

Lens MIMO Based Millimeter Wave Broadcast Channel

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Abstract—We consider the beamforming design for the millimeter wave (mmWave) broadcast channel using lens array antenna based multiple-input-multiple-output (MIMO) communication system (also referred to as “lens MIMO” in this work). Recently, lens MIMO based communication was proposed as a promising scheme for the single-user mmWave network to greatly reduce the computational and signal processing complexity of the system. In this paper, we propose a simple beamforming scheme for lens MIMO in broadcast channels which performs as good as the recently proposed hybrid beamforming (HBF), but with much reduced hardware and power consumption cost, thanks to the energy focusing property of lens array.

Index Terms—Millimeter Wave communication, Lens MIMO, Hybrid beamforming.

I. INTRODUCTION

Millimeter Wave (mmWave) communication has been proposed as one of the most important components of the upcoming 5G wireless communication technologies [1]–[6]. The main advantage of the mmWave communication comes from the large bandwidth available at the high frequency millimeter waves which can enable high data rate communication [2]. However, at such high frequencies, the wireless channel becomes very different from the traditional propagation channels. Firstly, for the mmWave communication at 28 GHz and above, the wireless channel becomes highly sparse due to limited scattering and diffraction, and thus, there are only few dominant paths from the transmitter to the receiver. Secondly, the mmWave signals are very lossy, and therefore, have short transmission range up to about 200 metres [2], [4], [7]. However, the signal propagation loss can be compensated by beamforming using large number of antennas at the transceivers which can be packed in a small form factor, thanks to the short wavelength of the millimeter waves.

A major challenge in the mmWave communication is the beamforming design for the large antenna arrays when only limited number of radio frequency (RF) chains are available at the transceivers [8]. Since digital beamforming for large antenna arrays require large number of RF chains, it can result in large power consumption and hardware complexity. To this end, a hybrid combination of digital and analog beamforming designs, i.e., hybrid beamforming (HBF) has been proposed in [8], where it is shown that even with limited number of RF chains, we can achieve sum-rate performances close to the unconstrained digital beamforming, which is possible mainly due to the mmWave channel sparsity. Other low complexity hybrid beamforming algorithms followed, especially for the

single-user transmission [9]–[11]. While the aforementioned works can achieve the optimal multiplexing gain with limited number of RF chains, they still require large number of phase shifters which incur huge power expenditure and hardware complexity [12].

In another line of work, electromagnetic (EM) lens antenna arrays have been proposed for the mmWave networks which significantly reduce the signal processing complexity (as they do not use active phase shifters), and yet perform close to the digital beamforming in terms of the network sum-rate [13], [14]. A recent promising research towards beamforming in mmWave network has been proposed in [15] which also utilizes the lens antenna arrays but unlike [13], integrates the EM lens and the antenna array (referred to as “lens MIMO”), resulting in a new “sinc” array response function at the transceivers. The lens MIMO beamforming for mmWave networks not only obviates the need of multiple phase shifters, thereby greatly reducing the power consumption and signal processing complexity, but also leverages a new path division multiplexing (PDM) technique to achieve the optimal capacity of the network.

In this paper, we propose a simple beamforming scheme for the lens MIMO system [15] in multi-user broadcast channels. Specifically, we assume that the lens MIMO based beamforming is applied at the base station (BS), and phase shifter based analog beamforming is used at the mobile stations (MSs). We show that with limited number of RF chains at the BS, the proposed lens MIMO based beamforming scheme attains almost the same sum-rate performance as the HBF in [16]. However, unlike HBF, lens MIMO does not require active phase shifters and thus, significantly saves hardware and power consumption cost. Furthermore, the lens MIMO shows significant sum-rate improvement as compared to analog-only beamforming. It is also observed that by increasing the number of RF chains, the sum-rate of the lens MIMO can be further improved.

II. SYSTEM DESCRIPTION

Before we describe the system model for our broadcast channel, we firstly give a brief overview on the lens antenna array architecture introduced in [15], as well as the conventional uniform planar array (UPA) architecture.

A. Lens Antenna Array

As shown in Fig. 1, a lens antenna array in general consists of a planar electromagnetic (EM) lens of size $D_y \times D_z$ on the

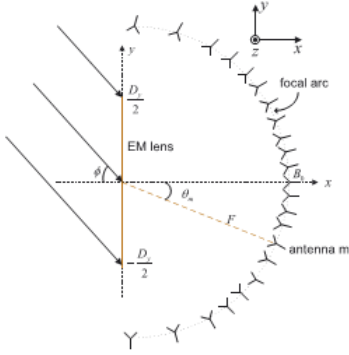


Fig. 1: A lens antenna array with an incident uniform plane wave at AoA ϕ

y-z plane, and a matching antenna array with elements located on the focal arc of the lens at a distance F from the lens center (please refer to [15] for details). We assume that the MSs are significantly far away from the BS and therefore, the mmWave signals arrive at the lens array in the azimuth plane only. Let M denote the number of antennas and $\theta_m \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ denote the angle of the m^{th} antenna element relative to the x-axis. We further assume that the antenna elements are critically spaced on the focal arc, i.e., $\tilde{\theta}_m \triangleq \sin(\theta_m)$ are equally spaced in the interval $[-1, 1]$ as

$$\tilde{\theta}_m = \frac{m}{\tilde{D}}, \quad m \in \mathcal{M}, \quad (1)$$

where $\tilde{D} \triangleq \frac{D_y}{\lambda}$ is the lens's y-dimension normalized by signal wavelength λ , and $\mathcal{M} \triangleq \{0, \pm 1, \dots, \pm \frac{M-1}{2}\}$ is the set of antenna indices. It can be checked that $M = 1 + \lfloor 2\tilde{D} \rfloor$, with $\lfloor x \rfloor$ denoting the largest integer no greater than x .

The array response of lens antenna array is given as [15]

$$a_m(\phi) \approx \sqrt{A} \text{sinc}(m - \tilde{D}\tilde{\phi}), \quad m \in \mathcal{M}, \quad (2)$$

where $A \triangleq \frac{D_y D_z}{\lambda^2}$ denotes the normalized lens aperture, $\tilde{\phi} \triangleq \sin(\phi) \in [-1, 1]$ denotes the *spatial frequency*, and ϕ denotes the azimuth Angle-of-Arrival (AoA) of the signal. Essentially, the array response function in (2) states that for a planar wave incident on the lens antenna array with AoA ϕ , only those antennas with indices near $\tilde{D} \sin \phi$ receive significant signal power, whereas all other antennas receive negligible power as justified by the “sinc” function in (2).

B. Uniform Planar Arrays

We consider UPAs at the MSs in our model. Assuming signal reception in the azimuth plane, the response vector for the UPA is given as

$$\mathbf{a}(\phi) = \frac{1}{\sqrt{N_{MS}}} [1, e^{j\Delta_2(\phi)}, \dots, e^{j\Delta_{(N_{MS})}(\phi)}]^T, \quad (3)$$

where $\Delta_m(\phi) \triangleq \frac{2\pi}{\lambda}(m-1)d\sin(\phi)$ denotes the phase shift of the m^{th} antenna with respect to the first antenna, d is the antenna spacing, and ϕ denotes the AoA in the azimuth plane.

C. MmWave Multi-User Broadcast Channel

We consider a lens MIMO broadcast channel (lens MIMO-BC) where a BS equipped with a lens antenna array of N_{BS}

elements is intended to transmit independent messages to K MSs, each of which is equipped with the conventional UPA of N_{MS} elements [17]. For cost-effective implementation, the BS is equipped with N_{RF} RF chains, where $K \leq N_{RF} \leq N_{BS}$. On the other hand, since the MSs need cheaper hardware, we assume that each MS has only one RF chain, and hence it can receive only one data stream using *analog beamforming*. An example of a lens MIMO-BC is shown in Fig. 2 in which a lens MIMO BS transmits data streams to three UPA based MSs with each MS receiving the signals along two paths.

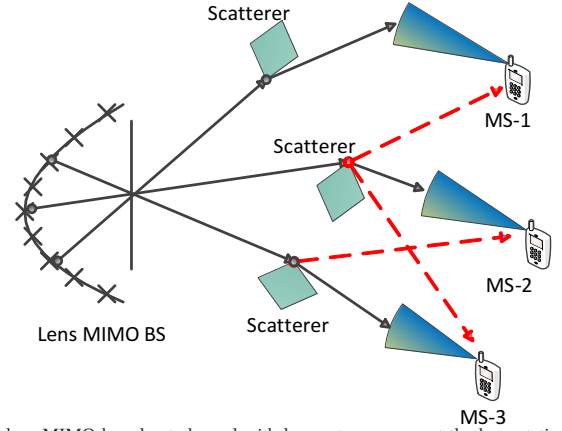


Fig. 2: A lens MIMO broadcast channel with lens antenna array at the base station and UPA at the MSs. Each MS receives its signals via two paths. The interfering paths are shown in red.

We consider a narrowband mmWave MIMO channel, where the channel from the lens array BS to the k^{th} MS is given as

$$\mathbf{H}_k = \sum_{l=1}^{L_k} \alpha_{k,l} \mathbf{a}(\phi_{k,l}) \mathbf{b}^H(\theta_{k,l}), \quad (4)$$

where L_k denotes the number of significant channel paths of the k^{th} MS, $\alpha_{k,l}$ denotes the complex-valued path gain of the l^{th} path of the k^{th} MS (described in detail in Section IV), $\phi_{k,l}$ and $\theta_{k,l}$ respectively denote the AoA and the AoD corresponding to the l^{th} path of the k^{th} MS, and $\mathbf{a} \in \mathbb{C}^{N_{MS} \times 1}$ and $\mathbf{b} \in \mathbb{C}^{N_{BS} \times 1}$ respectively denote the UPA receive response vector (see (3)) and the lens array transmit response vector as in (2).

Note that our system model has the flexibility to utilize all the available RF chains at the BS to improve the network throughput. This is different from the model in [16] where only K RF chains are used for serving the K users. We assume that each MS can receive along multiple paths or AoAs (on an average, an MS can receive along three paths [7]) out of which only one path is the desired signal path. For example, in Fig. 2, each MS is connected to the BS via two paths. Since the MS has only one RF chain, it receives its desired data along only one path whereas the signals received from the other $(L_k - 1)$ paths are treated as interfering signals.

Since each MS receives its desired data stream along a single path, a transmit antenna corresponding to the AoD of that path is selected at the BS. Note that the AoD of the MS's desired path may or may not align with any of the BS antennas. If the AoD aligns exactly with any BS antenna as shown in

Fig. 2, that antenna is selected as the transmitting antenna for the MS. In this case, due to the energy focusing capability of the lens MIMO, most of the energy of the transmitted data stream is focussed along that AoD.

However, when the AoD of the desired path does not align with any of the BS antennas, the BS antennas closest to the desired propagation path are selected so that maximum possible powers from the selected antennas are coupled with the path. One attractive feature of the lens MIMO system is that the antenna selection can be made simply based on the received power of the antenna arrays [18], and we do not require explicit AoD estimation [19] which is more difficult than the power measurement based antenna selection. Specifically, for a given AoD θ_{kl_0} corresponding to the *desired path* (denoted by l_0) of the k^{th} MS, a set of antennas denoted by $\mathcal{M}_{kl_0}$ can be selected, where $\mathcal{M}_{kl_0}$ is given as [15]

$$\mathcal{M}_{kl_0} \triangleq \left\{ m \in \mathcal{M} : |m - \tilde{D}_T \sin(\theta_{kl_0})| < \Delta \right\}, \quad l = 1, \dots, L_k, \quad (5)$$

and $\Delta > 0$ is defined such that $|\text{sinc}(m - \tilde{D}_T \sin(\theta_{kl_0}))|^2 \approx 0$ for $|m - \tilde{D}_T \sin(\theta_{kl_0})| \geq \Delta$.

As mentioned above, overall $N \triangleq |\bigcup \mathcal{M}_{kl_0}|$ BS antennas are selected for data transmission to all the users. Thus, an $N \times K$ broadcast channel is obtained with each receiver having N_{MS} antennas. Denote the selected BS antennas set as $\mathcal{N} \triangleq \{m_1, m_2, \dots, m_N\}$, where $m_n \in \mathcal{M}$ ($\mathcal{M}$ is defined above (2)) denotes the index of the selected antenna. For example, consider a 3-user system where we assume that the antennas $\{-3, -2\}$, $\{-2, -1\}$ and $\{5, 6\}$ are selected corresponding to the desired paths of MSs 1, 2 and 3. We denote these five selected antennas as $\{m_1, m_2, m_3, m_4, m_5\} \equiv \{-3, -2, -1, 5, 6\}$.

Then, the channel matrix for the k^{th} receiver in (4) can be written in a truncated form as

$$\tilde{\mathbf{H}}_k = [\mathbf{h}_{km_1}, \mathbf{h}_{km_2}, \dots, \mathbf{h}_{km_N}], \quad (6)$$

where $\mathbf{h}_{km_t} \in \mathbb{C}^{N_{MS} \times 1}$ is the channel from the transmitter- m_t ($t \in \mathcal{N}$) to the k^{th} MS, and is defined as

$$\mathbf{h}_{km_t} = \sum_{l=1}^{L_k} \sqrt{A_t} \text{sinc}(m_t - \tilde{D}_T \sin(\phi_{kl})) \alpha_{kl} \mathbf{a}(\phi_{kl}), \quad (7)$$

where $\sqrt{A_t}$ denotes the normalized lens aperture of the transmitter. Note that $\text{sinc}(m_t - \tilde{D}_T \sin(\phi_{kl}))$ in (7) denotes the coupling coefficient of the m_t -th transmit antenna to the l^{th} path of the k^{th} MS.

The above truncated channel $\tilde{\mathbf{H}}_k$ denotes the channel from the BS to the k^{th} MS, and is of dimension $N_{MS} \times N$. Now, the BS applies a baseband precoder matrix of dimension $N \times K$ on the data, i.e., $\mathbf{U} = [\mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_K]$, so that the transmitted signal is given as

$$\tilde{\mathbf{x}} = \mathbf{U} \mathbf{x}, \quad (8)$$

where $\mathbf{x} = [x_1, x_2, \dots, x_K]^T$ denotes the transmitted signal vector, and x_k denotes the data symbol for the k^{th} MS. We assume that the transmit power is equally distributed over

all the data streams, i.e., $\mathbb{E}\{\mathbf{x}\mathbf{x}^H\} = \frac{P}{K} \mathbf{I}_K$, where P is the average total transmitted power.

The signal $\mathbf{y}_k \in \mathbb{C}^{N_{MS} \times 1}$ received by the k^{th} MS is given as

$$\mathbf{y}_k = \sum_{l=1}^K \tilde{\mathbf{H}}_k \mathbf{u}_l x_l + \mathbf{n}_k, \quad (9)$$

where $\tilde{\mathbf{H}}_k$ is defined in (6), and $\mathbf{n}_k \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \mathbf{I}_{N_{MS}})$ is the noise vector at the k^{th} MS. Finally, the k^{th} MS applies analog beamforming filter $\mathbf{w}_k \in \mathbb{C}^{N_{MS} \times 1}$ to obtain

$$\hat{x}_k = \mathbf{w}_k^H \mathbf{y}_k = \mathbf{w}_k^H \sum_{l=1}^K \tilde{\mathbf{H}}_k \mathbf{u}_l x_l + \mathbf{w}_k^H \mathbf{n}_k \quad (10)$$

III. THE ZERO-FORCING BEAMFORMING

In this section, we propose to use a simple zero-forcing beamforming scheme on the truncated channels possible due to the lens MIMO model. To this end, the k^{th} MS designs an analog receive beamforming filter $\mathbf{w}_k$ which is, in fact, the receive array response of the MS along the desired AoA, i.e., the direction along which the MS receives its desired signal, and is given as

$$\mathbf{w}_k = \mathbf{a}(\phi_{kl_0}), \quad (11)$$

where $\mathbf{a}(\phi_{kl_0})$ denotes the array response vector of the k^{th} MS along its desired AoA denoted by ϕ_{kl_0} .

Note that if the effective channel information, i.e., in our case, only the AoAs of all the MSs and the selected antennas information are known at the BS (using training and feedback from the MSs to the BS prior to the data transmission), the BS can compute $\mathbf{g}_k = \mathbf{w}_k^H \tilde{\mathbf{H}}_k$ which is the “effective channel” row vector from the BS to the k^{th} MS after receive combining. The received signal at the k^{th} MS in (10) can then be re-written in terms of the effective channel as

$$\hat{x}_k = \mathbf{g}_k \mathbf{u}_k x_k + \sum_{l \neq k} \mathbf{g}_k \mathbf{u}_l x_l + \mathbf{w}_k^H \mathbf{n}_k. \quad (12)$$

Thus, after receive combining, the channel from the BS to each MS is simplified to a multiple-input-single-output (MISO) channel, and the overall network becomes a K -user MISO broadcast channel (MISO-BC). Once the BS knows the effective channels $\mathbf{g}_k \forall k$, it can apply a zero-forcing (ZF) beamforming or any other advanced precoding algorithm such as weighted-sum minimum mean square error (WMMSE) precoder design to improve the network throughput. In this paper, we use ZF beamforming, and show that the ZF scheme achieves almost the same sum-rate performance as the analog-digital hybrid beamforming in [16].

Let the effective channel matrix of all the users be denoted as $\mathbf{G} = [\mathbf{g}_1^T, \mathbf{g}_2^T, \dots, \mathbf{g}_K^T]^T$. Then the BS constructs the matrix $\tilde{\mathbf{G}}$ as

$$\tilde{\mathbf{G}} = \mathbf{G}^H (\mathbf{G} \mathbf{G}^H)^{-1}, \quad (13)$$

and the precoder for the k^{th} user is then constructed as

$$\mathbf{u}_k = \frac{\tilde{\mathbf{G}}(:, k)}{\|\tilde{\mathbf{G}}(:, k)\|}. \quad (14)$$

IV. NUMERICAL RESULTS

In this section, we show the sum-rate performance of the proposed beamforming scheme for our network model and compare the performance with the benchmark UPA-based analog-digital hybrid precoding proposed for the broadcast channel in [16]. We consider the example shown in Fig. 2 where the BS is a lens MIMO system for which the transmit aperture $A_T = 20$ and $\tilde{D}_T = 10$. Note that $\tilde{D}_T = 10$ corresponds to $N_{BS} = 21$. Similar to [15], for fairness of comparison, the UPA based BS is assumed to have the same aperture as the lens MIMO, and therefore, the number of BS antennas in the UPA-based BS can be given as $N_{BS,U} = 80$ [15]. The MSs are UPA based array antennas and the number of antennas at each MS, i.e., $N_{MS} = 16$.

As shown in Fig. 2, we assume that each MS receives signal from the BS along two paths, i.e., $L_k = 2$ in (4). For example, the first MS receives its desired signal from its desired antenna as well as an interfering signal from another BS antenna which, in fact, intends to transmit data to the second MS.

We assume that the complex-valued channel gains $\alpha_{k,l}$ are modeled as $\alpha_{k,l} = \sqrt{N_{MS}} \sqrt{\beta \kappa_{k,l}} e^{j\eta_{k,l}}$, $k \in \mathcal{K} = \{1, 2, \dots, K\}$, $l \in \mathcal{L}_k = \{1, 2, \dots, L_k\}$ [7], where $\sqrt{N_{MS}}$ accounts for the receiver array gain, β denotes the large-scale attenuation including path-loss and shadowing factor, $\kappa_{k,l}$ denotes the power fractional ratio for the l^{th} path of the k^{th} MS with $\sum_{l=1}^{L_k} \kappa_{k,l} = 1$, and $\eta_{k,l} \sim U[0, 2\pi]$ denotes the phase shift of the l^{th} path of the k^{th} MS. β is based on the generic model given in [7] as $-\beta_{dB} = c_1 + 10c_2 \log_{10}(d) + \xi$, where c_1 and c_2 denote the model parameters, d is the communication distance in meters, and $\xi \sim \mathcal{CN}(0, \epsilon^2)$ denotes the lognormal shadowing. We assume that the mmWave system operates at 28 GHz for which the channel parameters are obtained from [7] as: $c_1 = 72$, $c_2 = 2.92$, $\epsilon = 8.7dB$. We also assume that all the MSs are equidistant from the BS with $d = 100m$ which ensures that the average receive SNR of each MS is the same. Thus, the difference in the channels of the users comes mainly from the shadowing and short-term fading. The path-loss for each MS is thus, 130.4 dB, or $\mathbb{E}\{\beta\} = -130.4dB$. Furthermore, the multi-path power distribution $\kappa_{k,l}$ can be modeled as $\kappa_{k,l} = \frac{\kappa'_{k,l}}{\sum_{i=1}^{L_k} \kappa'_{k,i'}}$ with $\kappa'_i = U_i^{r_\tau - 1} 10^{-0.1Z_i}$, where $U_i \sim U[0, 1]$ and $Z_i \sim \mathcal{CN}(0, \zeta^2)$ are random variables which account for the variations in delay and lognormal shadowing among different paths, respectively [7]. For mmWave frequencies at 28 GHz, $r_\tau = 2.8$ and $\zeta = 4$ [7]. We assume that the system bandwidth is $W = 500$ MHz, and the noise power spectrum density is $N_0 = -174$ dBm/Hz. The average SNR at each MS is given as $SNR \triangleq \frac{PE\{\beta\}}{\sigma_\beta^2}$.

In Fig. 3, we take fixed AoDs and AoAs for the users. Specifically, the AoDs (in radians) for the first, second and the third users are chosen as $\phi_1 = -0.4115$, $\phi_2 = -0.1002$ and $\phi_3 = 0.3047$ respectively. Note that with the above chosen values, the BS antennas with indices -4, -1 and +3 are selected as the transmitting antennas for the first, second and

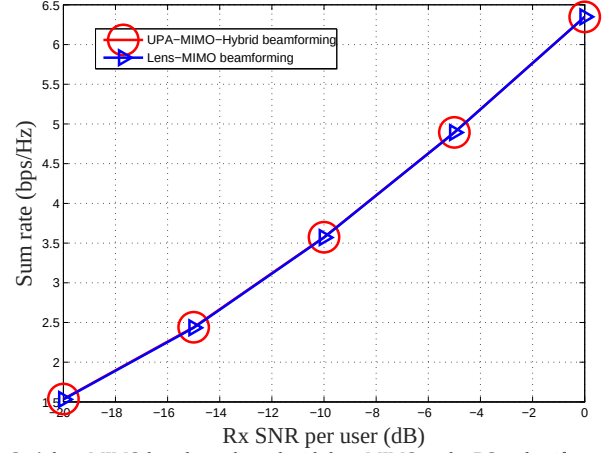


Fig. 3: A lens MIMO broadcast channel with lens MIMO at the BS and uniform planar arrays (UPA) at the MSs. Here, the AoDs are exactly aligned with the antennas on the BS.

the third users respectively, and are exactly aligned with the corresponding AoDs. Similarly, the AoAs for the two paths of the first MS are chosen as $\phi_{1,1} = -0.4363$ and $\phi_{1,2} = 0.2793$, the AoAs for the two paths of the second user are chosen as $\phi_{2,1} = -0.6283$ and $\phi_{2,2} = 0.3840$, and the AoAs for the two paths of the third user are chosen as $\phi_{3,1} = 0.1920$ and $\phi_{3,2} = -0.7330$, respectively.

It is observed that even with only 21 BS antennas and no active phase shifters, the lens MIMO based system shows almost the same sum-rate performance as the benchmark UPA-MIMO based hybrid precoding approach [16]. Note that in the UPA-MIMO approach, since there are 80 BS antennas and 3 RF chains, 240 phase shifters are required in total. Thus, the lens MIMO based system significantly reduces the hardware and signal processing complexity as compared to the UPA-MIMO system without losing any performance.

Next, in Fig. 4, we plot the sum-rate performances of the lens antenna array based broadcast channel model and the UPA-MIMO based broadcast channel model in more realistic scenarios. Here, the AoDs of the signal paths of the users are chosen randomly, and hence may not be aligned with any of the BS antennas. Moreover, the AoDs corresponding to the desired paths of the users are assumed to be sufficiently separated, and six RF chains are used to serve the three users in the lens MIMO system. The sum-rates of the different algorithms are averaged over 10000 channel realizations. In the lens MIMO broadcast channel, we have the flexibility to use all the available six RF chains and the performance is very close to the UPA-MIMO based broadcast network when perfect CSI is used for the UPA-MIMO system. It is worth noting that the UPA-MIMO achieves slightly higher sum-rate because of the continuous phase angle based beam steering using 240 phase shifters.

However, in realistic scenarios, the phase shifters of UPA-MIMO do not assume continuous values and in our simulation, we assume that the phase angles of RF precoder in UPA-MIMO are quantized using six bits, i.e., as large as 64 quantized directions are available for analog beamformer

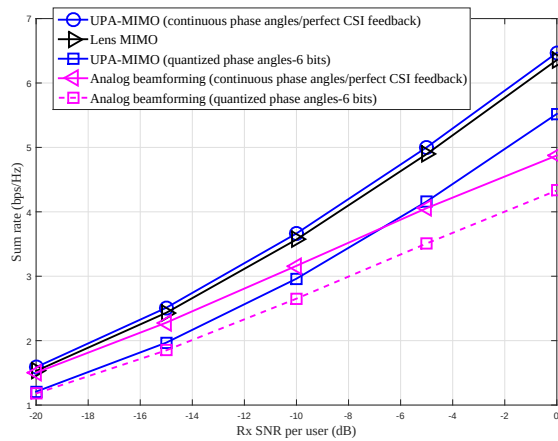


Fig. 4: A lens MIMO broadcast channel with lens MIMO at the BS and uniform planar arrays (UPA) at the MSs. The AoDs are not aligned with the BS antennas.

design in UPA-MIMO. We observe that using quantized phase shifting, the UPA-MIMO performance degrades significantly. On the other hand, in lens MIMO system, AoD estimation is not necessary and energy-based antenna selection suffices [18]. Thus, under practical assumptions, lens MIMO indeed shows the best sum-rate performance with lesser channel estimation overhead, and saves significant hardware and signal processing complexity as compared to the UPA-MIMO based system.

V. CONCLUSION

In this paper, we studied a lens MIMO based broadcast channel and compared its performance with a standard phase-shifter based analog-digital hybrid beamforming (HBF) scheme for the broadcast channel. We showed that in general, the lens MIMO system shows almost the same sum-rate performance as the UPA-MIMO based HBF but it saves significantly large amount of power and signal processing complexity. Thus, the lens MIMO based broadcast channel is much more energy-efficient. We also considered a more realistic situation where quantized phase angles are used for beam steering in the UPA-MIMO based HBF. In this case, the lens MIMO system, which does not require any beam steering, shows much better sum-rate performance as compared to the UPA-MIMO system.

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