IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 23 June 2022, accepted 11 July 2022, date of publication 14 July 2022, date of current version 21 July 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3190866

RESEARCH ARTICLE

Energy and Spectral-Efficient Lens Antenna Subarray Design in MmWave MIMO Systems

LIZA AFEEF[1], GOKHAN MUMCU[2], (Senior Member, IEEE), AND HÜSEYIN ARSLAN[1,2], (Fellow, IEEE)

[1]Department of Electrical and Electronics Engineering, İstanbul Medipol University, 34810 İstanbul, Turkey
[2]Department of Electrical Engineering, University of South Florida, Tampa, FL 33620, USA

Corresponding author: Liza Afeef (liza.shehab@std.medipol.edu.tr)

This work was supported in part by the U.S. National Science Foundation under Award ECCS-1923857.

ABSTRACT Lens antenna subarray (LAS) is one of the recently introduced technologies for future wireless networks that significantly improves the energy efficiency of multiple-input multiple-output (MIMO) systems while achieving higher spectral efficiency compared to single-lens MIMO systems. However, a control mechanism for the LAS-MIMO design is considered a challenging task to efficiently manage the network resources and serve multiple users in the system. Therefore, in this paper, a sub-grouped LAS-MIMO architecture along with a hybrid precoding algorithm are proposed to reduce the cost and hardware overhead of traditional hybrid MIMO systems. Specifically, the LAS structure is divided into sub-groups to serve multiple users with different requirements, and an optimization problem based on the achievable sum-rate is formulated to maximize the spectral efficiency of the system. By splitting the sum-rate problem into sub-rate optimization problems, we develop a low-complexity hybrid precoding algorithm to effectively control the proposed architecture and maximize the achievable sum-rate of each subgroup. The proposed precoding algorithm selects the beam of each lens from a predefined set within a subgroup that maximizes the subgroup sum-rate, while the phase shifters and digital precoders in each subgroup are computed independently. The link between subgroups is updated based on successive interference cancelation to minimize interference between users of different subgroups. Our analysis and simulation results show that the proposed precoding algorithm of the sub-grouped LAS-MIMO architecture performs almost as well as traditional fully-connected hybrid MIMO systems in terms of spectral efficiency at low and high signal-to-noise ratio (SNR). It also outperforms traditional fully-connected and sub-connected hybrid MIMO systems in terms of energy efficiency, even when a large number of lenses are employed.

INDEX TERMS Lens antenna subarray (LAS), sub-grouped, MIMO, mmWave, hybrid precoding, energy efficiency, spectral efficiency.

I. INTRODUCTION

Millimeter-wave (mmWave) systems are the key technology for next-generation wireless communications systems that support higher data rates and wide bandwidths. The mmWave bands enable the use of multiple antenna technologies such as multiple-input multiple-output (MIMO) due to the short wavelength that allows a large antenna array to be packed into small form factors. Although MIMO systems can provide directional transmission with high gain, each antenna element requires its own radio-frequency (RF) chain in digital beamforming, resulting in high cost and power consumption [1]. To overcome this problem, various hybrid beamforming architectures have been developed that have a smaller number of RF chains compared to fully digital beamforming systems [2]. In these systems, hybrid precoding algorithms are developed to optimize beamforming in both the analog and digital domains. They are based either on spatially sparse precoding techniques as in [3] or on a codebook with an iterative search procedure as in [4] to calibrate a small number of RF chains with a large number of antenna elements in the array.

The associate editor coordinating the review of this manuscript and approving it for publication was Fulvio Schettino.

Many wireless systems using hybrid beamforming architectures require a large number of phase shifters (PSs) to provide uniform data transmission, resulting in power consumption that outweighs the energy-saving benefits of using fewer RF chains, as discussed in [2]. Therefore, alternative designs such as lens antenna array (LAA) [5] along with beamspace MIMO channel representation [6] are introduced to make the hybrid beamforming MIMO systems more applicable in practice and replace the bulky PS network with a simple switching network.

The LAA enables the representation of the mmWave MIMO channel in sparse beamspace domain by using a unitary discrete Fourier transform matrix. In addition, LAA has the ability to focus the signal power beam on different antenna elements. Due to the sparseness of the beamspace channel in mmWave systems, the number of focused energy beams is much less than that of the number of antenna elements, leading to the use of beam selection techniques [7]–[9]. The design of a beamforming system for a large antenna array, as in massive MIMO [10]–[12], with only a single-lens array presents some difficulties, including power leakage problem [13], large focal depth of the lens [14], and lack of scalability, since a larger/smaller lens must be redesigned when the number of antenna elements changes. Therefore, dividing the aperture area occupied by a large single lens into smaller lenses is proposed in [15]–[17] under the name of lens antenna subarray (LAS) to obtain a competitive system in terms of RF design feasibility and power consumption reduction with minimal impact on per-chain capacity.

In order to investigate the performance of the hybrid LAS-MIMO architecture shown in Figure 1(a), an analog/digital precoding technique was used based on an exhaustive search in [17]. The results in [17] show that the hybrid LAS architecture remarkably improves spectral efficiency and energy efficiency compared to a single-lens system under various mmWave channel conditions. Compared to a MIMO system without a lens array, i.e., hybrid traditional array (TA)-MIMO architecture [3], the LAS design shows a significant improvement in energy efficiency at sufficient data rate levels. However, the practical use of a fully-connected hybrid LAS-MIMO architecture with a precoding algorithm based on exhaustive search is challenging due to its high computational complexity. Therefore, in this paper, we propose a sub-grouped LAS-MIMO architecture with a low-complexity hybrid precoding design for mmWave MIMO systems.

The contributions of this work can be summarized as follows:

- We design a sub-grouped LAS structure in mmWave MIMO systems for multi-user communication scenarios. In the proposed sub-group design, the RF paths are grouped into subgroups, where each subgroup is associated with a part of the lens subarray to serve different users located in different environments with diverse requirements. This grouping of RF chains reduces the implementation complexity of the fully-connected LAS structure presented in [17], resulting in a reduction of RF power consumption.
- We propose a beam selection-based sum-rate maximization algorithm and an associated precoder to drive the proposed sub-grouped LAS-MIMO design. Since the transmitted beam and the sub-beams of the lens array have no direct relationship, the conventional beam selection methods cannot be directly applied to the lens subarray design. Therefore, the proposed precoding algorithm divides the optimization problem in a fully-connected LAS-MIMO system into sub-rate optimization ones. In each sub-rate optimization problem, the conventional exhaustive search-based full beam selection is simplified and partially applied to optimize the beam selection network and reduce the time required to implement the algorithm. For a given sub-group process, user interference between subgroups is then suppressed by removing the contribution of the previously solved sub-rate optimization problem of the previous sub-group from the current sub-rate optimization problem using the successive interference cancellation (SIC) concept.
- The performance of the proposed sub-grouped LAS-MIMO architecture and the proposed precoding algorithm are investigated in terms of power consumption, complexity, spectral efficiency, and energy efficiency. Simulation results demonstrate that the proposed precoding algorithm achieves similar sum-rate level as the fully-connected hybrid TA-MIMO systems while matching the performance of fully and sub-connected hybrid TA-MIMO systems in terms of energy efficiency with nearly 400% and 45% at high signal-to-noise ratio (SNR) levels for 8 users in the system.

The remaining parts of this paper are organized as follows. Section II presents the mmWave MIMO system using LAS design along with its design issue. Section III presents the system design of the proposed sub-grouped hybrid LAS architecture along with the proposed precoding algorithm. In this section, the complexity of the proposed algorithm is calculated and the energy consumption model for the systems using the fully-connected and the proposed sub-grouped hybrid LAS-MIMO architecture is also provided. Section IV presents the numerical results for the power consumption and efficiency of the systems using both the fully-connected and the sub-grouped hybrid LAS-MIMO architectures. Finally, Section V concludes the paper and provides directions for the future.

Notation: bold uppercase $\mathbf{A}$, bold lowercase $\mathbf{a}$, and unbold letters A and a are used to denote matrices, vectors, and scalar values, respectively. $\|\mathbf{a}\|_F$ is the Frobenius norm. $|\cdot|$ denotes the determinant operation. $tr\{\cdot\}$, $(\cdot)^H$, $(\cdot)^T$, and $(\cdot)^{-1}$ denote the trace, Hermitian, transpose, and inverse, respectively. diag($\mathbf{a}$) is the diagonal matrix with the vector $\mathbf{a}$ on its diagonal. $\mathbb{C}^{M\times N}$ denotes the space of $M \times N$ complex-valued matrices. Finally, $\mathbf{I}_N$ is the $N \times N$ identity matrix.

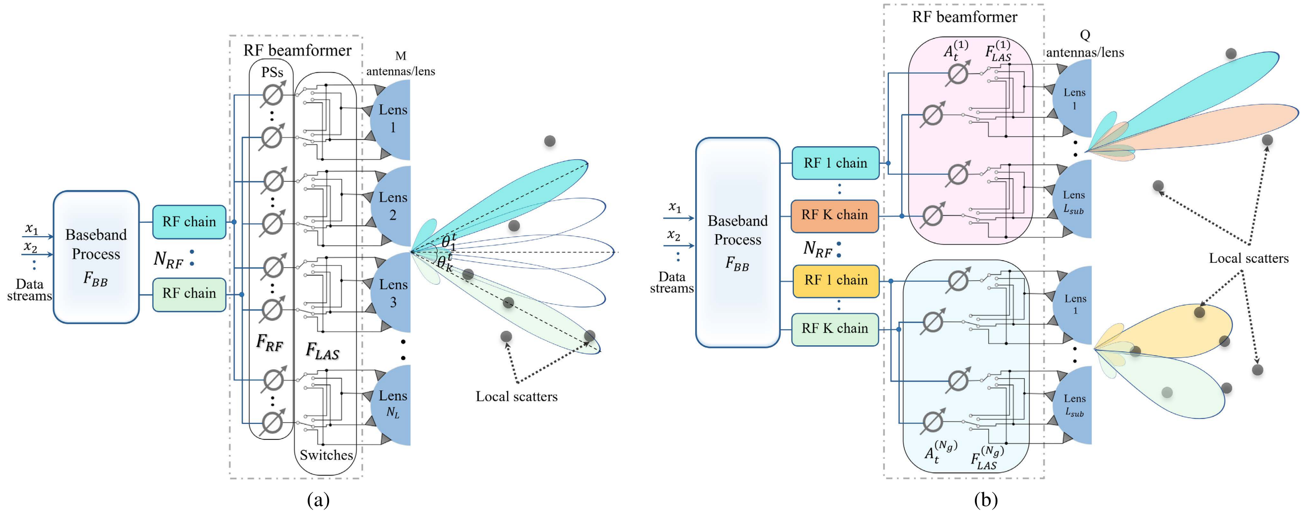

FIGURE 1. LAS-MIMO system model for (a) fully-connected and (b) proposed sub-grouped architectures.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. LAS-MIMO SYSTEM MODEL

Consider a downlink mmWave MIMO system using LAS. The base station (BS) uses N_t antenna elements connected to N_L lenses. Each lens has M antenna elements, so $M = N_t/N_L$ where M is integer, as shown in Fig. 1(a). Note that all M lens sizes are much smaller than a typical single-lens [5] system, hence the architecture is referred to as LAS. In addition, the BS has N_{RF} RF chains to simultaneously serve K single-antenna users. Since the total number of active users can be arbitrarily larger than N_{RF} in practice, we assume that the BS first selects N_{RF} users from the total active user pool before transmission to achieve full multiplexing gains [18], [19].

As in Fig. 1(a), the data stream is first passed through a baseband precoder $\mathbf{F}_{\mathrm{BB}} \in \mathbb{C}^{N_{\mathrm{RF}}\times N_{\mathrm{RF}}}$. Then, the output of each RF chain is passed through a B-bit PS network with $\mathbf{f}_{\mathrm{RF}}$ precoding vector. The PS precoder of the k-th RF chain is

$$\mathbf{f}_{\mathrm{RF}}^{(k)} = \frac{1}{\sqrt{N_L}}\left[e^{j\phi_{1,k}}, e^{j\phi_{2,k}}, \ldots, e^{j\phi_{N_L,k}}\right]^T, \tag{1}$$

where $\phi_l = \frac{2\pi b}{2^B}, l = 1, 2, \cdots, N_L$. b can take any value from $b = \{b; b = 0, 1, \ldots, 2^B - 1\}$ [20]. The total PS precoder at all RF chains is $\mathbf{F}_{\mathrm{RF}} = [\mathbf{f}_{\mathrm{RF}}^{(1)}, \mathbf{f}_{\mathrm{RF}}^{(2)}, \ldots, \mathbf{f}_{\mathrm{RF}}^{(N_{\mathrm{RF}})}]$. After that, the analog signal is routed through a switching mechanism modeled by a $\mathbf{F}_{\mathrm{LAS}}$ precoder to the lenses for transmission, given as follows

$$\mathbf{F}_{\mathrm{LAS}} = \begin{bmatrix} \mathbf{s}_t^{(1)} & \mathbf{0}_{M\times 1} & \cdots & \mathbf{0}_{M\times 1} \\ \mathbf{0}_{M\times 1} & \mathbf{s}_t^{(2)} & & \mathbf{0}_{M\times 1} \\ \vdots & & \ddots & \vdots \\ \mathbf{0}_{M\times 1} & \mathbf{0}_{M\times 1} & \cdots & \mathbf{s}_t^{(N_L)} \end{bmatrix}, \tag{2}$$

where $\mathbf{s}_t^{(l)}$ is the $M \times 1$ beam selection vector at lens l overlaid by all RF chains. For $\boldsymbol{x}$ transmitted streams, the received signal at user k is given as

$$y_k = \mathbf{h}_k\mathbf{F}_{\mathrm{LAS}}\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\boldsymbol{x} + n_k, \tag{3}$$

where $\mathbf{h}_k \in \mathbb{C}^{1\times N_t}$ is the narrowband channel of user k and $n \sim \mathcal{CN}(0, \sigma_o^2)$ is an additive white Gaussian noise. Here we use the clustered geometric channel representation, which is useful for modeling mmWave propagation, i.e., the k-th user channel is given as [21]

$$\mathbf{h}_k = \sum_{i=1}^{P_k} \beta_{i,k}\mathbf{a}^H(\theta_{i,k}^t), \tag{4}$$

where P_k is the number of channel paths of user k, $\beta_{i,k}$ is the channel coefficient with complex normal distribution $\mathcal{CN}(0, 1)$ on the i-th path for the k-th user, $\theta_{i,k}^t$ is the angle of departure (AoD), and $\mathbf{a}$ is the response vector of the transmit antenna array. For a uniformly spaced antenna array, the steering vector is given as

$$\mathbf{a}(\theta) = \left[1, e^{-j2\pi\frac{d}{\lambda}\sin\theta}, \ldots, e^{-j2\pi\frac{d}{\lambda}(N_t-1)\sin\theta}\right]^T, \tag{5}$$

where $d = \lambda/2$ being inter-element spacing and λ is the carrier wavelength.

B. PROBLEM FORMULATION

Assume that the total design precoding $\mathbf{F} = \mathbf{F}_{\mathrm{LAS}}\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}$, the achievable spectral efficiency for all users is given by [3]

$$R_{\mathrm{full}} = \log_2\left(\left|\mathbf{I}_{N_{\mathrm{RF}}} + \frac{\gamma}{N_{\mathrm{RF}}}\mathbf{H}\mathbf{F}\mathbf{F}^H\mathbf{H}^H\right|\right), \tag{6}$$

where γ is the SNR value, and $\mathbf{H} = [\mathbf{h}_1^T, \mathbf{h}_2^T, \ldots, \mathbf{h}_{N_{\mathrm{RF}}}^T]^T$ is the channel matrix of all users.

In general, the precoding design aims to maximize the spectral efficiency overall users, taking into account the transmit power constraint and the constant modulus constraint of the analog beamformers. Therefore, the problem is formulated as follows

$$\begin{aligned}(\mathbf{F}_{\mathrm{LAS}}^{\mathrm{opt}}, \mathbf{F}_{\mathrm{RF}}^{\mathrm{opt}}, \mathbf{F}_{\mathrm{BB}}^{\mathrm{opt}}) = \underset{\mathbf{F}_{\mathrm{LAS}},\mathbf{F}_{\mathrm{RF}},\mathbf{F}_{\mathrm{BB}}}{\arg\max} \; & R_{\mathrm{full}}, \\ \text{s.t. } & \mathbf{F}_{\mathrm{RF}} \in \mathcal{F}_{\mathrm{RF}}, \\ & \mathbf{F}_{\mathrm{LAS}} \in \mathcal{F}_{\mathrm{LAS}}, \\ & \mathrm{tr}\left(\mathbf{F}_{\mathrm{BB}}^{H}\mathbf{F}_{\mathrm{RF}}^{H}\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\right) = N_{\mathrm{RF}}, \\ & ||\mathbf{F}_{\mathrm{RF}}||_F^2 = 1, \end{aligned} \quad (7)$$

given that $\mathcal{F}_{\mathrm{LAS}}$ is the set containing all feasible LAS selected beams [17] while $\mathcal{F}_{\mathrm{RF}}$ is the set of feasible RF precoders, i.e., the set of $N_t \times N_{\mathrm{RF}}$ matrices for $\mathbf{F}_{\mathrm{RF}}$ matrix with constant magnitude entries [3].

It is assumed that the BS perfectly estimates the channel matrix $\mathbf{H}$ using an effective channel estimation scheme such as the techniques presented in [22]–[28] to obtain the estimated channel $\hat{\mathbf{H}}$. Other estimation techniques depending on the proposed lens architecture can be explored in future work.

The problem in (7) is ideally solved by an exhaustive search over all possible sets for the precoder $\mathbf{F}_{\mathrm{LAS}}$ and $\mathbf{F}_{\mathrm{RF}}$, while the digital precoder $\mathbf{F}_{\mathrm{BB}}$ can be computed by using zero-forcing technique according to [29] as follows

$$\mathbf{F}_{\mathrm{BB}} = \left(\mathbf{F}_{\mathrm{RF}}^{H}\mathbf{F}_{\mathrm{LAS}}^{H}\hat{\mathbf{H}}^{H}\hat{\mathbf{H}}\mathbf{F}_{\mathrm{LAS}}\mathbf{F}_{\mathrm{RF}}\right)^{-1}\left(\hat{\mathbf{H}}\mathbf{F}_{\mathrm{LAS}}\mathbf{F}_{\mathrm{RF}}\right)^{H}. \quad (8)$$

However, it should be noted that due to the non-convex feasibility constraint $\mathbf{F}_{\mathrm{RF}} \in \mathcal{F}_{\mathrm{RF}}$, there is no general solutions to (7) [3], and the optimization over $\mathbf{F}_{\mathrm{LAS}}$ and $\mathbf{F}_{\mathrm{RF}}$ jointly is unfeasible for the following reasons:

1) To design $\mathbf{F}_{\mathrm{RF}}$, an exhaustive search from a predefined set is required to find an optimal solution. However, the possible choices in the set increase exponentially with the increase in lenses and PSs resolutions.
2) In beam selection matrix $\mathbf{F}_{\mathrm{LAS}}$, as defined in [17], the complexity is limited to the number of lenses N_L and antenna elements associated with each lens M. For a fixed M, as the number of N_L in the system increases, the number of search angles increases exponentially, since each lens has its own angle that must be set optimally.

Consequently, we propose a MIMO system using a sub-grouped hybrid LAS architecture (i.e., sub-grouped LAS-MIMO system) to reduce the complexity of the precoder and to further improve the energy efficiency of the system.

III. PROPOSED SUB-GROUPED LAS TRANSCEIVER DESIGN

In this section, we first present the proposed sub-grouped LAS transceiver design, where the conventional LAS-MIMO system is grouped into sub-grouped LAS-MIMO. Then, a sub-grouped-based precoding is proposed for the presented LAS design. After that, the complexity of the proposed algorithm is calculated, and the model for estimating the energy efficiency of the fully connected and the proposed sub-grouped LAS architectures is presented.

A. TRANSCEIVER DESIGN

In conventional fully-connected LAS-MIMO design, as shown in Figure 1(a), the signal out of each RF chain is passed from all PSs to the activated antenna element by a switching network under each lens in the LAS structure. Hence, the transmitted beam is launched from all N_L lenses in the design. This results in producing similar beam gains as in conventional fully-connected TA-MIMO system with significantly less hardware requirement and thus less power consumption [17]. However, as the size of the antenna array increases, the channel realization varies in each part of the antenna array. Therefore, different users served by this system face diverse environments. For instance, user at 30° direction experiences a high-sparse channel with only one line-of-sight (LoS) path. This user would prefer to be served with the maximum beamforming gain that the system can provide. Another user, who is in the 130° direction, may be faced with multiple scatterers that create a multipath channel. To serve this user, an optimized beamforming gain is required based on the realization of his channel, which is different from that of the first user.

In order to serve multiple users with different requirements and further improve the energy efficiency of the conventional fully-connected LAS-MIMO system, a sub-grouped LAS design is proposed in this work by dividing the multiple lenses structure in fully-connected LAS-MIMO design into N_g sub-groups. In each sub group, there are $L_{\mathrm{sub}} = \frac{N_L}{N_g}$ lenses with $K_{\mathrm{sub}} = \frac{N_{\mathrm{RF}}}{N_g}$ RF chains connected to all L_{sub} lenses as shown in Figure 1(b), given that K_{sub} is chosen to be an integer and there are Q antenna elements under each lens. Unlike the conventional fully-connected LAS-MIMO design, in the proposed sub-grouped LAS-MIMO structure, the signal generated from one RF chain belongs to only one sub group and does not connect to other lenses in the other sub groups. Figure 1(b) illustrates the transmitter design of the proposed sub-grouped LAS-MIMO architecture, while the receiver obeys the inverse architecture. The following subsection focuses on the hybrid precoding design to control the proposed sub-grouped LAS architecture.

B. PROPOSED SUB-GROUPED-BASED PRECODING

In the proposed sub-grouped architecture, the hybrid precoder turns to be a spatial block diagonal such as $\mathbf{F} = \mathrm{diag}\{\mathbf{F}_{(1)}, \mathbf{F}_{(2)}, \ldots, \mathbf{F}_{(n)}, \cdots, \mathbf{F}_{(N_g)}\} = [\mathbf{F}'_{(1)}, \mathbf{F}'_{(2)}, \ldots, \mathbf{F}'_{(N_g)}]$. This is due to the simplified structure of $\mathbf{F}_{\mathrm{LAS}}$, $\mathbf{F}_{\mathrm{RF}}$, and $\mathbf{F}_{\mathrm{BB}}$, given as follows

$$\mathbf{F}_{\mathrm{LAS}} = \begin{bmatrix} \mathbf{F}_{\mathrm{LAS}}^{(1)} & \mathbf{0}_{QL_{\mathrm{sub}}\times L_{\mathrm{sub}}} & \cdots & \mathbf{0}_{QL_{\mathrm{sub}}\times L_{\mathrm{sub}}} \\ \mathbf{0}_{QL_{\mathrm{sub}}\times L_{\mathrm{sub}}} & \mathbf{F}_{\mathrm{LAS}}^{(2)} & & \mathbf{0}_{QL_{\mathrm{sub}}\times L_{\mathrm{sub}}} \\ \vdots & & \ddots & \vdots \\ \mathbf{0}_{QN_{L_{\mathrm{sub}}}\times N_{L_{\mathrm{sub}}}} & \mathbf{0}_{QL_{\mathrm{sub}}\times L_{\mathrm{sub}}} & \cdots & \mathbf{F}_{\mathrm{LAS}}^{(N_g)} \end{bmatrix}, \quad (9)$$

$$\mathbf{F}_{\mathrm{RF}} = \begin{bmatrix} \mathbf{A}_t^{(1)} & \mathbf{0}_{L_{\mathrm{sub}} \times K_{\mathrm{sub}}} & \cdots & \mathbf{0}_{L_{\mathrm{sub}} \times K_{\mathrm{sub}}} \\ \mathbf{0}_{L_{\mathrm{sub}} \times K_{\mathrm{sub}}} & \mathbf{A}_t^{(2)} & & \mathbf{0}_{L_{\mathrm{sub}} \times K_{\mathrm{sub}}} \\ \vdots & & \ddots & \vdots \\ \mathbf{0}_{L_{\mathrm{sub}} \times K_{\mathrm{sub}}} & \mathbf{0}_{L_{\mathrm{sub}} \times K_{\mathrm{sub}}} & \cdots & \mathbf{A}_t^{(N_g)} \end{bmatrix}, \tag{10}$$

$$\mathbf{F}_{\mathrm{BB}} = \begin{bmatrix} \mathbf{F}_{\mathrm{BB}}^{(1)} & \mathbf{0}_{K_{\mathrm{sub}} \times K_{\mathrm{sub}}} & \cdots & \mathbf{0}_{K_{\mathrm{sub}} \times K_{\mathrm{sub}}} \\ \mathbf{0}_{K_{\mathrm{sub}} \times K_{\mathrm{sub}}} & \mathbf{F}_{\mathrm{BB}}^{(2)} & & \mathbf{0}_{K_{\mathrm{sub}} \times K_{\mathrm{sub}}} \\ \vdots & & \ddots & \vdots \\ \mathbf{0}_{K_{\mathrm{sub}} \times K_{\mathrm{sub}}} & \mathbf{0}_{K_{\mathrm{sub}} \times K_{\mathrm{sub}}} & \cdots & \mathbf{F}_{\mathrm{BB}}^{(N_g)} \end{bmatrix}, \tag{11}$$

where $\mathbf{A}_t$ is a $L_{\mathrm{sub}} \times K_{\mathrm{sub}}$ matrix where its vector follows (1) with L_{sub} elements.

In addition to the above beamformer constraints, the constraints in (7) for the optimization problem are also considered in the proposed sub-grouped scheme. Considering that the precoding on different sub-grouped in the LAS architecture is independent, the optimization problem can be divided into a set of suboptimization problems as stated in [30] using the SIC concept. Therefore, based on the proposed model for sub-grouped systems, (6) can be modified as follows

$$R_g = \sum_{n=1}^{N_g} \log_2 \left(\left| \mathbf{I}_{K_{\mathrm{sub}}} + \frac{\gamma}{N_{\mathrm{RF}}} (\mathbf{F}'_{(n)})^H \hat{\mathbf{H}}^H \mathbf{V}_{n-1}^{-1} \hat{\mathbf{H}} \mathbf{F}'_{(n)} \right| \right), \tag{12}$$

where $\mathbf{F}'_{(n)}$ is $N_t \times K_{\mathrm{sub}}$ sub matrix of matrix $\mathbf{F}$, and $\mathbf{V}_n = \mathbf{I}_{N_{\mathrm{RF}}} + \frac{\gamma}{N_{\mathrm{RF}}} \hat{\mathbf{H}} \mathbf{F}_n \mathbf{F}_n^H \hat{\mathbf{H}}^H$ is the auxiliary matrix for interference cancellation between the sub-groups with $\mathbf{V}_0 = \mathbf{I}_{N_{\mathrm{RF}}}$ where $\mathbf{F}_n$ is $N_t \times nK_{\mathrm{sub}}$ matrix contain the first nK_{sub} columns of $\mathbf{F}$. Thus, since $\mathbf{F}'_{(n)}$ has non-zero values at $\mathbf{F}_{(n)}$ only, the sub-optimization problem can be equivalently written as

$$\mathbf{F}_{(n)}^{\mathrm{opt}} = \arg\max_{\mathbf{F}_{(n)}} \log_2 \left(\left| \mathbf{I}_{K_{\mathrm{sub}}} + \frac{\gamma}{N_{\mathrm{RF}}} (\mathbf{F}'_{(n)})^H \hat{\mathbf{H}}^H \mathbf{V}_{n-1}^{-1} \hat{\mathbf{H}} \mathbf{F}'_{(n)} \right| \right), \tag{13}$$

which follows the constraints stated in (7). The optimization problem starts by optimizing the achievable spectral efficiency of the first sub-grouped array $\mathbf{F}_{(1)}$ by excessively searching all possible switches' and PS's set for the $\mathbf{F}_{\mathrm{LAS}}^{(1)}$ and $\mathbf{A}_t^{(1)}$ optimization, respectively. To relax the optimization problem, the ℓ-th column in the sub-grouped PS precoder $\mathbf{A}_t^{(1)}$ can be modeled by a beamforming vector as follows

$$\mathbf{a}_t^{\ell} = \frac{1}{\sqrt{L_{\mathrm{sub}}}} \left[1, e^{j2\pi \frac{dL_{\mathrm{sub}}}{\lambda} \sin\theta_\ell}, \ldots, e^{j2\pi \frac{dL_{\mathrm{sub}}}{\lambda} (L_{\mathrm{sub}}-1)\sin\theta_\ell} \right]^T, \tag{14}$$

where $\sin\theta_\ell = \Phi_\ell$ with $\Phi_\ell = b/2^B$ and b is chosen so that θ_ℓ is approximately equal to the AoD of the user ℓ (i.e., $\theta_\ell \approx \hat{\theta}_\ell$). After selecting $\mathbf{F}_{\mathrm{LAS}}^{(1)}$ from the predefined set $\mathcal{F}_{\mathrm{LAS}}$, $\mathbf{F}_{\mathrm{BB}}^{(1)}$ is calculated by modifying (8) as follows

$$\mathbf{F}_{\mathrm{BB}}^{(1)} = \left(\left(\mathbf{H} \mathbf{F}_{\mathrm{LAS}}^{(1)} \mathbf{A}_t^{(1)} \right)^H \mathbf{H} \mathbf{F}_{\mathrm{LAS}}^{(1)} \mathbf{A}_t^{(1)} \right)^{-1} \left(\mathbf{H} \mathbf{F}_{\mathrm{LAS}}^{(1)} \mathbf{A}_t^{(1)} \right)^H, \tag{15}$$

where $\mathbf{H}$ is $K_{\mathrm{sub}} \times QL_{\mathrm{sub}}$ sub matrix of matrix $\hat{\mathbf{H}}$ that is corresponding to the given sub-grouped. Then, the matrix $\mathbf{V}_1$ is updated. The same procedures are accomplished for the other sub-grouped antennas until the last sub-grouped array. The proposed sub-grouped precoding is summarized in Algorithm 1.

Algorithm 1: Proposed Hybrid Precoding Algorithm of the Proposed Sub-Grouped LAS-MIMO System

---

Input: $N_g, N_{\mathrm{RF}}, \hat{\mathbf{H}}, \gamma, N_L, B$
Output: $R_{g,\max}$
Initialize $\mathbf{V}_0 = \mathbf{I}_{N_{\mathrm{RF}}}$,
Build all possible sets for $\mathcal{F}_{\mathrm{LAS}}$ for the proposed sub-grouped LAS-MIMO design
for $n = 1, 2, \ldots, N_g$ **do**
  for $\ell = 1, 2, \ldots, K_{sub}$ **do**
    Define $\theta_\ell \approx \hat{\theta}_\ell$ based on resolution value B,
    Define $\mathbf{a}_t^{\ell}$ as in (14).
  end
  for $i = 1, 2, \ldots,$ *all possible set in* $\mathcal{F}_{LAS}$ **do**
    Select the beams in $\mathbf{F}_{\mathrm{LAS}}^{(n,i)}$ from $\mathcal{F}_{\mathrm{LAS}}$ beams set,
    Calculate $\mathbf{F}_{\mathrm{BB}}^{(n,i)}$ using (15),
    Calculate $\mathbf{F}_{(n,i)} = \mathbf{F}_{\mathrm{LAS}}^{(n,i)} \mathbf{A}_t^{(n,i)} \mathbf{F}_{\mathrm{BB}}^{(n,i)}$,
    Calculate $R_{(n,i)} = \log_2 \left(\left| \mathbf{I}_{K_{\mathrm{sub}}} + \frac{\gamma}{N_{\mathrm{RF}}} (\mathbf{F}_{(n,i)})^H \hat{\mathbf{H}}^H \mathbf{V}_{n-1}^{-1} \hat{\mathbf{H}} \mathbf{F}_{(n,i)} \right| \right)$.
  end
  $\mathbf{F}_{(n)}^{\mathrm{opt}} = \arg\max R_{(n)}$,
  $R_n^{\max} = \max R_{(n)}$,
  Calculate $\mathbf{V}_n = \mathbf{I}_{N_{\mathrm{RF}}} + \frac{\gamma}{N_{\mathrm{RF}}} \hat{\mathbf{H}} \mathbf{F}_n \mathbf{F}_n^H \hat{\mathbf{H}}^H$.
end
$R_{g,\max} = \sum_{n=1}^{N_g} R_n^{\max}$

It is worth mentioning that in the sub-grouped LAS-MIMO system, each sub-group has a lower antenna gain compared to the fully-connected architecture, which may prevent the coverage of the distant users that can be covered by the fully-connected architecture. However, the LAS-MIMO system is able to provide less interference to all nearby users that are close enough to a particular subgroup. This is due to the ability of the proposed precoding algorithm to optimize each subgroup independently before updating the auxiliary matrix $\mathbf{V}_n$.

C. COMPLEXITY EVALUATION

A complexity evaluation is performed to show that the search procedure for the optimal precoder design is simplified with the proposed sub-grouped LAS-MIMO system as opposed to the fully-connected LAS-MIMO system. To obtain the optimal precoder, we first need to select a candidate $\mathbf{F}_{\text{LAS}}$ and the $\mathbf{F}_{\text{RF}}$, and then calculate the $\mathbf{F}_{\text{BB}}$ according to the (8). Since the constraint (7) for the fully-connected LAS-MIMO system contains $M \times N_L$ nonzero elements, the search process requires $2^{M\times N_L}$ possible $\mathbf{F}_{\text{LAS}}$, while $(2^B)^{N_L \times N_{\text{RF}}}$ requires possible $\mathbf{F}_{\text{RF}}$ quantities for $\mathcal{F}_{\text{LAS}}$, where B represents the bit resolution of the PSs. Therefore, $(2^B)^{N_L\times N_{\text{RF}}} \times 2^{M\times N_L}$ possible search can be obtained to design optimal $\mathbf{F}_{\text{LAS}}$, $\mathbf{F}_{\text{RF}}$, and $\mathbf{F}_{\text{BB}}$ which makes the computational cost prohibitive due to the large N_t in mmWave massive MIMO systems (i.e., for $M = 8$, $N_t = 64$, $N_L = 8$, and $B = 4$ the number of searches required is $(2^4)^8 \times 2^{8\times 8} \approx 8 \times 10^{28}$ for each RF chain).

On the other hand, in the proposed sub-grouped LAS-MIMO system, the number of searches required is significantly reduced because the precoders in the different subgroups are independent. Therefore, the search process is performed independently in each group. Moreover, the PS precoder is fixed and is set based on the direction of the users. Thus, for a given subgroup, the number of searches required for $\mathbf{F}^{(n)}_{\text{LAS}}$ is $2^{Q\times L_{\text{sub}}}$. Therefore, only $N_g \times 2^{Q\times L_{\text{sub}}}$ needs to be searched to find the appropriate precoder for the proposed sub-grouped LAS-MIMO design (i.e., considering $N_t = 64$, $N_L = 8$, $N_g = 4$ subgroups, and $Q = 8$ antennas per lens, the number of searches required is $4 \times 2^{8\times 2} \approx 2.6 \times 10^5$). According to the numerical results regarding the number of required searches, the precoding algorithm proposed in Algorithm 1 is suitable and affordable for the proposed sub-grouped LAS-MIMO system.

D. ENERGY EFFICIENCY

Energy efficiency can be defined as the number of bits that can be transmitted per unit of energy, or as the ratio between the achievable sum rate and the total power consumed by the system, as in [17], [31], which can be expressed as follows

$$EE = \frac{C}{P_c + \frac{P_x}{\rho}} = \frac{\text{Bw}\, R}{P_c + \frac{P_x}{\eta_{\text{PA}}\ \eta_{\text{SW}}}}, \tag{16}$$

where R is the spectral efficiency of a given system. C, Bw, P_c, and P_x represent the system capacity, the available system bandwidth, the total circuit power consumed, and the total RF power to be transmitted by the antenna elements, respectively. In addition, η_{PA} is the power amplifier efficiency and η_{SW} is the efficiency of the switches, which can be expressed as $\eta_{\text{SW}} = 10^{-\zeta \text{IL}_{\text{SW}}/10}$, where ζ is the number of series switches needed to implement the architecture under each lens and IL_{SW} is the insertion loss for the switch.

In order to calculate the energy efficiency of the LAS-MIMO systems, a power model is proposed for the Fig. 1(a) in [17] where the power consumption is defined as

$$P_c = N_{\text{RF}} N_L P_{\text{PS}} + \zeta N_{\text{RF}} N_L P_{\text{SW}} + N_{\text{RF}} P_{\text{RF}}, \tag{17}$$

where P_{PS}, P_{SW}, and P_{RF} are the power consumption of PS, switches, and RF chain, respectively. For the proposed sub-grouped LAS-MIMO architecture shown in Fig. 1(b), the power consumption model of the fully-connected LAS-MIMO architecture given in (17) needs to be modified as

$$P'_c = N_{\text{RF}} \frac{N_L}{N_g} P_{\text{PS}} + \zeta N_{\text{RF}} \frac{N_L}{N_g} P_{\text{SW}} + N_{\text{RF}} P_{\text{RF}}. \tag{18}$$

TABLE 1. Simulation parameters.

Parameters	Value
Bandwidth Bw	500 MHz
Carrier frequency	28 GHz
Phase shifter bit resolution B	4
BS antenna elements N_t	64
N_{RF} at BS side	1, 4, 8
N_{RF} at user equipment (UE) side	1
Channel paths P_k for each UE	4
P_{PS}	30 mW [2], [32]
P_{SW}	10 mW [17]
P_{RF}	220 mW [17]
η_{PA}	0.2 [17]
IL_{SW}	1 dB [17]
Number of series switches ζ	$\log_2(M)$

IV. SIMULATION RESULTS

In this section, the spectral and energy efficiency performances of the proposed sub-grouped LAS-MIMO system are evaluated when the proposed hybrid precoder is used by the system. The performances are compared with those of the TA-MIMO systems when the TA systems use three well-established precoders,which are defined as 1) TA fully-connected: optimal unconstrained precoding based on the single value decomposition (SVD) of the channel matrix for fully-connected hybrid beamforming MIMO structure, 2) TA sparse: spatially sparse precoding algorithm introduced in [3] and applied on a fully-connected hybrid beamforming MIMO structure, and 3) TA sub-connected: the SIC-based precoding introduced in [30] and applied on a sub-connected hybrid beamforming MIMO structure. Furthermore, the proposed precoding algorithm is applied on a fully-connected LAS design with $N_L = 4$ by assuming one group in the proposed sub-grouped LAS structure. TA performance evaluations assume that full-resolution PSs are used in all three system designs. In addition, as in [33], a sub-connected MIMO system model with one lens in each subgroup is considered, where each RF chain is connected to only one lens.

Simulation parameters set for all results are shown in Table 1. The transmit power is assumed to be $P_x = \text{EIRP} - G_{dB}$, where EIRP $= 45$ dBm is the effective isotropic radiated power and G represents the antenna array gain calculated with aperture efficiencies of 90% and 80% for the two architectures TA and LAS, respectively [17]. Each lens in the LAS system has an area of $M(\frac{\lambda}{2})^2$ with M antenna elements uniformly connected under this area. The AoD is assumed to follow a uniform distribution within $[-\pi/2, \pi/2]$ with 5° spreading. Finally, the two related spectral and energy efficiency results are averaged over 500 random channel realizations and reported.

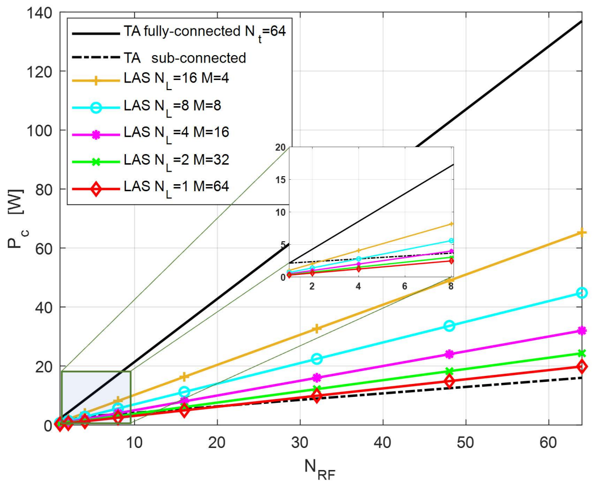

FIGURE 2. Power consumption vs N_{RF} for different N_L in the fully-connected LAS-MIMO system architecture.

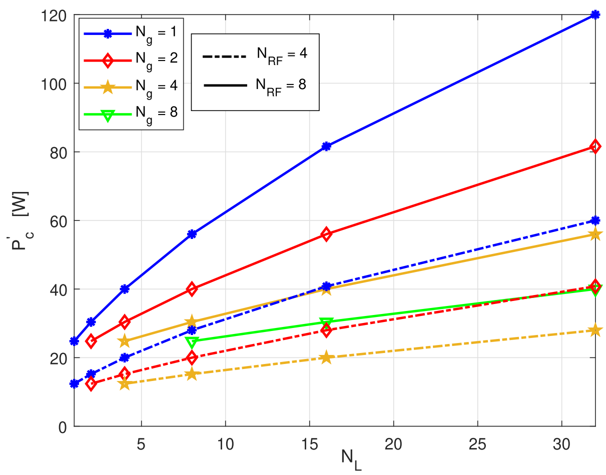

FIGURE 3. Power consumption vs N_L for different sub grouping at $N_{RF} = 4$ (dash lines) and $N_{RF} = 8$ (solid lines) in the proposed sub-grouped LAS-MIMO architecture.

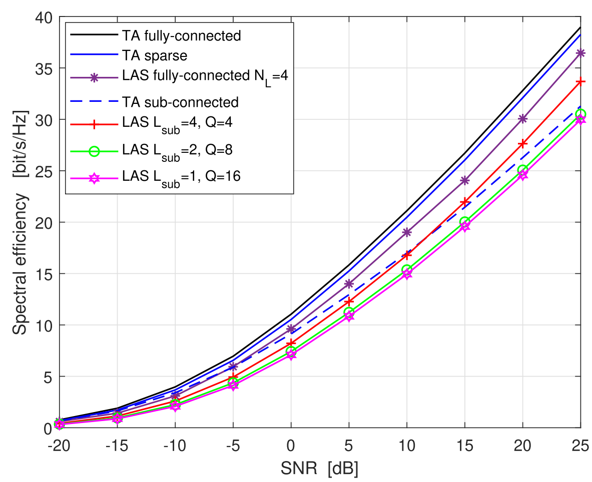

FIGURE 4. Spectral efficiency vs SNR for $N_{RF} = 4$ in the proposed sub-grouped LAS-MIMO architecture.

In Figure 2, a comparison for the power consumption at different numbers of RF chains is provided for the different fully-connected LAS-MIMO architectures, fully-connected TA-MIMO architecture, and sub-connected TA-MIMO architecture when the total number of antennas is $N_t = 64$. It is noticed that the fully-connected TA-MIMO architecture has the worst performance in terms of power consumption even with a high number of lenses in the LAS architectures. The power consumption of the LAS architectures increases with increasing the number of lenses due to the need for more PSs in the system to connect and control the added lenses. For example, an LAS architecture with 16 lenses consumes around 16 W at $N_{RF} = 16$ while the fully-connected TA-MIMO architecture consumes around 34 W. At a low number of RF chains, the LAS-MIMO architectures have lower power consumption than the sub-connected TA-MIMO architecture which makes it more applicable in a system with a high sparsity level since small numbers of RF chains can be only activated in the system if the channel is sparse as in mmWave channels [34].

The power consumption for the sub-grouped LAS-MIMO architecture versus N_L is illustrated in Figure 3 at different number of grouping. Given that the number of sub-group is between 1 (the design becomes equal to a fully-connected one) and N_{RF} (the design becomes similar to sub-connected design), it is noticed that as the number of sub-grouping increases, the power consumption reduces even at high N_L lenses for both 4 and 8 RF chains. Note that the best performance is obtained when the number of sub-grouping is equal to the number of RF chains where each sub-group has only one RF chain since decreasing the number of sub-grouping converts the hybrid beamforming structure from sub-grouped model to a fully-connected one.

Figure 4 shows the spectral efficiency comparison in mmWave MIMO system, where the number of RF chains is set to 4, $N_t = 64$, and $N_g = N_{RF}$. Note that N_g is set to be equal to the number of RF chains in the system to have a fair comparison with the sub-connected TA-MIMO system. The TA and TA sparse methods are referred to as fully-connected models where each RF path is connected to all antenna elements while LAS fully-connected method refers to our proposed precoding method when $N_g = 1$. Means that our proposed sub-grouped LAS design becomes equal to conventional fully-connected LAS design as in [17]. In TA sub-connected model, each RF path is connected to N_t/N_{RF} antenna elements only independently from other RF path connections. Figure 4 shows that the proposed sub-grouped precoder achieves a reasonable spectral efficiency performance with less than 30% difference from the fully-connected TA-MIMO model at 0 dB SNR with a much less power consumption, and exceeds the sub-connected TA precoder's performance as the number of lenses in each sub-grouped and the SNR level increase while achieving better energy efficiency as shown in Figure 5. Note that increasing the number of lenses within the sub group enhances the performance due to better beam flexibility that the multiple lenses can provide

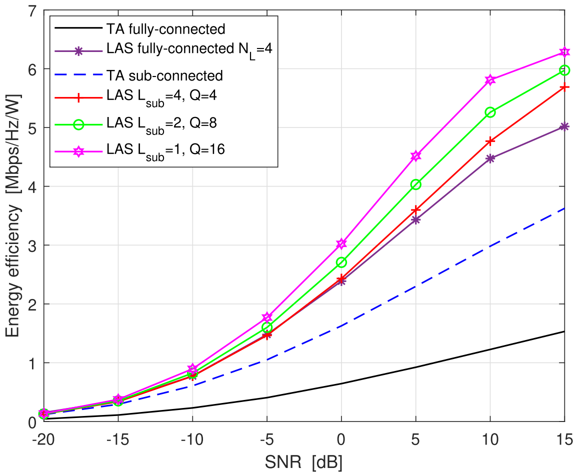

FIGURE 5. Energy efficiency vs SNR for $N_{\mathrm{RF}} = 4$ in the proposed sub-grouped LAS-MIMO architecture.

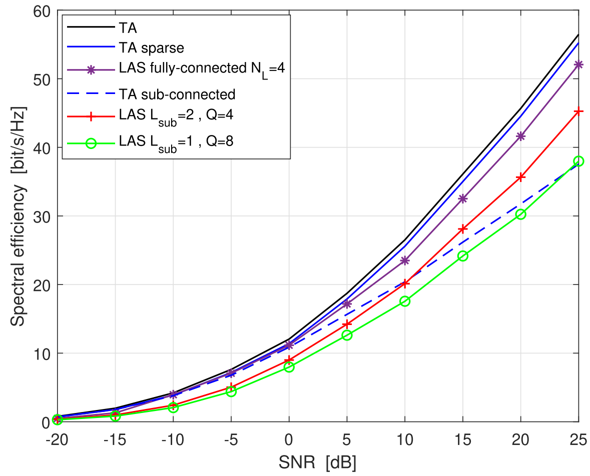

FIGURE 6. Spectral efficiency vs SNR for $N_{\mathrm{RF}} = 8$ in the proposed sub-grouped LAS-MIMO architecture.

to steer the beam to the desired direction compared to single lens structure.

Figure 5 shows the energy efficiency comparison against the SNR levels for the same system design given in Figure 4. It is observed that the proposed sub-grouped LAS-MIMO system for all the cases can achieve higher energy efficiency than the fully-connected and sub-connected TA MIMO systems. Higher energy efficiency for a given SNR is achieved as the number of lenses decreases due to the decrease in the number of PSs. This increase in energy efficiency can clearly be observed at high SNR levels. From Figure 4, it is noticed that a system of $L_{\mathrm{sub}} = 1$ (one lens in each subgroup) has the worst performance in terms of the spectral efficiency for a given SNR, however, it has the lowest consumed power value compared to other system designs which make it preferable for the energy-efficient systems. It can be stated that the energy efficiency and spectral efficiency trade-off depends on the model design. If the priority is the spectral efficiency, the number of lenses in the design is preferred to be high since each lens has a smaller size and compact, and provides more control on the beam compared to the $L_{\mathrm{sub}} = 1$ case. On the other hand, if the priority is energy efficiency, the number of lenses is required to be less to get an energy-efficient system design. Furthermore, if a scenario is required to have a spectral and energy-efficient system, a joint optimization problem should be formulated and solved, where the spectral efficiency and energy efficiency metrics of the system should be maximized to extract the optimum sub-grouping structure in the proposed sub-grouped LAS-MIMO design.

Figure 6 compares the spectral efficiency vs SNR for 8 RF chains in the LAS-MIMO systems. Again, it is shown that the performance of the proposed sub-grouped precoding algorithm is close to the traditional sub-connected and fully-connected MIMO systems and can outperform the sub-connected traditional MIMO system for a larger number of lenses in the system at high SNR levels.

The energy efficiency performance vs transmitted power P_x is compared in Figure 7 considering the same

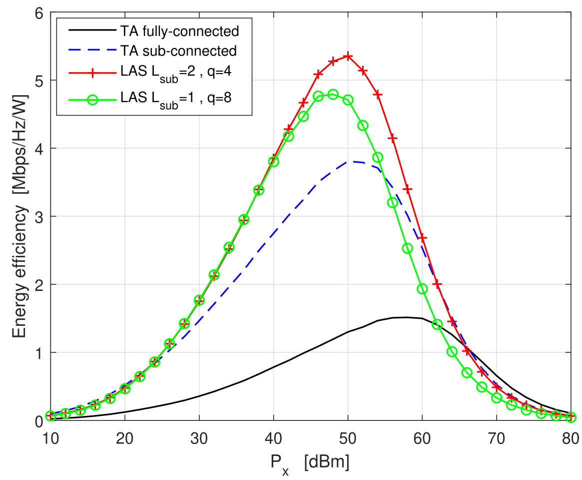

FIGURE 7. Energy efficiency vs transmitted power P_x for $N_{\mathrm{RF}} = 8$ in the proposed sub-grouped LAS-MIMO architecture.

assumptions given in Fig. 6. The figure shows that the proposed sub-grouped LAS-MIMO system outperforms the fully-connected and sub-connected traditional MIMO systems when the number of RF chains is set to 8. This result confirms that the proposed system can be exploited even with the higher number of RF chains. From Figure 7, it is clear that the cases of subgroups consisting of $L_{\mathrm{sub}} = 1$ or $L_{\mathrm{sub}} = 2$ lenses perform near-identical energy efficiency. Comparing these $N_{\mathrm{RF}} = 8$ cases with the $N_{\mathrm{RF}} = 4$ cases of Figure 5 shows that increasing number of RF chains causes the energy efficiency of systems to become more independent of the subgroup configuration. This is due to the fact that the gain in spectral efficiency with increasing N_{RF} is much higher than the increase in power consumption. In the presented $N_{\mathrm{RF}} = 8$ cases, $L_{\mathrm{sub}} = 2$ clearly becomes a better choice over $L_{\mathrm{sub}} = 1$ by providing higher spectral efficiency with near-identical energy efficiency. Although the energy efficiency can be increased by increasing the transmitted power, after a certain power level, the energy efficiency will decrease again to a level worse than traditional MIMO systems in a unimodal function behavior. Therefore, an optimum transmitted power level needs to be defined in each system design. It is noticed from the figure that the optimum transmitted power points of the proposed sub-grouped LAS designs are less than in the conventional TA-MIMO design which makes our design more appealing for the green cellular networks.

V. CONCLUSION

In this paper, we propose a sub-grouped LAS-MIMO architecture with low-complexity beam selection and associated precoding based on the partial exhaustive search and SIC-based algorithm. The proposed sub-grouped system was introduced to improve the energy efficiency of a recently presented fully-connected LAS-MIMO system. In the proposed design, the LAS grouping can be selected to maximize the energy efficiency while achieving a useful sum-rate performance with the proposed precoding method. In addition, the power consumption models for the fully-connected and the proposed sub-grouped LAS-MIMO system are presented. Comparisons with fully- and sub-connected hybrid TA-MIMO systems show that the proposed sub-grouped LAS-MIMO architecture provides significant improvement in energy efficiency while achieving spectral efficiency approaching that of the traditional sub-connected MIMO system as the number of lenses in each sub-group increases. For an optimal design of the sub-grouped LAS-MIMO system, a trade-off between energy efficiency and spectral efficiency should be considered. This is because when the number of lenses in each subgroup increases, the spectral efficiency increases to a sub-optimal solution, but a degradation in the energy efficiency of the system is observed. Our future work will focus on modifying the proposed precoding algorithm for a massive antenna array under imperfect channel estimation.

VI. ACKNOWLEDGMENT

The authors would like to thank Sinasi Cetinkaya for his comments and suggestions to improve the quality of the paper.

REFERENCES

[1] S. He, Y. Wu, D. W. K. Ng, and Y. Huang, "Joint optimization of analog beam and user scheduling for millimeter wave communications," *IEEE Commun. Lett.*, vol. 21, no. 3, pp. 2638–2641, Dec. 2017.

[2] R. Méndez-Rial, C. Rusu, N. González-Prelcic, A. Alkhateeb, and R. W. Heath, Jr., "Hybrid MIMO architectures for millimeter wave communications: Phase shifters or switches?" *IEEE Access*, vol. 4, pp. 247–267, 2016.

[3] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. W. Heath, Jr., "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[4] J. Tan, L. Dai, J. Li, and S. Jin, "Angle-based codebook for low-resolution hybrid precoding in millimeter-wave massive MIMO systems," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Oct. 2017, pp. 1–5.

[5] Y. Zeng and R. Zhang, "Millimeter wave MIMO with lens antenna array: A new path division multiplexing paradigm," *IEEE Trans. Commun.*, vol. 64, no. 4, pp. 1557–1571, Apr. 2016.

[6] W. U. Bajwa, J. Haupt, A. M. Sayeed, and R. Nowak, "Compressed channel sensing: A new approach to estimating sparse multipath channels," *Proc. IEEE*, vol. 98, no. 6, pp. 1058–1076, Jun. 2010.

[7] R. Pal, A. K. Chaitanya, and K. V. Srinivas, "Low-complexity beam selection algorithms for millimeter wave beamspace MIMO systems," *IEEE Commun. Lett.*, vol. 23, no. 4, pp. 768–771, Apr. 2019.

[8] H. Yu, W. Qu, Y. Fu, C. Jiang, and Y. Zhao, "A novel two-stage beam selection algorithm in mmWave hybrid beamforming system," *IEEE Commun. Lett.*, vol. 23, no. 6, pp. 1089–1092, Jun. 2019.

[9] Z. Cheng, Z. Wei, and H. Yang, "Low-complexity joint user and beam selection for beamspace mmWave MIMO systems," *IEEE Commun. Lett.*, vol. 24, no. 9, pp. 2065–2069, Sep. 2020.

[10] T. Kwon, Y.-G. Lim, B.-W. Min, and C.-B. Chae, "RF lens-embedded massive MIMO systems: Fabrication issues and codebook design," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 7, pp. 2256–2271, Jul. 2016.

[11] Y. Zeng, R. Zhang, and Z. N. Chen, "Electromagnetic lens-focusing antenna enabled massive MIMO: Performance improvement and cost reduction," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1194–1206, Jun. 2014.

[12] X. Gao, L. Dai, S. Han, L. Chih-Lin, and X. Wang, "Reliable beamspace channel estimation for millimeter-wave massive MIMO systems with lens antenna array," *IEEE Trans. Wireless Commun.*, vol. 16, no. 9, pp. 6010–6021, Sep. 2017.

[13] T. Xie, L. Dai, D. W. K. Ng, and C.-B. Chae, "On the power leakage problem in millimeter-wave massive MIMO with lens antenna arrays," *IEEE Trans. Signal Process.*, vol. 67, no. 18, pp. 4730–4744, Sep. 2019.

[14] H. Tataria, M. Matthaiou, P. J. Smith, G. C. Alexandropoulos, and V. F. Fusco, "Impact of RF processing and switching errors in lens-based massive MIMO systems," in *Proc. IEEE 19th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jun. 2018, pp. 1–5.

[15] M. Karabacak, G. Mumcu, and H. Arslan, "Hybrid MIMO architecture using lens arrays," U.S. Patent 10 714 836, Jul. 14, 2020.

[16] G. Mumcu, M. Kacar, and J. Mendoza, "Mm-wave beam steering antenna with reduced hardware complexity using lens antenna subarrays," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 9, pp. 1603–1607, Sep. 2018.

[17] M. Karabacak, H. Arslan, and G. Mumcu, "Lens antenna subarrays in mmWave hybrid MIMO systems," *IEEE Access*, vol. 8, pp. 216634–216644, 2020.

[18] A. Alkhateeb, G. Leus, and R. W. Heath, "Limited feedback hybrid precoding for multi-user millimeter wave systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, pp. 6481–6494, Nov. 2015.

[19] J. Du, W. Xu, H. Shen, X. Dong, and C. Zhao, "Hybrid precoding architecture for massive multiuser MIMO with dissipation: Sub-connected or fully connected structures?" *IEEE Trans. Wireless Commun.*, vol. 17, no. 8, pp. 5465–5479, Aug. 2018.

[20] H. Li, M. Li, and Q. Liu, "Hybrid beamforming with dynamic subarrays and low-resolution PSs for mmWave MU-MISO systems," *IEEE Trans. Commun.*, vol. 68, no. 1, pp. 602–614, Jan. 2020.

[21] R. W. Heath, N. González-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, "An overview of signal processing techniques for millimeter wave MIMO systems," *IEEE J. Sel. Topics Signal Process.*, vol. 10, no. 3, pp. 436–453, Apr. 2016.

[22] L. Dai, X. Gao, S. Han, I. Chih-Lin, and X. Wang, "Beamspace channel estimation for millimeter-wave massive MIMO systems with lens antenna array," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Jul. 2016, pp. 1–6.

[23] X. Gao, L. Dai, S. Zhou, A. M. Sayeed, and L. Hanzo, "Wideband beamspace channel estimation for millimeter-wave MIMO systems relying on lens antenna arrays," *IEEE Trans. Signal Process.*, vol. 67, no. 18, pp. 4809–4824, Sep. 2019.

[24] C. Hu, L. Dai, T. Mir, Z. Gao, and J. Fang, "Super-resolution channel estimation for mmWave massive MIMO with hybrid precoding," *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 8954–8958, Sep. 2018.

[25] J. Yang, C. K. Wen, S. Jin, and F. Gao, "Beamspace channel estimation in mmWave systems via cosparse image reconstruction technique," *IEEE Trans. Commun.*, vol. 66, no. 10, pp. 4767–4782, Oct. 2018.

[26] H. He, C.-K. Wen, S. Jin, and G. Y. Li, "Deep learning-based channel estimation for beamspace mmWave massive MIMO systems," *IEEE Wireless Commun. Lett.*, vol. 7, no. 5, pp. 852–855, Oct. 2018.

[27] Z. Zhang, Y. Li, H. Lingna, L. Ding, and F. Yang, "A practical channel estimation scheme for sub-connected hybrid massive MIMO systems," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast. (BMSB)*, Jun. 2019, pp. 1–5.

[28] F. Dong, W. Wang, Z. Huang, and P. Huang, "High-resolution angle-of-arrival and channel estimation for mmWave massive MIMO systems with lens antenna array," *IEEE Trans. Veh. Technol.*, vol. 69, no. 11, pp. 12963–12973, Nov. 2020.

[29] T. Lin, J. Cong, Y. Zhu, J. Zhang, and K. B. Letaief, "Hybrid beamforming for millimeter wave systems using the MMSE criterion," *IEEE Trans. Commun.*, vol. 67, no. 5, pp. 3693–3708, May 2019.

[30] X. Gao, L. Dai, S. Han, I. Chih-Lin, and R. W. Heath, "Energy-efficient hybrid analog and digital precoding for mmWave MIMO systems with large antenna arrays," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 4, pp. 998–1009, Apr. 2016.

[31] E. Björnson, J. Hoydis, and L. Sanguinetti, "Massive MIMO networks: Spectral, energy, and hardware efficiency," *Found. Trends Signal Process.*, vol. 11, nos. 3–4, pp. 154–655, Nov. 2017.

[32] C. Chen, Y. Dong, X. Cheng, and L. Yang, "Low-resolution PSs based hybrid precoding for multiuser communication systems," *IEEE Trans. Veh. Technol.*, vol. 67, no. 7, pp. 6037–6047, Jul. 2018.

[33] M. A. Almasi, R. Amiri, H. Jafarkhani, and H. Mehrpouyan, "MmWave lens-based MIMO system for suppressing small-scale fading and shadowing," *IEEE Trans. Wireless Commun.*, vol. 19, no. 8, pp. 5292–5306, Aug. 2020.

[34] J. Brady, N. Behdad, and A. M. Sayeed, "Beamspace MIMO for millimeter-wave communications: System architecture, modeling, analysis, and measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3814–3827, Jul. 2013.

LIZA AFEEF received the B.S. degree in communication technology engineering from Al-Balqa' Applied University, Jordan, in 2014, and the M.S. degree in electrical engineering/wireless communication from the Jordan University of Science and Technology (JUST), Jordan, in 2018. She is currently pursuing the Ph.D. degree with İstanbul Medipol University, Turkey. Her research interests include beamforming, massive MIMO, lens antenna, MIMO channel modeling, MIMO channel estimation, RIS, mmWave, and 5G and beyond wireless systems.

GOKHAN MUMCU (Senior Member, IEEE) was born in Bursa, Turkey, in 1982. He received the B.S. degree in electrical engineering from Bilkent University, Ankara, Turkey, in 2003, and the M.S. and Ph.D. degrees in electrical and computer engineering from The Ohio State University, Columbus, OH, USA, in 2005 and 2008, respectively.

He is currently a Professor with the Department of Electrical Engineering, University of South Florida. His research interests include reconfigurable antennas and RF circuits with mm-Wave applications, additive manufacturing of structural antennas and phased array antennas, microfluidics for highly reconfigurable RF devices and new concepts (e.g., metamaterials, volumetric 3D reactive loading, polymers) for designing conformal, miniature, and multifunctional antennas. He was a recipient of the 2014 CAREER Award from the U.S. National Science Foundation, the 2014 Faculty Outstanding Research Award from the University of South Florida, the Best Paper Award from the 2008 URSI National Radio Science Meeting, and the 2008 Outstanding Dissertation Award from The Ohio State University, ElectroScience Laboratory. He was also a recipient of the 1999 International Education Fellowship of the Turkish Ministry of Education. He ranked first on the national university entrance exam taken annually by over 1.5 million Turkish students in 1999. He has served as the Technical Program Committee Chair for the 2013 IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, the 2016 International Workshop on Antenna Technology, and the 2022 IEEE Wireless and Microwave Technology Conference (WAMICON).

HÜSEYIN ARSLAN (Fellow, IEEE) received the B.S. degree from Middle East Technical University (METU), Ankara, Turkey, in 1992, and the M.S. and Ph.D. degrees from Southern Methodist University (SMU), Dallas, TX, USA, in 1994 and 1998, respectively.

From January 1998 to August 2002, he was with the Research Group of Ericsson, where he was involved with several projects related to 2G and 3G wireless communication systems. Since August 2002, he has been with the Electrical Engineering Department, University of South Florida, where he is currently a Professor. In December 2013, he joined İstanbul Medipol University to found the Engineering College, where he has worked as the Dean of the School of Engineering and Natural Sciences. In addition, he has worked as a part-time Consultant for various companies and institutions, including Anritsu Company and The Scientific and Technological Research Council of Turkey. He conducts research in wireless systems, with emphasis on the physical and medium access layers of communications. His current research interests include 5G and beyond radio access technologies, physical layer security, interference management (avoidance, awareness, and cancellation), cognitive radio, multi-carrier wireless technologies (beyond OFDM), dynamic spectrum access, co-existence issues, non-terrestrial communications (high altitude platforms), and joint radar (sensing) and communication designs. He has been collaborating extensively with key national and international industrial partners and his research has generated significant interest in companies, such as InterDigital, Anritsu, NTT DoCoMo, Raytheon, Honeywell, and Keysight Technologies. Collaborations and feedback from industry partners has significantly influenced his research. In addition to his research activities, he has also contributed to wireless communication education. He has integrated the outcomes of his research into education which led him to develop a number of courses at the University of South Florida. He has developed the unique "Wireless Systems Laboratory" course (funded by the National Science Foundation and Keysight Technologies) where he was able to teach not only the theory but also the practical aspects of wireless communication system with the most contemporary test and measurement equipment.

He has served as the general chair, the technical program committee chair, a session and symposium organizer, the workshop chair, and a technical program committee member for several IEEE conferences. He is a member of the Editorial Board for the IEEE Communications Surveys and Tutorials and the *Sensors* journal. He has also served as a member of the Editorial Board for the IEEE Transactions on Communications, the IEEE Transactions on Cognitive Communications and Networking, and several other scholarly journals by Elsevier, Hindawi, and Wiley Publishing.