compared to no lens, the achievable gain of the SULA was 12–17 dB higher with half power beamwidth (HPBW) of ±10° on average. While nearly zero directivity and low gain were measured for no lens, the SULA achieved a distinctive directivity (small HPBW) and gain even for the smallest 1 × 1 SULA. In addition, if we compare SULA $N/2 \times N/2$ and $1 \times N$, we can see that even with the same number of single SULAs, depending on the structure, a narrower beam can be formed while having identical gain. Figure 3b presents the measured $S$-parameters, which were given at most –10 dB for 27.8–28.4 GHz,

[2] One might argue that 1 × 4 and 4 × 4 antenna arrays do not have enough antenna elements to achieve a wide beam scanning angle for beam switching. The goal of this article is to first demonstrate the feasibility of the lens to be used in the mmWave hybrid beamforming system. Our future plan is to generalize the array up to a 64 × 64 configuration.

[3] Note that "no lens" indicates the removal of the lens from any type of lens antenna so that only the remaining patch antenna array is evaluated. For example, for SULA, "no lens" will indicate the 2 × 2 patch array antenna that is placed underneath the lens. For the 4 × 4 MULA, "no lens" will be the 4 × 4 patch array antenna.

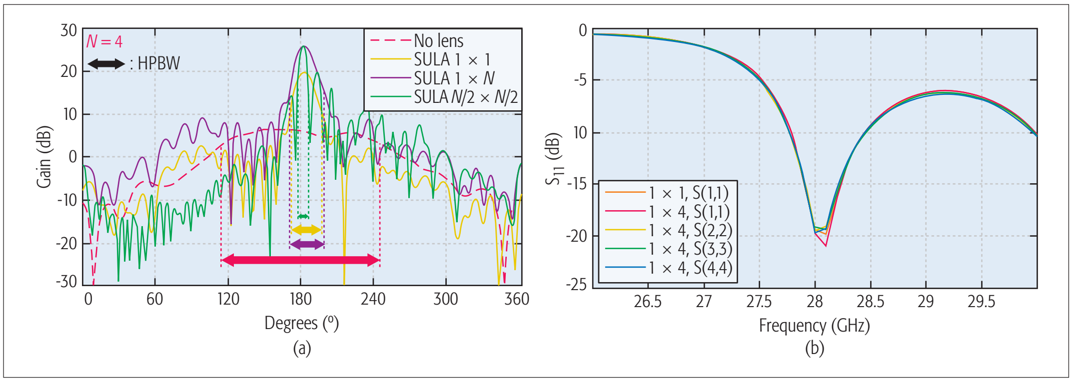
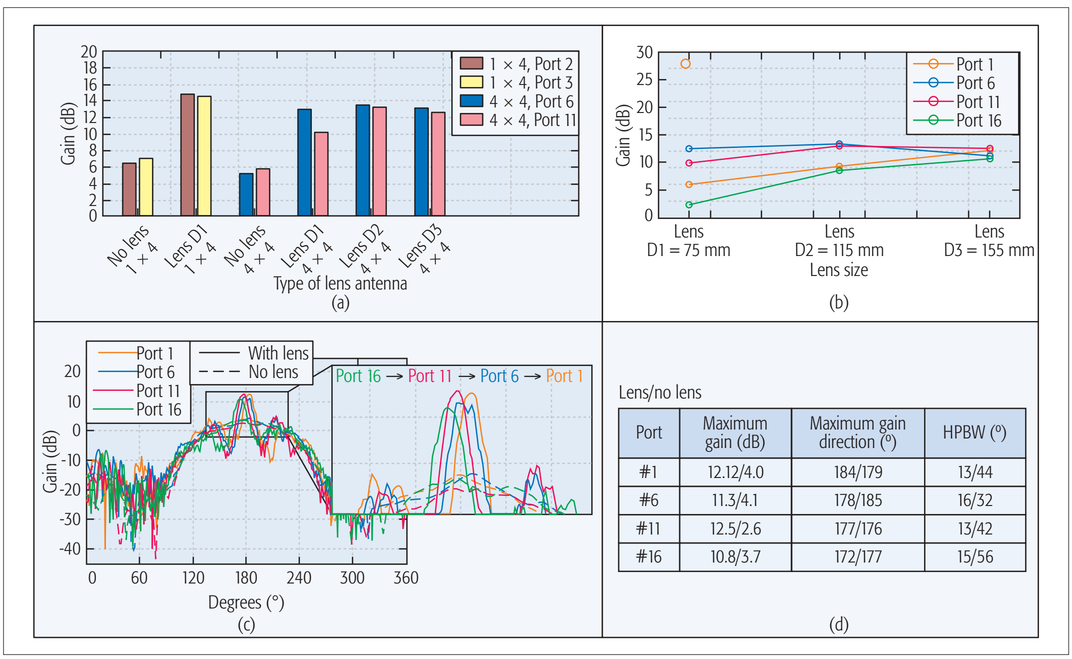



**Figure 3.** Measured and simulated antenna radiation pattern and S-parameters for the SULA (vertical plane): a) antenna radiation pattern for the SULA; b) S-parameters for 1 × 1 and 1 × 4 SULA.




| Port | Maximum gain (dB) | Maximum gain direction (°) | HPBW (°) |
|---|---|---|---|
| #1 | 12.12/4.0 | 184/179 | 13/44 |
| #6 | 11.3/4.1 | 178/185 | 16/32 |
| #11 | 12.5/2.6 | 177/176 | 13/42 |
| #16 | 10.8/3.7 | 172/177 | 15/56 |

**Figure 4.** Measurement-based performance analysis of the MULA (vertical plane): a) maximum achievable gain comparison for differently activated ports of 1 × 4 and 4 × 4 MULA; b) maximum achievable gain comparison of 4 × 4 MULA for differently sized lenses; c) antenna radiation pattern for 4 × 4 MULA with largest lens ($D_3$ = 155 mm) compared to no lens; d) statistics of maximum gain and beamwidth for 4 × 4 MULA compared to no lens.

This article evaluates two types of lens antenna prototypes: static-user lens antenna (SULA) and mobile-user lens antenna (MULA). The SULA is for applications where the user is static, so beam-switching is unnecessary and all that is needed for high performance is directivity gain. The MULA is for applications where the user is mobile, so both beam-switching and high directivity gain should be achieved.

demonstrating that the patch antenna covers the 28 GHz frequency well.

Second, in Fig. 4, we analyze the MULA mainly in three aspects: power gain, directivity, and beam-switching feasibility. In Fig. 4a, the maximum achievable gains of the different types of MULA and no lens are compared for activated ports near the center of the lens. For both 1 × 4 and 4 × 4 MULAs, using a lens yielded higher achievable gain for all activated ports of maximum 8 dB. For the 4 × 4 MULA, increasing the size of the lens had a minor effect on the gain, which indicates that for the same gain, a smaller lens is a reasonable choice regarding the tradeoff between size and gain. To further investigate the effect of lens size, Fig. 4b illustrates the gain depending on the lens size for four ports: 1, 6, 11, and 16 (diagonal order in the 4 × 4 MULA). When the lens was enlarged, the ports near the edge of the lens (ports 1 and 16) benefited more than those near its center (ports 6 and 11). This is reasonable, since the edge ports are more likely to be out of range of the lens focal region, a problem that is solved when the lens gets larger and provides more coverage.

Analyzed in Figs. 4c and 4d are the directivity and beam-switching feasibility of the 4 × 4 MULA. Figure 4c depicts the radiation pattern of a 4 × 4 MULA at the vertical plane with a lens size of $D_3$ = 155 mm and no lens. For no lens, the radiation pattern for all activated ports are nearly identical without any directivity or gain difference. When a lens is used, however, the maximum gain beam direction is shifted to the right in decreasing order of port index (port 16 → 11 → 6 → 1). For more detailed analysis, we present the statistics for maximum gain, maximum gain beam direction, and HPBW in Fig. 4d. The table shows that the gap in both gain and beamwidth between using a lens and no lens is large. The HPBW shows at most a 41° gap between lens and no lens with gain difference of at most 10 dB.

From the analysis above, we can summarize that SULA achieves a high gain of maximum 25

The results for gain, directivity, and beam-switching property of the MULA indicate that switching the activated ports in diagonal order shifts the maximum gain direction of the lens antenna with HPBW as small as ±6.5° and gain as high as 12.5 dB. Such properties of our prototypes strongly support their feasibility for use in the targeted mmWave lens hybrid beamforming system.

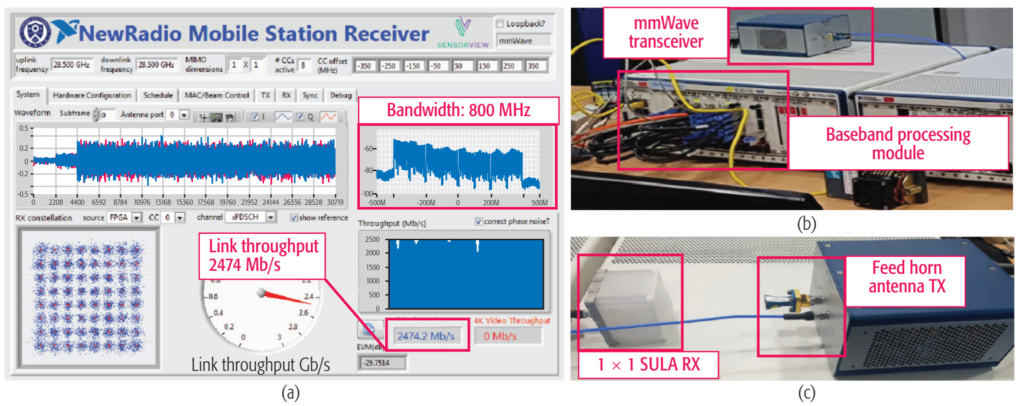



**Figure 5.** a) Link-level performance analysis of 1 × 1 SULA at 28:5 GHz; b) system equipment for the link-level analysis; c) antenna configuration example.

dB — approximately 17 dB higher than "no lens." The results for gain, directivity, and beam-switching property of the MULA indicate that switching the activated ports in diagonal order shifts the maximum gain direction of the lens antenna with HPBW as small as ±6.5° and gain as high as 12.5 dB. Such properties of our prototypes strongly support their feasibility for use in the targeted mmWave lens hybrid beamforming system.

To further test our lens antenna, the link-level performance of the 1 × 1 SULA was evaluated by using a mmWave transceiver SDR setup. Note that the 1 × 1 SULA is a lower bound for achievable link-level performance of SULA, as it has the lowest gain amongst the SULAs. We used the peripheral component interconnect express extensions for instrumentation (PXIe) platform and multi-field programmable gate array (FPGA) processing to implement the SDR system. A single data stream is transmitted and received in 64-quadrature amplitude modulation (QAM) (Figs. 5a–5c) with transmission length of 70 cm. Our results showed a maximum throughput of 2474 Mb/s.[4]

## System-Level Analysis of the Lens Antenna in Real Environments

The system-level analysis of our lens antennas in real environments is presented in this section. Using the measurement data from earlier, we carried out a system-level analysis in outdoor and indoor environments using 3D ray-tracing. We considered three scenarios:

1. Backhaul usage of SULA outdoors
2. MU-MIMO of MULA with beamforming outdoors
3. MU-MIMO of MULA with beamforming indoors

For all scenarios, with 28 GHz center frequency and 2 GHz bandwidth, the lens antennas with the highest gain and directivity from each SULA and MULA were used to represent the upper bound of the achievable performance of our proposed lens antenna.

To model urban outdoor scenarios 1 and 2, we modeled, as shown in Fig. 6a, an actual region in Rosslyn, Virginia. For the backhaul scenario 1, two cases were considered — #1: closer Tx-Rx distance, 450 m, with NLoS link, and #2: further Tx-Rx distance, 636 m, with LoS link. In both cases, the 2 × 2 SULA was used for both Tx and Rx as a backhaul base station assuming perfect beam alignment with a transmit power of 43 dBm. For case #1, the achievable throughput was 16.9 Gb/s when a lens is used and 3.9 Gb/s when a lense is not used. For case #2, the throughput was 34.3 Gb/s and 18.8 Gb/s for lens and no lens, respectively The presence of blockage clearly has a more negative effect on throughput than a longer Tx-Rx distance since case #2 has nearly two times the throughput of case #1 when using a lens. Moreover, using a lens yields significantly higher throughput (> 10 Gb/s) than no lens for both cases.

For the outdoor mobile scenario 2, we simulated a beam-switching[5] MULA Tx with a total transmit power of 38 dBm, which is capable of transmitting 8, 16, 32, and 64 beams with HPBW of ±10.5°, ±5°, ±2.5°, and ±1.25°, respectively. The boresight was fixed to approximately ±75° for all cases. The Rxs are omnidirectional antennas and uniformly deployed around the Tx inside a rectangular area of 20 m × 200 m, with an inter-user distance of 2 m. Each beam of the Tx has the radiation pattern of the 4 × 4 MULA with the largest lens ($D_3$ = 155 mm), activated port 11. We utilized the measured pattern of the 4 × 4 MULA to generate a virtual 1 × $N$ beamforming MULA capable of activating $N$ ports, as in Fig. 6a. At every simulation trial, the Tx simultaneously sent five beams where each beam was the optimal one for each of the randomly chosen five users among a total of 1100 users. After 220 trials, the average throughput was derived from the signal-to-interference-plus-noise ratio (SINR) for lens and no lens. The effect of the height gap, $h_g$, between the Tx and Rx was also evaluated, where Rx height was fixed to 3 m, and Tx height was either 3 m or 6 m.

In Fig. 6b, the results showed that using a lens provided a higher maximum throughput of 4 Gb/s than no lens for the same transmit power. This is because when the beams are well aligned, the lens antenna's sharp beam yields higher gain for each user while lowering the interference signal power. Results also imply that the height gap between Tx and Rx has a minor effect on throughput. Eight beams with lens has the least improvement from

[4] Full demo video is available at http://www.cbchae.org/

[5] Regarding the switch loss, which is the power loss and time delay incurred from the RF switch used for switching beams, we assumed a power amplifier that compensated for the 10–20 dB power loss [12] and considered time delay negligible in our snapshot-like 3D ray tracing scenario since five beams were simultaneously transmitted and time variation was not considered.

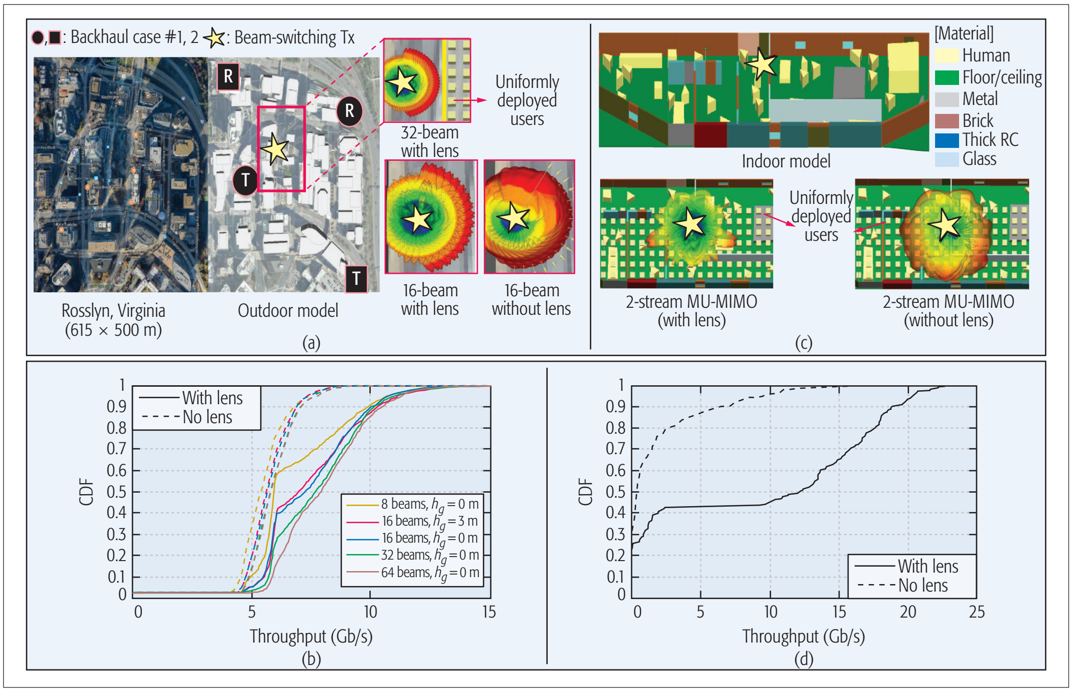



**Figure 6.** System-level analysis in real environments by 3D ray-tracing: a) outdoor scenario for backhaul and MU-MIMO beamforming performance analysis; b) average throughput CDF of outdoor MU-MIMO; c) indoor scenario for MU-MIMO beamforming performance analysis; d) average throughput CDF of indoor MU-MIMO.

For the system-level analysis we built a virtual hybrid beamformer with the MULA using simulation and derived results showing that using the lens antenna with mmWave hybrid beamforming can achieve throughput performance much higher than when a lens is not used in both outdoor and indoor scenarios.

using the lens compared to the other numbers of beams. Hence, if the number of beams is too small, using a lens becomes less effective. Moreover, as the number of beams is increased up to 64, the performance improvement slows down, indicating that the performance improvement from increasing the number of beams may not be favorable due to the rather high cost in hardware and complexity. This saturation of performance as the number of beams increases implies that the trade-off between hardware costs and achieved gain has to be considered when choosing a reasonable number of beams.

The indoor environment for scenario (3) was modeled as a 30 m × 10 m indoor space where blockages, walls, and floors were all updated to reflect the mmWave propagation channel (Fig. 6c). The Tx of height 3 m with a total transmit power of 13 dBm sent two data streams with equal power, each directed to the right and left, where the beams' main direction angles were separated at 120°. The same radiation pattern used for scenario #2 was used for the Tx. The Rxs are omnidirectional antennas and were uniformly deployed around the entire indoor space with an inter-user distance of 1 m and a height of 1.5 m. We evaluated the SINR of all users and calculated the averaged throughput for lens and no lens. Figure 6d shows results congruent with those obtained in the outdoor MU-MIMO, indicating that using a lens yields higher achievable throughput of more than 10 Gb/s on average.

Given the performance analysis of the proposed lens antenna prototypes presented above, the lens antenna proves to be more than sufficient and feasible to implement in an mmWave hybrid beamforming system. For the system-level analysis we built a virtual hybrid beamformer with the MULA using simulation and derived results showing that using the lens antenna with mmWave hybrid beamforming can achieve throughput performance much higher than when a lens is not used in both outdoor and indoor scenarios. Moreover, the SULA performance, which can be seen as parallel to the analog beamforming performance of a single data stream, also shows a capacity to yield high throughput.

## Conclusion

In this article we propose prototypes of 28 GHz lens antennas for static and mobile usage as future devices for a lens-embedded mmWave hybrid beamforming system. Our measurement- and simulation-based analyses offer insight into the profitable properties of lens antennas of much higher gain and directivity compared to those in which no lens is used. The lens antennas' beam-switching feasibility is verified by demonstrating the shift in the beam's main direction when changing the activated port sequentially. The lens antennas' design issues are also considered by analyzing the effect of enlarging the lens size. In addition, we present link-level and system-level performance evaluations that show the high throughput performance of the lens antennas in real indoor and outdoor scenarios. Our future work aims to implement an ultra-fast beam-switchable lens antenna based on an mmWave hybrid beamforming system with low-complexity algorithms that exploit mmWave massive MIMO properties [15].

### Acknowledgment

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We presented link-level and system-level performance evaluations that show the high throughput performance of the lens antennas in real indoor and outdoor scenarios. Our future work aims to implement an ultra-fast beam-switchable lens antenna based on an mmWave hybrid beamforming system with low complexity algorithms which exploit mmWave massive MIMO properties.

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