Received 5 November 2022, accepted 21 November 2022, date of publication 28 November 2022,
date of current version 1 December 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3225441

METHODS

Resource Allocation for Joint Communication and Localization Systems With MU-MIMO

YACHUAN BAO[1], BAOGUO YU[1], BENQUAN YIN[2], XUENI LUO[2], AND XIAOFENG LU[2]
[1]State Key Laboratory of Satellite Navigation System and Equipment Technology, The 54th Research Institute, CETGC, Shijiazhuang 050081, China
[2]State Key Laboratory of Integrated Services Networks, Xidian University, Xi'an 710071, China

Corresponding author: Xiaofeng Lu (luxf@xidian.edu.cn)

This work was supported in part by the National Key Research and Development Program of China under Grant 2021YFB3900800, in part by the Natural Science Foundation of China under Grant 62132004, and in part by the National Natural Science Foundation of China under Grant U1705263.

ABSTRACT Joint communication and localization is an attractive technique to simultaneously provide data transmission and localization services, and efficient resource allocation could bring a high data rate and high localization accuracy in limited resources, which is significant for multi-user conditions. In this paper, we concentrate on the joint multiple resource allocation to achieve a trade-off between the performance of the communication and localization process in the millimeter multi-user Multiple Input Multiple Output(MU-MIMO) system. We first develop a robust beam scheduling and user grouping approach using the mutual angle information and channel correlation coefficient to reduce the multi-user interference. Then, we formulate a multi-domain resource allocation problem, where the joint impact of beamforming, bandwidth reservation, and power control is considered. Furthermore, an efficient algorithm is proposed to iteratively perform the sub-carrier and power allocation until satisfying the data rate and localization error-bound constraints after decomposing the large-scale problem into two small-scale sub-problems by the difference of the convex function algorithm. Numerical results show that the proposed algorithm achieves a good trade-off between data rate and localization error and has better performance than other previously proposed algorithms in the literature.

INDEX TERMS Joint communication and localization, millimeter wave, MU-MIMO, user grouping, beamforming.

I. INTRODUCTION

Until now, many countries have completed the construction and operation of the fifth generation (5G) communication systems, and gradually shift the focus to the sixth generation (6G) standard research and development. In [1] and [2], the authors describe the picture of the 6G communication systems and emphasize that there would be more emerging applying fields and scenarios, such as unmanned driving [3], [4], crowd sensing [5], [6], Internet-of-Things (IoT) [7], [8] and so on, which demand high-quality wireless communication connectivity as well as robust and accurate location sensing capability to increase the quality of experience in wireless networks [9], [10]. And there would be severe resource competition to realize a trade-off between each user's communication needs and localization needs because of the limited amount of wireless resources, such as beam, power, bandwidth, and so on [11], which emphasize the importance of efficient resource allocation algorithm.

Much research work has been performed on resource allocation for the framework of joint communication and localization. In [12], the author investigates the performance trade-off between the data rate and localization error under single-user scenarios. And [13] generalizes the conclusion to multi-user scenarios. Remun Koirala et al. [14], [15] analyze the optimal beamforming solutions and investigate the trade-off in a framework comprising both localization and communication services after different beam optimization and beam resource partitioning scheme combined with [12] and [13]. However, these surveys do not pay enough attention to

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

spectrum resources which is a critical issue in multi-user systems for the development of user-dense areas. And the authors [16] study user scheduling and resource block allocation. Reference [17], [18] propose the specific sub-carrier allocation focusing on a single sub-carrier. Reference [19] study the process of cross-layer carrier allocation scenario. And the author [20] generalizes the conclusion to the multi-sub-carriers allocation, which also means bandwidth allocation. On the downside, the power consumption of those algorithms is extremely high to low energy efficiency and goes against the concept of green communication. Besides bandwidth allocation, [21] propose a double-objective optimization target for energy efficiency and system throughout based on the power allocation, which is however not tailored for joint communication and localization. On the basis of focus, [22] investigate the performance trade-off after beam and power resource allocation in a multi base station(BS) multi-user scenario, which lacks the consideration of bandwidth allocation.

To the best of our knowledge, there is no existing work about joint multiple resource allocation including the beam, bandwidth, and power in joint communication and localization systems. And there is still an optimization for resource utilization rate in the space, time, and frequency domain. To solve this problem, we propose an efficient joint resource allocation algorithm to realize the trade-off between data rate and localization error in a MU-MIMO scenario.

Against the existing approaches, the major contributions of this paper could be summarized as follows:

- To develop beam selection and user grouping criteria under MU-MIMO scenario respectively. These criteria are the basis of the joint resource allocation algorithm for the joint communication and localization systems. To ensure robust communication links and high-performance gains in real systems, we develop the beam selection and user grouping criteria by the relationship of users' mutual angle information and channel correlation coefficient.
- To formulate a multi-domain resource allocation problem for the optimization of joint communication and localization in MU-MIMO systems. To minimize the localization error on the premise that the users' different data rate demands are satisfied, we propose a user grouping scheme to achieve spatial multiplexing gain by grouping co-channel users. At the same time, bandwidth and power resources would be allocated orthogonally to different groups to reduce interference and achieve more performance gain.
- To propose an efficient joint resource allocation algorithm for solving the joint optimization problem by decomposing it into two smaller-scale sub-problems. As the high complexity is caused by high-dimension resource allocation, the traditional optimization algorithm is unable to solve the problem efficiently. Our proposed new efficient solution algorithm, which combines the difference of the convex function algorithm (DCFA) with iterative greedy strategy, can decompose the initial problem into two convex sub-problems, and can also be solved in limited iteration times.

The rest of the paper is organized as follows. Section II describes the related research work. Section III introduces the system model in terms of the mmWave orthogonal frequency division multiplexing (OFDM) system with MU-MIMO and correlated work. Section IV formulates the performance metrics and synthesis problem. The proposed schemes are presented in Section V, including beam selection, user grouping, and resource allocation algorithm. Section VI shows the numerical simulation results and performance analysis. Finally, the conclusions are stated in Section VII. And here are some notations to be used in this paper:

- $\mathrm{P}(\cdot)$: Probability operation.
- $\mathrm{E}(\cdot)$: Expectation operation.
- $(\cdot)^{\mathrm{T}}$, $(\cdot)^{\mathrm{H}}$: Transposition, hermitian, respectively.
- $(\cdot)^{\mathrm{R}}$, $(\cdot)^{\mathrm{I}}$: Real and imaginary component, respectively.
- $\boldsymbol{A}$: All vectors are presented in boldface.
- $\mathrm{A}_{n\times m}$: All matrixs have the subscript which n and m denote the numbers of row and column respectively.

II. RELATED WORK

This section introduces some related search work in this article, including mmWave, MU-MIMO, and beam selection.

A. MILLIMETER WAVE

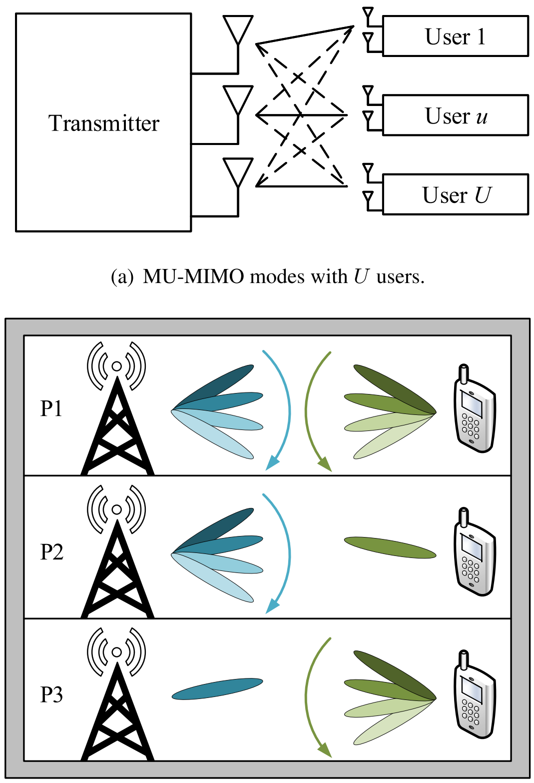
As one of the significant technologies in 5G, the millimeter wave is expected to be one of the key enablers for future wireless systems. Owing to the large frequency spectrum range, mmWave could be applied in constantly emerging high-tech fields with extremely high channel bandwidth [1] and data rates of more than megabits per second. Therefore, mmWave would continue to play a big role in the era of 5G and 6G. However, the path loss increases greatly with the transmission distance by utilizing mmWave, especially in non-line-of-sight (NLoS) scenarios. Therefore, mmWave was used in line-of-sight (LoS) scenarios at first. Then, beam selection is used to construct highly oriented [23] transmission paths between different big antenna arrays deployed in BS and users. And the resolutions of the angle of arrival (AoA) and angle of departure (AoD) are promoted against the great large-scale fading. To some extent, beamforming (BF) could be used for user localization according to this angle information to increase the accuracy of localization. In a word, joint communication and localization could be organically implemented in mmWave systems. Hence, the paper assumes that all users are connected and located by mmWave LoS links.

B. MU-MIMO

MU-MIMO is also called virtual MIMO, which means generating a virtual MIMO channel between BS and terminal sites to alleviate the antennas demand from the user equipment. And in comparison with traditional MIMO systems, MU-MIMO systems enhance the multi-user diversity effect and would have more antennas, that is, the system throughout would be promoted noteworthily by reusing time-frequency resource blocks, as Fig. 1 shows, which has U users to form the virtual MIMO. Therefore, there is widespread concern about resource allocation technology in MU-MIMO systems, especially for joint communication and localization business. Right now, there is a lot of research on the resource allocation scheme based on MU-MIMO systems, including channel state estimation [16], [17], [18], [21], relative user grouping [19], and subcarriers allocation [24]. Consequently, Tseng et al. [19] deduces the most optimal subcarriers allocation conditions on account of minimum bandwidth increment, and the conclusion is applied in the MU-MIMO uplink transmission to promote the data rate and quality of service (QoS). In [24], the author proposes a user scheduling and resource allocation scheme combined with reinforcement learning to better match users with resource blocks. And [11], [18] make survey research on joint dynamic user grouping and resource block allocation in the context of uplink multi-cell of MU-MIMO single-carrier frequency division multiple access (SC-FDMA) systems. And the author proposes several corresponding less complex resource allocation schemes. In this paper, spatial and resource blocks are allocated in MU-MIMO systems [11]. In spatial, a consequence of the independent fading across MIMO links of different users, called spatial multiplexing diversity, could increase the system capacity owing to transmission over parallel spatial channels. Besides, there would exist an independent fading at some time when several users are far apart in distance. And MU-MIMO systems could exploit this fading to be simultaneously scheduled in specific channel conditions. Therefore, we utilize the combination of mmWave and MU-MIMO to consider beam selection and resource allocation.

C. BEAM SELECTION

As the description of mmWave above, propagation conditions for mmWave are significantly harsher compared to traditional sub-6GHz bands in the same scenarios. Hence, mmWave systems need to perform BF to concentrate the signal energy in a small angular space against the high path loss and sensitivity to blockage. Beam sweeping, regarded as the most significant stage of BF, is referred to as the process where the BS or the user covers a spatial area by constantly transmitting and receiving reference signals in order [25]. By the way, beam sweeping has three different procedures, namely, beam selection, beam refinement for the BS, and beam refinement for the user respectively, as Fig.1(b) shows. Combined with the scenarios in Fig.1(a), in the first procedure named P1, both the BS and the UE perform beam sweeping in a certain angle scope. Then in the P2, the UE would fix its beam while the BS performs beam sweeping. And in the P3, the BS would also be fixed its beam while the UE performs sweeping. In general, these three procedures are conceptual and P1 alone could realize beam selection in some practical scenarios. And there is some interesting research about the beam selection of mmWave MIMO systems. Specifically, Bingpeng Zhou et al. [26] proposes a new successive



(a) MU-MIMO modes with U users.

(b) Beam sweeping types: P1(beam selection), P2(BS beam refinement), and P3(UE beam refinement).

FIGURE 1. MU-MIMO modes and procedures of beam sweeping.

localization and BF scheme on account of jointly user's location and instant channel state information estimation. Numerical results prove that this scheme attains great performance gains on terminal site localization. Xuanli Wu et al. [27] proposed a joint resource allocation and power allocation to maximize energy efficiency by multiple beams. In [15], the author proposes an initial beam selection scheme based on localization error bound, which reduces the initial access delay as compared to traditional initial access.

D. JOINT COMMUNICATION AND SENSING

As a potential technology feature for 6G wireless networks, joint communication, and sensing require more complete reliable multi-user communication and more accurate environment sensing. In general, joint communication and sensing approaches are always processed with the utilization of radar. And the consideration of systems that jointly perform communication and a sense of the environment are hot topics. In [28], the author proposes a new system named radar BS to communicate with mobile users and sense the surrounding environment in the same frequency range. And [29] proposes the future development trends, prospects, and application fields for the joint radar and communication systems. On account of it, there are many approaches to the development and application of this field. In [30], the article proposes a promising mode, which is Rate-Splitting Multiple Access. It is a new communication strategy applied in multi-user and multi-antenna systems, which could be regarded as multiple access and interference management policies. And [31] proposes iterative and incremental joint multi-user communication and environmental sensing schemes. The simulation results prove its strong sensing abilities. Besides, [32] presents the precoding vectors design, downlink communication, and sensing to compare the balance between imperfect channel state information and perfect channel state information, which also realizes the balance of signal to noise (SNR). In [33], the author proposes multi-metric waveform optimization for joint communication and sensing systems. Furthermore, joint communication and localization are a significant part of joint communication and sensing, which is also the main background of this paper.

III. SYSTEM MODEL

In this section, we introduce the mmWave MU-MIMO system and the downlink link of the joint communication and localization network model at first. Then, we present two key technologies in this paper, that is, beam selection and user grouping.

A. MILLIMETER WAVE MU-MIMO SYSTEMS STRUCTURE

In the mmWave MU-MIMO system, BS and users with different services are located on the same two-dimensional plane. And the BS is equipped with T uniform linear array (ULA) antennas array, and each user only deploys with one antenna. Assumed that U, T, and C are defined as the number of users, the number of generated beams, and the number of available subcarriers respectively.

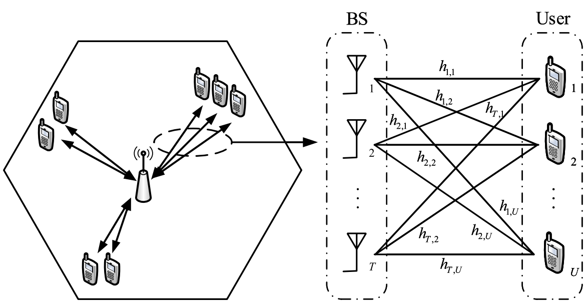


FIGURE 2. Millimeter wave MU-MIMO systems model and specified channel model.

As depicted in Fig. 2, there are bidirectional links between BS and users evaluated by the corresponding channel gain. Hence, there exist several allocation factors for subcarrier allocation and beam selection of users. In this paper, $f_{c,u} \in \{0, 1\}$ and $e_{t,u} \in \{0, 1\}$ are defined for subcarrier and beam respectively while the assignment is successful when the value is equal to 1. And the initial channel state could be formulated as:

$$\mathrm{H}_{T\times U} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,U} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,U} \\ \vdots & \vdots & \ddots & \vdots \\ h_{T,1} & h_{T,2} & \cdots & h_{T,U} \end{bmatrix}. \quad (1)$$

In the joint communication and localization network model, different users could share the same time-frequency resource blocks to improve the comprehensive system performance both in the communication and localization process owing to MU-MIMO. Therefore, it is significant to allocate limited resources while ensuring the high utilization of resource allocation during the joint communication and localization process.

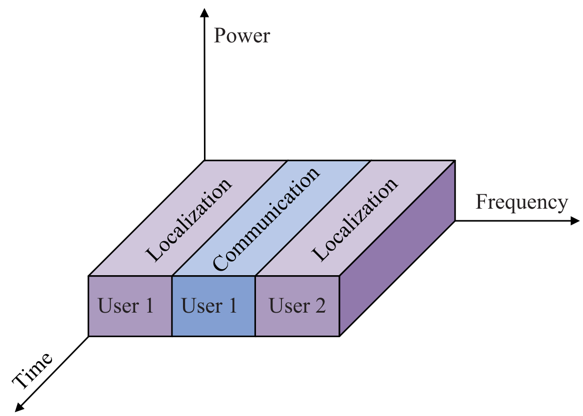


FIGURE 3. Frequency division multiplexing mode in joint communication and localization systems.

As shown in Fig. 3, the whole time slot could be simultaneously processed communication and localization by dividing the available frequency band through the OFDM system. On account of the array response and path loss of mmWave, the individual channel gain could be extended as:

$$H_{t,c,u} = \sqrt{\mathrm{Loss}_{t,u}} h_{t,u} e^{-j2\pi\tau_{t,u}\frac{c\bar{B}}{C}} \mathbf{a}_t^{\mathrm{H}}\left(\theta_u^t\right) \mathbf{a}_r\left(\theta_u^r\right), \quad (2)$$

where $H_{t,c,u}$ denotes the channel gain between t-th beam in BS and u-th user through c-th subcarrier. And the path loss is defined as $\mathrm{Loss}_{t,u}$, which could be computed by the Close-In path loss model [34]. Besides, $\tau_{t,u}$, θ_u^t, and θ_u^r indicate the time delay between BS and user, the AoD, and the AoA respectively. $\bar{B}$ denotes the bandwidth. In addition, the pilot assignment and noise model could also influence the accuracy of the comprehensive channel model. To simplify the channel estimation process, we assume that the channel state information used is perfect.

Also, assume that the number of units of antennas is odd and the array centroid is the reference point, then the array response in BS could be formulated as:

$$\mathbf{a}_t(\theta_u^t) = \frac{1}{\sqrt{T}}\left[e^{-j\left(\frac{T-1}{2}\right)\mathrm{AR}_u^t}, \ldots, e^{-j\left(\frac{1-T}{2}\right)\mathrm{AR}_u^t}\right]_{T\times 1}^{\mathrm{T}}, \quad (3)$$

where $\mathrm{AR}_u^t = \frac{2\pi}{\lambda_t} i \cos\left(\theta_u^t\right)$, and λ_t and i denote the signal wavelength and antennas interval respectively.

And the array response in the user could be formulated as:

$$\mathbf{a}_r(\theta_u^r) = \frac{1}{\sqrt{T}} \left[e^{-j\left(\frac{T-1}{2}\right)\mathrm{AR}_u^r}, \ldots, e^{-j\left(\frac{1-T}{2}\right)\mathrm{AR}_u^r} \right]_{T\times 1}^{\mathrm{T}}, \quad (4)$$

where $\mathrm{AR}_u^r = \frac{2\pi}{\lambda_t} i \cos\left(\theta_u^r\right)$.

Hence, the received signal $\boldsymbol{y}_{t,c,u}$ in the user could be presented as:

$$\boldsymbol{y}_{t,c,u} = \sqrt{P_{t,u}} \boldsymbol{w}_u^{\mathrm{H}} H_{t,c,u} \boldsymbol{f}_c \boldsymbol{s}_c + \tilde{\mathbf{n}}, \quad (5)$$

where $\sqrt{P_{t,u}}$ indicates the transmitted power, $\boldsymbol{w}_u$ and $\boldsymbol{f}_c$ denote the BF vector in the user and precoding vector in BS respectively. $\boldsymbol{s}_c$ means the transmitted signal and would be presented in detail in Section IV. and $\tilde{\mathbf{n}}$ denotes the additive white Gaussian noise.

For the localization process, we would adopt the single station passive positioning method causing there to be one BS on account of the coarse position results according to Global Navigation Satellite System (GNSS). And it would realize better localization accuracy than other methods, like the single station active positioning method. Combined with Fig. 3, the communication and localization process would be influenced by resource allocation. In addition, the data rate and the localization error would be the main measurement parameters of the joint communication of the localization system model. And they would be presented elaborately in Section IV.

B. BEAM SELECTION

The BS and the user have pre-determined analog beam codebooks in the MU-MIMO system. In the beam selection procedure (P1), the BS or the user sequentially utilizes beams pointing to different degrees from the whole codebook to find the best beam pairs between the BS and the user for the data transmitting and stable channel.

According to (2), θ_u^t is assumed as the AoD of the BS to the u-th user. In [35], the author utilizes the Butler method to form T beams, and the array coefficient of the t-th beam can be represented as:

$$A_t\left(\theta_u^t\right) = \frac{\sin\left(0.5\, T\pi \cos(\theta_u^t) - \chi_t\right)}{T \sin\left(0.5\pi \cos(\theta_u^t) - \frac{1}{T}\chi_t\right)}, \quad (6)$$

where t denotes the index of T beams and $\chi_t = \pi\left(t - \frac{T+1}{2}\right)$.

Then, the directivity coefficient between t-th beam and u-th user could be formulated as:

$$U_{t,u}\left(\theta_u^t\right) = \frac{2\left(A_t\left(\theta_u^t - \chi_t\right)\right)}{\int_0^{\pi} (A_t(\psi))^2 \sin(\psi) d\psi}. \quad (7)$$

In addition, the formulation of (7) could be simplified as:

$$U_{t,u}\left(\theta_u^t\right) = \mathrm{T}\left[A_t\left(\theta_u^t\right)\right]^2. \quad (8)$$

And (8) could represent the BF vector to some extent which would be expanded in Section IV.

C. USER GROUPING

In the downlink MU-MIMO systems, multiple orthogonal beams are generated through the BF technique, which means that multiple spatial streams have realized downlink communication. Hence, users could construct communication links with a little user interference without user grouping. And the interference between users could be eliminated by user grouping. Considering the time-frequency correlation, we assume that all subcarriers in the same resource block have the same channel state information which could be obtained by taking the average of the channel state information of the subcarriers with the resource block. And there are several user grouping algorithms' brief introductions in the following. Assume that all users are divided into D groups.

Firstly, it is assumed there is a group composed of M users. As for the $(M+1)$-th user, we should compute its correlation with this group by (9).

$$\varphi = \left| \frac{\sum_{m=1}^{M} h_{M+1} h_m^{\mathrm{H}}}{M h_{M+1} h_{M+1}^{\mathrm{H}}} \right|, \quad (9)$$

where φ denotes the correlation factor between $(M+1)$-th user and the M users' group, and $h_{(\cdot)}$ means the channel gain of the corresponding user. The complexity of grouping for a new user is $\mathcal{O}(M)$.

Secondly, user interference would be thoroughly eliminated when these channels are completely orthogonal. And the user grouping criterion would be measured by the orthogonality coefficient Θ by (10).

$$\Theta = \frac{(a_{ii} + a_{jj}) - (a_{ij} + a_{ji})}{\mathrm{Tr}(\Upsilon)}, \quad (10)$$

where $\mathrm{Tr}(\cdot)$ represents the trace of the matrix, and Υ could be formulated as:

$$\Upsilon = \begin{pmatrix} a_{ii} & a_{ij} \\ a_{ji} & a_{jj} \end{pmatrix} = \begin{pmatrix} \mathrm{E}\left[h_i h_i^{\mathrm{H}}\right] & \mathrm{E}\left[h_i h_j^{\mathrm{H}}\right] \\ \mathrm{E}\left[h_j h_i^{\mathrm{H}}\right] & \mathrm{E}\left[h_j h_j^{\mathrm{H}}\right] \end{pmatrix}, \quad (11)$$

where Υ indicates the orthogonal channel matrix, and a_{ij} denotes the channel cross-correlation coefficient between i-th and j-th user. And the complexity of grouping for a new user is $\mathcal{O}(M)$ when M is large enough.

Finally, user grouping could also be utilized by computing the determinant coefficient Ψ.

$$\Psi = \frac{|\Upsilon|}{\mathrm{Tr}(\Upsilon)} = \frac{a_{ii}a_{jj} - a_{ij}a_{ji}}{a_{ii} + a_{jj}}, \quad (12)$$

where $|\Upsilon|$ denotes the determinant of the channel orthogonal coefficients. This algorithm is similar to the second algorithm, and the complexity of grouping for a new user is $\mathcal{O}(M)$ when M is large enough.

IV. PROBLEM FORMULATION

In this section, the synthesis problem would be presented. On account of the joint communication and localization network, the simultaneous provision of communication and localization functionalities is challenged because the resource blocks are limited, although they could share. And to ensure localization performance, we would like to realize the trade-off between the communication and localization process with the priority of localization. Based on this point, the weighted localization error is regarded as the optimal minimum target of the resource allocation strategy. And the number of BS would be set to 1.

A. PROBLEM FORMULATION

From a macro perspective, the initial problem objective is comprised of the beam, power, and subcarriers, which are also the optimization variables and are presented by data rate constraints, and power constraints. Then, this problem could be formulated by:

$$\begin{aligned} \min_{f_{c,u},e_{c,u},g_{c,u},P_{c,u}} & \sum_{u=1}^{U} E_u^d, \\ s.t.\ & \mathrm{AC}\,1: R \geq R_{th} \\ & \mathrm{AC}\,2: E_u^d \leq \varepsilon_{thr}, \forall u \in U \\ & \mathrm{AC}\,3: \sum_{u=1}^{U} \sum_{c=-C/2}^{C} g_{c,u}^d P_{c,u}^d \leq P_{\max} \\ & \mathrm{AC}\,4: P_{c,u}^d \in [0, P_{\max}], \forall c \in C, \forall d \in D, \forall u \in U \end{aligned} \tag{13}$$

where E_u^d denotes the individual localization error in the specific d-th group and would be presented in the next part in detail. And AC 1 indicates that the overall data rate should be no less than the rate threshold in the mmWave MU-MIMO system. And AC 2 indicates that the localization error should also be constrained by the corresponding threshold, which means that the initial problem should be solved for each user to achieve local optimization firstly. The constraints of power allocation are presented by AC3 and AC4. And AC 3 shows the overall power constraint while AC 4 presents the available power allocation range for the u-th user in the d-th user group on the c-th subcarrier, where $g_u^d \in \{0, 1\}$ means u-th user is divided into d-th group whether or not.

B. PERFORMANCE METRICS

In practice, there are some metrics to evaluate the performance of different resource allocation schemes, that is, the data rate for the communication process, and localization error for the localization process.

1) DATA RATE

There are different kinds of metrics for communication performance evaluation, including SNR, BER, data rate, and so on. And in this section, the data rate is selected as the performance metric of the communication process on account of the flexible user numbers.

Considering the directivity coefficient, the transmitted signal's power $S_{c,u}^d$ could be computed by (14).

$$S_{c,u}^d = \left(\sum_{t=1}^{T} g_{t,u}^d e_{t,u}^d f_{c,u}^d \left| H_{t,c,u} \right| \sqrt{U_{t,u}\left(\theta_u^t\right) P_{c,u}^d} \right)^2, \tag{14}$$

where $e_{t,u}^d$ and $f_{c,u}^d$ are expanded to present the u-th user in d-th group.

Combined with (5), the overall interference power $I_{c,u}^d$ in the receiver could be formulated as:

$$I_{c,u}^d = \sum_{u' \notin d} \sum_{t=1}^{T} e_{t,u'} f_{c,u'} \left| H_{t,c,u} \right|^2 U_{t,u'}\left(\theta_{u'}^t\right) P_{c,u'}. \tag{15}$$

Then the data rate of u-th user $r_{c,u}^d$ is formulated as:

$$r_{c,u}^d = B_u \log_2 \left(1 + \frac{S_{c,u}^d}{I_{c,u}^d + N_0} \right), \tag{16}$$

where B_u denotes the allocated bandwidth for u-th user.

The overall data rate of d-th user group could be presented as (17) formulates.

$$R^d = \sum_{c=-C/2}^{C/2} \sum_{u=1}^{U} r_{c,u}^d. \tag{17}$$

2) LOCALIZATION ERROR

For the localization process, there are two significant indices to describe the localization performance, that is the specific coordinates and angle information. However, the channel state information could only be presented as (18) shows, which is comprised of time delay, AoD, AoA, and channel gain.

$$\boldsymbol{\eta}_{c,u} = \left[\tau_{t,u}, \theta_u^t, \theta_u^r, H_{t,c,u}^{\mathrm{R}}, H_{t,c,u}^{\mathrm{I}} \right]_{1\times 5}, \tag{18}$$

where $H_{t,c,u}^{\mathrm{R}}$ and $H_{t,c,u}^{\mathrm{I}}$ denote the real and imaginary component respectively.

The inverse of the Bayes-Fisher Information Matrix (FIM) is the boundary of the mean square error (MSE) matrix of any known unbiased estimation and random parameter estimation. The relation expression could be formulated as

$$\mathrm{E}\left\{ \left(\hat{\boldsymbol{\eta}}_{c,u} - \boldsymbol{\eta}_{c,u}\right) \left(\hat{\boldsymbol{\eta}}_{c,u} - \boldsymbol{\eta}_{c,u}\right)^{\mathrm{T}} \right\} \geq J_{\boldsymbol{\eta}_{c,u}}^{-1}, \tag{19}$$

and

$$J_{\boldsymbol{\eta}_{c,u}} \triangleq \mathrm{E}_{\mathbf{y}|_{\boldsymbol{\eta}_{c,u}}} \left[-\frac{\partial^2 \ln f\left(\mathbf{y} \mid \boldsymbol{\eta}_{c,u}\right)}{\partial \boldsymbol{\eta}_{c,u} \partial \boldsymbol{\eta}_{c,u}^{\mathrm{T}}} \right], \tag{20}$$

where $f\left(\mathbf{y} \mid \boldsymbol{\eta}_{c,u}\right)$ denotes the likeihood function of random receiving vector $\mathbf{y}$ based on $\boldsymbol{\eta}_{c,u}$.

Besides, the FIM for u-th user comprised of L subcarriers could be extended as:

$$J_{\boldsymbol{\eta}_u} = \sum_{c=-L/2}^{L/2} J_{\boldsymbol{\eta}_{c,u}} = \left(\begin{array}{c|c} \boldsymbol{\Phi}_{1,u} & \mathbf{0}_{2\times 3} \\ \hline \mathbf{0}_{3\times 2} & \boldsymbol{\Phi}_{4,u} \end{array} \right)_{5\times 5}, \tag{21}$$

where

$$\mathbf{\Phi}_{1,u} = \begin{bmatrix} \Phi\left(\tau_u, \tau_u\right) & 0 \\ 0 & \Phi\left(\theta_u^t, \theta_u^t\right) \end{bmatrix}_{2\times 2}, \tag{22}$$

$$\mathbf{\Phi}_{4,u} = \begin{bmatrix} \Phi\left(\theta_u^r, \theta_u^r\right) & \Phi_{1\times 2} \\ \Phi_{2\times 1} & \Phi_{2\times 2} \end{bmatrix}_{3\times 3}, \tag{23}$$

and $\mathbf{0}_{2\times 3}$ and $\mathbf{0}_{3\times 2}$ denote that these are 2×3 and 3×2 null matrices respectively.

Also, the first three diagonal elements of J_{η_u} could be formulated as:

$$\Phi\left(\tau_u, \tau_u\right) = \left(\sum_{c=-C/2}^{C/2} \Phi_c\left(\tau_{t,u}, \tau_{t,u}\right)\right)^{-1}, \tag{24}$$

$$\Phi\left(\theta_u^t, \theta_u^t\right) = \left(\sum_{c=-C/2}^{C/2} \Phi_c\left(\theta_u^t, \theta_u^t\right)\right)^{-1}, \tag{25}$$

$$\Phi\left(\theta_u^r, \theta_u^r\right) = \left(\sum_{c=-C/2}^{C/2} \Phi_c\left(\theta_u^r, \theta_u^r\right)\right)^{-1}, \tag{26}$$

and

$$\Phi_c\left(\tau_{t,u}, \tau_{t,u}\right) = 4\pi^2\sigma_{t,u}\bar{B}^2\left|H_{t,u}\right|^2 d_{0,u}\mathbf{a}_t^{\mathrm{H}}\mathbf{X}\mathbf{a}_t, \tag{27}$$

$$\Phi_c\left(\theta_u^t, \theta_u^t\right) = \sigma_{t,u}\left|H_{t,u}\right|^2 d_{0,u}\dot{\mathbf{a}}_t^{\mathrm{H}}\mathbf{X}\dot{\mathbf{a}}_t, \tag{28}$$

$$\Phi_c\left(\theta_u^r, \theta_u^r\right) = \sigma_{t,u}\left|H_{t,u}\right|^2 d_{2,u}\mathbf{a}_t^{\mathrm{H}}\mathbf{X}\mathbf{a}_t, \tag{29}$$

where

$$\sigma_{t,u} = \frac{2P_{t,u}T\,\mathrm{Loss}_{t,u}}{N_0}, \tag{30}$$

$$d_{0,u} = \left\|\boldsymbol{w}_u^{\mathrm{H}}\mathbf{a}_r\right\|_2^2, \tag{31}$$

$$d_{1,u} = \mathbf{a}_r\boldsymbol{w}_u^{\mathrm{H}}\frac{d}{d\theta_u^r}\boldsymbol{w}_u^{\mathrm{H}}\mathbf{a}_r, \tag{32}$$

$$d_{2,u} = \left\|\frac{d}{d\theta_u^r}\boldsymbol{w}_u^{\mathrm{H}}\mathbf{a}_r\right\|_2^2, \tag{33}$$

and $\dot{\mathbf{a}} = d\mathbf{a}/d\theta_u$.

As for the localization process, the channel state information should be replaced with $\boldsymbol{\mu}_u = \left[p_u^x, p_u^y, a_u, H_{t,u}^{\mathrm{R}}, H_{t,u}^{\mathrm{I}}\right]_{1\times 5}$, where p_u^x and p_u^y denote the horizontal and vertical coordinates of u-th user respectively, and a_u indicates the relative degrees between BS and u-th user. Then, the modified FIM could be formulated as:

$$J_{\boldsymbol{\mu}_u} = \mathbf{T}_u J_{\eta_u}(\mathbf{X})\mathbf{T}_u^{\mathrm{T}}, \tag{34}$$

and

$$\mathbf{T}_{u,5\times 5} \triangleq \frac{\partial \boldsymbol{\eta}_u^{\mathrm{T}}}{\partial \boldsymbol{\mu}_u}, \tag{35}$$

$$\mathbf{X} = |s_c|^2\boldsymbol{f}_c\boldsymbol{f}_c^{\mathrm{H}}, \tag{36}$$

where $\mathbf{T}_u$ denotes the jacobian matrix.

Hence, the localization error E_u^d of u-th user in the d-th user group could be acquired by computing the inverse of $J_{\boldsymbol{\mu}_u}$ as (37) formulates.

$$\begin{aligned} E_u^d &= Tr(J_{\boldsymbol{\mu}_u}^{-1})_{1:3} \\ &= J_{\boldsymbol{\mu}_u}^{-1}(1,1) + J_{\boldsymbol{\mu}_u}^{-1}(2,2) + J_{\boldsymbol{\mu}_u}^{-1}(3,3) \\ &= w_\tau\left(\sum_{c=-C/2}^{C/2}\Phi_c\left(\tau_{t,u}, \tau_{t,u}\right)\right)^{-1} \\ &\quad + w_{\theta^t}\left(\sum_{c=-C/2}^{C/2}\Phi_c\left(\theta_u^t, \theta_u^t\right)\right)^{-1} \\ &\quad + w_{\theta^r}\left(\sum_{c=-C/2}^{C/2}\Phi_c\left(\theta_u^r, \theta_u^r\right)\right)^{-1}. \end{aligned} \tag{37}$$

C. SPECIFIED OPTIMAL PROBLEM

To present the correlation expressions clearly, we set four simplified parameters as the following shows:

$$\mathbf{G} = \left[g_{t,u}^d\right]_{\forall t\in[1,T],\forall u\in[1,U],\forall d\in[1,D]}, \tag{38}$$

$$\mathbf{E} = \left[e_{t,u}^d\right]_{\forall t\in[1,T],\forall u\in[1,U],\forall d\in[1,D]}, \tag{39}$$

$$\mathbf{F} = \left[f_{c,u}^d\right]_{\forall c\in[-C/2,C/2],\forall u\in[1,U],\forall d\in[1,D]}, \tag{40}$$

$$\mathbf{P} = \left[P_{c,u}^d\right]_{\forall c\in[-C/2,C/2],\forall u\in[1,U],\forall d\in[1,D]}. \tag{41}$$

Assume that there are N users in the d-th user group. Combined with the derived performance metrics for the communication and localization process, the initial problem could be divided into two subproblems, as (42) shows. And the specified optimal problem for the localization process could be formulated as:

$$\begin{aligned} \min_{\mathbf{G},\mathbf{E},\mathbf{F},\mathbf{P}} \varepsilon &= \sum_{d=1}^{D}\sum_{u=1}^{N_d} E_u^d \\ &= \sum_{d=1}^{D}\sum_{u=1}^{U}\left(w_\tau F_\tau + w_{\theta^t}F_{\theta^t} + w_{\theta^r}F_{\theta^r}\right), \\ s.t.\ \ &\mathrm{AC\,1}: \sum_{u=1}^{U} e_{t,u}^d \le 1, \forall t\in T, \forall u\in U, \forall d\in D \\ &\mathrm{AC\,2}: \sum_{t=1}^{T} e_{t,u}^d \le 1, \forall t\in T, \forall u\in U, \forall d\in D \\ &\mathrm{AC\,3}: \sum_{d=1}^{D} g_u^d = 1, \sum_{u=1}^{U} g_u^d \ge 1, \forall u\in U, \forall d\in D \\ &\mathrm{AC\,4}: \mathrm{AC1, AC2, AC\,3, AC\,4\ in\ (13)} \end{aligned} \tag{42}$$

where

$$F_\tau = \left(\sum_{c=-C/2}^{C/2}\Phi_c\left(\tau_{t,u}, \tau_{t,u}\right)\right)^{-1}, \tag{43}$$

$$F_{\theta^t} = \left(\sum_{c=-C/2}^{C/2}\Phi_c\left(\theta_u^t, \theta_u^t\right)\right)^{-1}, \tag{44}$$

$$F_{\theta^r} = \left(\sum_{c=-C/2}^{C/2}\Phi_c\left(\theta_u^r, \theta_u^r\right)\right)^{-1}, \tag{45}$$

Algorithm 1 Low Complexity Beam Selection Algorithm

Require: AoD of U users,
for user $u = 1$ to U **do**
  $A_u = \max \mathrm{U}_{t,u}(\theta_u^t) \leftarrow (8)$
end for
for beam $t = 1$ to T **do**
  if $\sum_{u=1}^{U} e_{t,u} > 1$ **then**
    $U^* = \max_{u \in U} \mathrm{U}_{t,u}(\theta_u^r) \times 10^{-\mathrm{Loss}_{t,u}/10}$
  end if
end for
Output:the set **E**.

and AC 1 and AC 2 indicate that the beam could only be allocated to a single user without sharing. AC 3 represents the basic principle of user grouping, that is, each user could only be grouped into a single user group and the final group numbers must be no less than 1.

V. COMPREHENSIVE SCHEME FOR BEAM SELECTION, USER GROUPING, AND RESOURCE ALLOCATION

In this section, the corresponding algorithms are proposed according to the problem of beam selection, user grouping criterion, and resource allocation.

A. BEAM SELECTION ALGORITHM

Aligned beam pairs are the significant basis for high-speed communication and high-oriented localization. In general, each user has the adaption of available beams. However, there would exist repeated beams in different beam pairs blocking beam selection. The solution is presented as Algorithm 1 shows.

In this way, all users could gain unique optimal beam pairs.

B. USER GROUPING ALGORITHM

In the following, we consider the user grouping in the frequency domain. Assume that all users are divided into D $(1 < D < U)$ groups. Since grouping by frequency division multiplexing, there is no interference between users between different spectrum groups.

Hence, the channel state information of the main path is linearly weighted with the channel state information of other subpaths. In the proposed user grouping algorithm, the eigenvalues are set to be the weighting factor to gain the weighted sum corresponding to the eigenvectors. The specific process is as follows: The channel autocorrelation matrix of the u-th user is:

$$\boldsymbol{R}_u = \mathrm{E}\left(H_{t,u}^{\mathrm{H}} H_{t,u}\right), \tag{46}$$

We perform an eigenvalue decomposition of the autocorrelation matrix $\boldsymbol{R}_u$ as (47) shows.

$$\boldsymbol{R}_u = \boldsymbol{\xi}_u \boldsymbol{\Lambda}_u \boldsymbol{\xi}_u^H, \tag{47}$$

where, $\boldsymbol{\xi}_u$ is the matrix consisting of the eigenvectors of $\boldsymbol{R}_u$, and $\boldsymbol{\Lambda}_u$ is the diagonal matrix consisting of the eigenvalues of $\boldsymbol{R}_u$. Without loss of generality, it is convenient to assume that $\lambda_{u,1} \geq \lambda_{u,2} \geq \cdots \geq \lambda_{u,L} \geq 0$. Since the eigenvectors of the autocorrelation matrix correspond to the directions of the subpaths, respectively, the larger the power of the subpaths, the larger the eigenvalues. Therefore, we can multiply the eigenvalues as weights with their respective eigenvectors and then sum them. this method can be used for user pairing to utilize more channel information, thus making the scheme more accurate and effective. Therefore, we define the channel state vector of the u-th user, which is used for user pairing, as follows:

$$\boldsymbol{\Gamma}_u = \sum_{l=1}^{L} \boldsymbol{\xi}_{u,l} \lambda_{u,l}, \tag{48}$$

Since the channel state vector of each user contains the angle state information and power state information of that user, the correlation between the channel state vectors of each user can be calculated. There would be more overlapping parts between users with greater correlation in the actual channels, so the interference that will exist while data is transferred between users will be greater. The correlation between users can be defined as follows:

$$\boldsymbol{\rho}(j,k) = \frac{\left|\mathrm{E}\left(\boldsymbol{\Gamma}_j^{\mathrm{H}} \boldsymbol{\Gamma}_k\right)\right|}{\left|\mathrm{E}\left(\boldsymbol{\Gamma}_j^{\mathrm{H}} \boldsymbol{\Gamma}_j\right)\right| \left|\mathrm{E}\left(\boldsymbol{\Gamma}_k^{\mathrm{H}} \boldsymbol{\Gamma}_k\right)\right|}, \tag{49}$$

The specific steps could be described as Algorithm 2 indicates:

Algorithm 2 Multi-User Grouping Algorithm Based on Channel Correlation Coefficient

Initialization: the reference threshold: α, the user group: $z = 0$, the user group set: $Z = \{\}$,
for $j = 1$ to U **do**
  for $k = j + 1$ to U **do**
    if $\alpha < \boldsymbol{\rho}(j,k) \leftarrow (49)$ **then**
      if $u_j \in U$ **then**
        $z = z + 1$, $D_z = D_z \cup \{u_j\}$, $U = U \backslash \{u_j\}$, $Z = Z \cup D_z$
      end if
      if $u_k \in U$ **then**
        $z = z + 1$, $D_z = D_z \cup \{u_k\}$, $U = U \backslash \{u_k\}$, $Z = Z \cup D_z$
      end if
    end if
  end for
end for
for user i=1 to $|U|$ **do**
  $D_q = \arg\min_{D_q \subseteq Z} \sum_{v=1}^{|D_q|} \boldsymbol{\rho}(v,i)$
  $D_q = D_q \cup \{u_i\}$
  Output:the set **G**.
end for

where $U = U \backslash \{u_i\}$ means that i-th user has been used to form an appropriate user group.

In this way, U users belong to D user groups where resources could be shared in different groups. And in the remaining of the paper, the basic analysis target is changed into the d-th group.

C. RESOURCE ALLOCATION ALGORITHM

On account of Algorithm 1 and 2, the allocation scheme for user grouping and beam selection, that is, the sets $\mathbf{G}$ and $\mathbf{E}$ are known. And the preliminary works have been finished on account of the achievement of Algorithm 1 and 2. Based on the output results, the remaining sets $\mathbf{F}$ and $\mathbf{P}$ could be solved from (42) and Algorithm 3.

Algorithm 3 Joint Optimization Algorithm

```
Require: the set G, E,
for group d = 1 to D do
    Stage I:  (V-C) ← (53)
    Stage II:  (54) ← (53)
    Record the set Q of smaller localization error
    if the traversal process is complete then
        Get the most optimal set Q
        F,P ← (50)
    end if
end for
Output:the set F, P.
```

It is noteworthy that there is a data rate constraint in (13) and (42), which means that the communication process should be satisfied at first under the resource competition. Hence, the resource allocation process could be divided into two stages. In the first stage, AC in (13) would be satisfied within the limited resource. And in the second stage, the remaining resource would be allocated to the corresponding users in the localization process. Besides, the two stages should be iterated to acquire the minimum localization error when AC 1 in (13) is satisfied.

Consider the value range of $f^d_{c,u}$, the $f^d_{c,u}$ and $P^d_{c,u}$ could be combined as the following shows:

$$\begin{cases} q_{b,c,u} = 0 & \leftarrow f^d_{c,u} = 0, P^d_{c,u} = 0, \\ q_{b,c,u} = P^d_{c,u} & \leftarrow f^d_{c,u} = 1, P^d_{c,u} \neq 0, \end{cases} \tag{50}$$

and

$$\mathbf{Q} = \left[f^d_{c,u} \cdot P^d_{c,u} \right]_{\forall c \in [-C/2, C/2], \forall u \in [1,U], \forall d \in [1,D]}, \tag{51}$$

As for Stage I, the corresponding problem could be presented as:

$$\begin{aligned} \max_{\mathbf{E},\mathbf{Q}} R^d &= \sum_{c=-C/2}^{C/2} \sum_{u=1}^{N_d} \bar{B} \log_2 \left(1 + \frac{S^d_{c,u}}{I^d_{c,u} + N_0} \right) \\ &= \underbrace{\sum_{c=-C/2}^{C/2} \sum_{u=1}^{U} \bar{B} \log_2 (S^d_{c,u} + I^d_{c,u} + N_0)}_{x(\mathbf{Q})} \\ &\quad - \underbrace{\sum_{c=-C/2}^{C/2} \sum_{u=1}^{U} \bar{B} \log_2 (I^d_{c,u} + N_0)}_{y(\mathbf{Q})}, \end{aligned} \tag{52}$$

$$s.t. \ \text{AC} : \text{AC1,AC2,AC4 in (42)}$$

To solve this problem, we utilize the characteristic of convex function difference and Taylor approximation of the first order to transform (V-C) into (53) which could be solved by the traditional algorithms such as the interior point method. And this new solving algorithm is called the DCFA.

$$\begin{aligned} &\min_{\mathbf{Q}} x(\mathbf{Q}) - y(\mathbf{Q}) \\ &= x(\mathbf{Q}) - y(\mathbf{Q}[s-1]) - \nabla y^T (\mathbf{Q}[s-1])(\mathbf{Q} - \mathbf{Q}[s-1]). \end{aligned} \tag{53}$$

Then, Stage II could be solved based on the resource allocation results of Stage I. Considering that $\log_2(\cdot)$ is a linear function, Stage II for the localization process could also be transformed (42) into (54).

$$\begin{aligned} \min_{\mathbf{E},\mathbf{Q}} \log_2 \varepsilon^d &= \sum_{u=1}^{N_d} \log_2 (E^d_u) \\ &= \underbrace{\sum_{u=1}^{U} \log_2 \left(w_\tau F_{\theta^t} F_{\theta^r} + w_{\theta^t} F_\tau F_{\theta^r} + w_{\theta^r} F_\tau F_{\theta^t} \right)}_{x(\mathbf{Q})} \\ &\quad - \underbrace{\sum_{u=1}^{U} \log_2 \left(F_\tau F_{\theta^t} F_{\theta^r} \right)}_{y(\mathbf{Q})}. \end{aligned} \tag{54}$$

And (54) could also be solved by (53). Besides, there is a direct competition between the communication and localization process as the AC1 and AC2 in (13) shows. Hence, there must be a trade-off when solving (53) and (54). And the joint resource algorithm could be presented as Algorithm 3 shows.

VI. PERFORMANCE EVALUATION AND ANALYSIS

In this section, the proposed algorithms are used to simulate the resource allocation performance of the joint communication and localization in the mmWave MU-MIMO system. And the beam selection and user grouping problems are solved by Algorithm 1 and Algorithm 2. In addition, the optimization results of the final optimal problem are acquired from Algorithm 3. To ensure the accuracy of the numeric results, we adopt the control variable method for the simulation process.

A. SIMULATION SETTING

We conduct the simulations based on the mmWave MU-MIMO system, and the parameter setting are configured in Table 1. Besides, the application scenarios are set as urban areas and suburbs to save unnecessary costs in antennas. As Table 1 shows, the deployable antennas are ranging

TABLE 1. Simulation parameter values.

Parameter	Configuration Value
Center Frequency	60GHz
Bandwidth	100MHz
Subcarrier Interval	150kHz
Number of Users	8-32
Antennas Number in BS	16-36
SNR	10dB
Transmit Power	1W-10W
Spectrum density of noise	-174dB/Hz

from 16 to 36, with the increment of antennas in the ULA, in which the antenna's interval is set to half of the signal wavelength to avoid the grating lobe. Besides, the users and BS are located at a two-dimensional area of 50m×50m. Therefore, the communication links are constructed at the same height as mmWave. And the location of all equipment is shown in Fig.4.

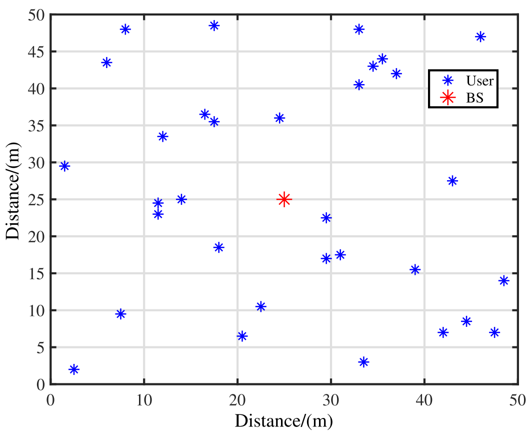


FIGURE 4. Initial network geometry with 1 known BS and 32 random users.

There are 32 users and 1 BS located in Fig.4, in which the red dot denotes the known BS located at (25,25), and the blue dot denotes the unknown user.

For comparison purposes, two other resource allocation algorithms under the joint communication and localization systems are implemented in the following simulations. The first one is the algorithm with the beam optimization and power allocation proposed in this paper [22] with multiple BSs. The second one is the algorithm with the bandwidth allocation proposed in this paper [20], where users are centered around one BS.

B. SIMULATION RESULTS

Fig.5 respectively shows the relationship between transmit power and data rate, as well as the relationship between

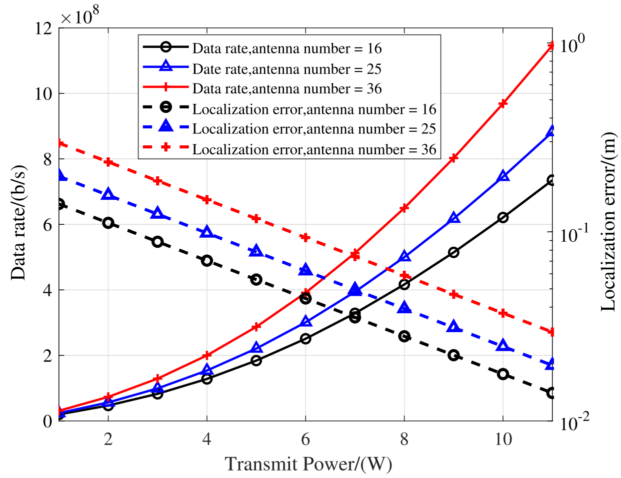


FIGURE 5. Graph about data rate and localization error in different transmit power and antenna number.

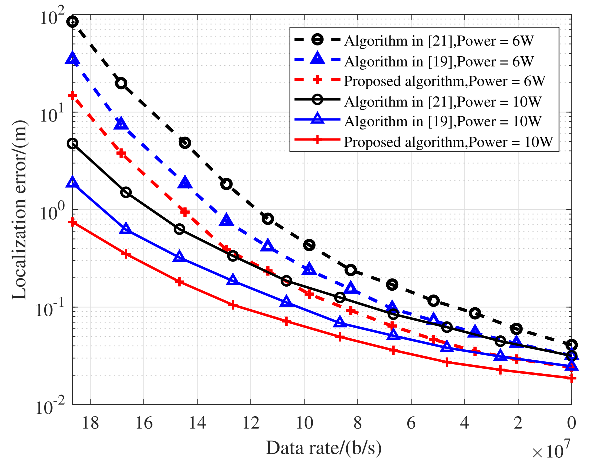


FIGURE 6. Graph about overall localization error and overall data rate in different resource allocation algorithms and transmit power.

transmit power and localization error. As (17) and (37) depict, the value of transmit power would significantly influence the data rate and localization error. And the performance of the communication and localization process would also be increased with the increment of antenna number, because of the added diversity gain. Besides, we set the transmit power as 6W and 10W to explore the performance balance between the data rate and localization error, as Fig.6 shows.

Fig.6 compares the performance trade-off between the achievable data rate and weighted localization error among the users for different resource allocation algorithms. In general, the proposed algorithm performs better than any other two algorithms both under the same data rate constraints and the same localization error constraints. And Algorithm in [22] performs the worst. Combined with the comprehensive optimization problem, there always exists resource competition between communication and localization performance with two strict constraints on data rate and localization error. According to (27)(42), the performance trade-off would be affected by the value of allocated power and bandwidth. And the results of beam selection would also affect the performance of the localization process. Therefore, our proposed algorithm would achieve better performance causing of the beam optimization and joint resource allocation including bandwidth, and power, while Algorithm in [22] doesn't consider the allocation of bandwidth, and Algorithm in [20] doesn't consider the allocation of power and beam optimization. In addition, considering the difference of transmit power, all algorithms with more power would have better performance both in the communication and localization process. It clearly shows that the data rate and the localization error are proportional to the transmission power, respectively. Hence, we set the transmission power of the following simulations to 10W.

Owing to the user grouping scheme, we simulate the effect of reference threshold α on communication and localization performance when SNR = 10dB, as Fig.7 and Fig.8 present.

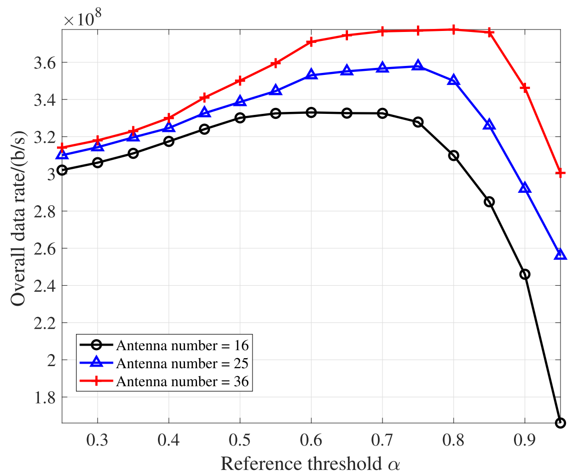


FIGURE 7. Relationship between reference threshold α and overall data rate.

Fig.7 describes the interactive effect between reference threshold α and the overall data rate of the MU-MIMO system as the antenna number changes in BS. As Fig.7 depicts, there always exists an optimal threshold value range for different antennas number. For example, when the antenna number is set to 16, the optimal threshold value is approximately between 0.5 and 0.75, while the range is between 0.6 and 0.85 when the antenna number is set to 36. Hence, the influence of the number of antennas on the optimal interval is very limited. And the grouping results would be worse when the reference threshold α is large than a number that depends on the channel gain. In addition, the overall data rate would increase first and then decrease. In general, with the increment of antennas number, different user pairs would be more and more uncorrelated. Then, in comparison with the low antenna numbers conditions, the quality of user grouping would be worse if decrease the reference threshold α. And when the value of α is increasing, there would be more precise and effective grouping conditions for most of the users.

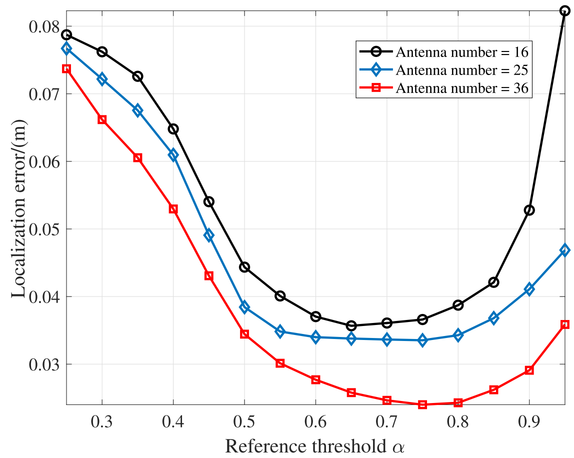


FIGURE 8. Relationship between reference threshold α and localization error.

Similar to Fig.7 above, Fig.8 is presented by the interactive effect between the reference threshold α and the localization error. As Fig.8 depicts, the optimal threshold value is approximately between 0.6 and 0.8, while the range is between 0.7 and 0.8 when the antenna's number increase from 16 to 36. And the influence of the number of antennas on the optimal interval is also very limited. Besides, the localization error would decrease first and then increase with the increment of reference threshold α. Therefore, we take the value of 0.7 to the reference threshold α in the remaining of this paper to acquire the best communication and localization performance. Hence, the proposed user grouping algorithm would be utilized combined with the proposed resource allocation in the remaining simulation process.

Fig.9 presents the performance trade-off between the communication and localization process of different user grouping conditions. In general, the proposed algorithm achieves better performance both in communication and localization, especially in comparison with Algorithm in [22] and Algorithm in [20] with no specific user grouping schemes. As for the fixed user grouping conditions, there are always existing redundant users or unfilled groups, which is also a performance penalty. And the proposed user grouping algorithm would dynamically distribute users into different groups to ensure high relevance among groups and low relevance within groups.

Fig.10 depicts the competition between communication and localization performance in different antenna numbers. An increase in the data rate for communication would result in a degradation of localization accuracy and vice versa, especially when communication and localization signals are orthogonally transmitted in different resource blocks, as Fig.10 shows. Hence, it is significant to allocate limited resources effectively to achieve the trade-off between data rate and localization error. Besides, the comprehensive performance is getting better when the antenna number increases. On the one hand, the antenna number is related to

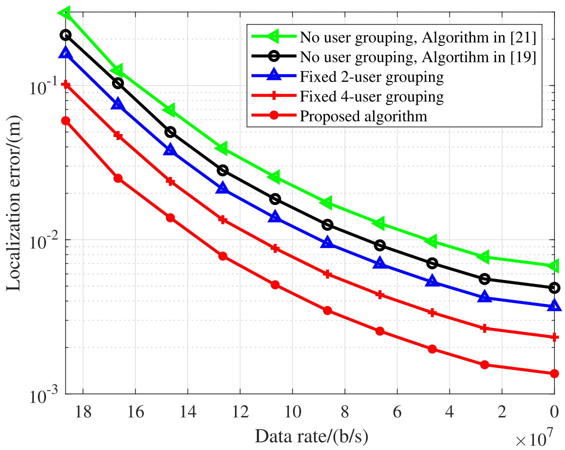


FIGURE 9. Graph about overall localization error and overall data rate in different user grouping algorithms.

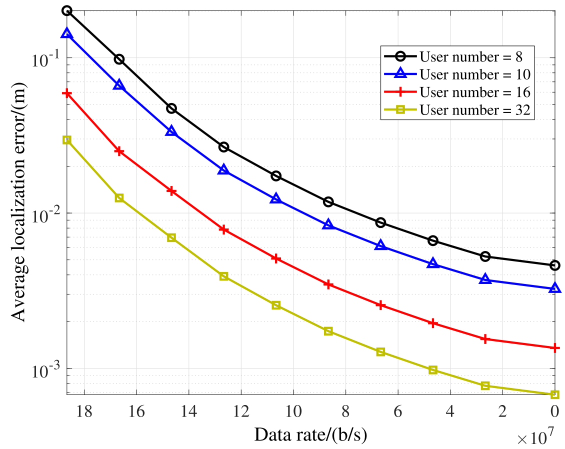


FIGURE 11. Graph about average localization error and overall data rate in different user numbers when $\alpha = 0.7$.

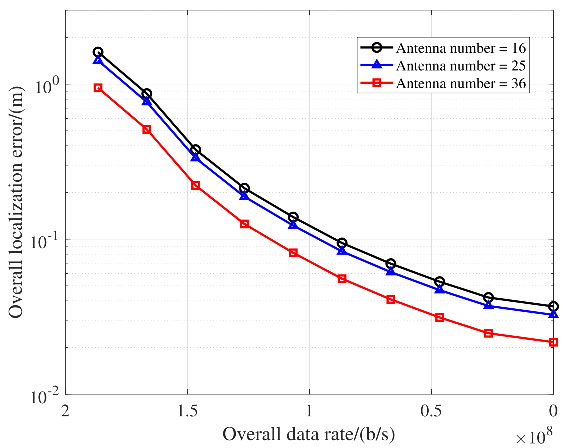


FIGURE 10. Graph about overall localization error and overall data rate in different antenna numbers when $\alpha = 0.7$.

the available beam numbers which influence the orientation of users and the user relevance. On the other hand, there exists spatial multiplexing diversity related to the antenna number as well. And independent data streams can be transmitted over parallel spatial channels, increasing the system capacity because of the spatial multiplexing diversity. However, it is expensive to deploy large numbers of antennas which means the antenna's number should be related to the real conditions.

Fig.11 shows the competition between communication and localization performance based on different user numbers. In comparison with Fig.10, the overall trend is consistent while removing the effect of the number of users and the antenna number. And the communication and localization performance would be getting better when the access user numbers increase. On the one hand, the interference between users would be reduced by the proposed user grouping algorithm. Because users could utilize the same time-frequency resource blocks in the same user group. On the other hand, there exists multiuser diversity when the number of users is large. Multiuser diversity is a kind of independent fading that could simultaneously schedule users with specific channel conditions. Hence, different data streams are sent to different users such that the performance metrics are optimized, such as the data rate, PEB, and OEB. In general, the comprehensive performance would be proportional to the number of users while a large number of users would increase the complexity of the resource allocation scheme.

C. COMPLEXITY ANALYSIS

In this section, we analyze the complexity of the beam selection algorithm, user grouping algorithm, and resource allocation algorithm, and present it with $\mathcal{O}(\cdot)$.

As for Algorithm 1, there are two separate ergodic processes prepared for users and beams. For the process of computing the maximum directivity coefficient, the complexity could be presented as $\mathcal{O}(UT)$, in which each user would have the optimal and unique beam. Then it ensures that each user has a unique and nonredundant beam, the complexity could be $\mathcal{O}(T)$ in the worst conditions, and $\mathcal{O}(1)$ in the best conditions. Hence, the overall complexity of Algorithm 1 could be presented as $\mathcal{O}(UT + T)$.

Besides, Algorithm 2 is utilized to group users. And assume there are already M users among groups. Then, it would be more than M times of computing coefficients. Then the complexity for grouping a new user could be $\mathcal{O}(M)$, which is equal to the mentioned corresponding algorithm in Section V. Combined with Fig. 5, the proposed user grouping algorithm could achieve better performance than existing algorithms under the same complexity condition.

On account of Algorithm 3, there is an iterated process between Stage I and Stage II. On the one hand, corresponding resources are distributed to maximize the data rate with k available allocation schemes. On the other hand, the remaining resource would be distributed to minimize the localization error. Assume the complexity of completing the loop once is $\mathcal{O}(A)$, and the overall complexity could be presented as $\mathcal{O}(kAD)$. In general, the complexity of the equal resource algorithm is approximately equal to $\mathcal{O}(UTCD)$ which is less than the proposed Algorithm 3. However, it is significant to acquire more performance gain in an era with such strong computing power, and the high complexity is acceptable.

VII. CONCLUSION

In this paper, a multiple-dimensional resource allocation algorithm in mmWave MU-MIMO systems is proposed. Through beam selection and user grouping, all users are divided into the optimal group to share the same time-frequency resource blocks at the minimum performance loss. Then, to solve the resource allocation problem, we transfer the original problem into a joint optimization problem with multiple control variables under joint communication and localization systems. Finally, an optimal allocation algorithm is developed to solve the multi-dimensional resource optimization problem, including beam, power, and subcarriers. Numeric simulation results also demonstrate that the proposed algorithm could improve comprehensive performance by efficiently exploiting wireless resources. Some of the interesting questions for further research include an extension to multi-cell multi-user scenarios, which exist the interference between different cells, and the theoretical study of the performance criteria for joint communication and localization.

REFERENCES

[1] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K. Karagiannidis, E. Björnson, K. Yang, C.-L. I, and A. Ghosh, "Millimeter wave communications for future mobile networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 1909–1935, Sep. 2017.

[2] W. Jiang, B. Han, M. A. Habibi, and H. D. Schotten, "The road towards 6G: A comprehensive survey," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 334–366, 2021.

[3] G. Bresson, Z. Alsayed, L. Yu, and S. Glaser, "Simultaneous localization and mapping: A survey of current trends in autonomous driving," *IEEE Trans. Intell. Veh.*, vol. 2, no. 3, pp. 194–220, Sep. 2017.

[4] J. Thomas, J. Welde, G. Loianno, K. Daniilidis, and V. Kumar, "Autonomous flight for detection, localization, and tracking of moving targets with a small quadrotor," *IEEE Robot. Autom. Lett.*, vol. 2, no. 3, pp. 1762–1769, Jul. 2017.

[5] R. Estrada, R. Mizouni, H. Otrok, A. Ouali, and J. Bentahar, "A crowd-sensing framework for allocation of time-constrained and location-based tasks," *IEEE Trans. Services Comput.*, vol. 13, no. 5, pp. 769–785, Sep. 2020.

[6] F. Zabini and A. Conti, "Inhomogeneous Poisson sampling of finite-energy signals with uncertainties in $\mathbb{R}^d$," *IEEE Trans. Signal Process.*, vol. 64, no. 18, pp. 4679–4694, Sep. 2016.

[7] S. G. Nagarajan, P. Zhang, and I. Nevat, "Geo-spatial location estimation for Internet of Things (IoT) networks with one-way time-of-arrival via stochastic censoring," *IEEE Internet Things J.*, vol. 4, no. 1, pp. 205–214, Feb. 2017.

[8] M. Z. Win, F. Meyer, Z. Liu, W. Dai, S. Bartoletti, and A. Conti, "Efficient multisensor localization for the Internet of Things: Exploring a new class of scalable localization algorithms," *IEEE Signal Process. Mag.*, vol. 35, no. 5, pp. 153–167, Sep. 2018.

[9] F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, Y. C. Eldar, and S. Buzzi, "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728–1767, Jun. 2022.

[10] W. Saad, M. Bennis, and M. Chen, "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems," *IEEE Netw.*, vol. 34, no. 3, pp. 134–142, May/Jun. 2020.

[11] E. Castañeda, A. Silva, A. Gameiro, and M. Kountouris, "An overview on resource allocation techniques for multi-user MIMO systems," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 239–284, 1st Quart., 2017.

[12] G. Destino and H. Wymeersch, "On the trade-off between positioning and data rate for mm-wave communication," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2017, pp. 797–802.

[13] D. Kumar, J. Saloranta, G. Destino, and A. Tolli, "On trade-off between 5G positioning and mmWave communication in a multi-user scenario," in *Proc. 8th Int. Conf. Localization GNSS (ICL-GNSS)*, Jun. 2018, pp. 1–5.

[14] R. Koirala, B. Denis, B. Uguen, D. Dardari, and H. Wymeersch, "Localization and throughput trade-off in a multi-user multi-carrier mm-wave system," *IEEE Access*, vol. 7, pp. 167099–167112, 2019.

[15] G. Ghatak, R. Koirala, A. De Domenico, B. Denis, D. Dardari, B. Uguen, and M. Coupechoux, "Beamwidth optimization and resource partitioning scheme for localization assisted mm-wave communication," *IEEE Trans. Commun.*, vol. 69, no. 2, pp. 1358–1374, Feb. 2021.

[16] X. Lu, Q. Ni, W. Li, and H. Zhang, "Dynamic user grouping and joint resource allocation with multi-cell cooperation for uplink virtual MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 3854–3869, Jun. 2017.

[17] X. Lu, K. Yang, N. Fan, H. Guo, and H. Zhang, "Joint clustering of users and resources for multi-cell VMIMO-SC-FDMA uplink systems," *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1417–1430, Feb. 2019.

[18] X. Lu, Q. Ni, D. Zhao, W. Cheng, and H. Zhang, "Resource virtualization for customized delay-bounded QoS provisioning in uplink VMIMO-SC-FDMA systems," *IEEE Trans. Commun.*, vol. 67, no. 4, pp. 2951–2967, Apr. 2019.

[19] S.-M. Tseng and Y.-F. Chen, "Average PSNR optimized cross layer user grouping and resource allocation for uplink MU-MIMO OFDMA video communications," *IEEE Access*, vol. 6, pp. 50559–50571, 2018.

[20] Z. Wang, K. Han, X. Shen, W. Yuan, and F. Liu, "Achieving the performance bounds for sensing and communications in perceptive networks: Optimal bandwidth allocation," *IEEE Wireless Commun. Lett.*, vol. 11, no. 9, pp. 1835–1839, Sep. 2022.

[21] S. Pan, Y. Yan, K. A. Bonsu, and W. Zhou, "Resource allocation algorithm for MU-MIMO systems with double-objective optimization under the existence of the rank deficient channel matrix," *IEEE Access*, vol. 7, pp. 61307–61319, 2019.

[22] G. Kwon, A. Conti, H. Park, and M. Z. Win, "Joint communication and localization in millimeter wave networks," *IEEE J. Sel. Topics Signal Process.*, vol. 15, no. 6, pp. 1439–1454, Nov. 2021.

[23] F. Lemic, J. Martin, C. Yarp, D. Chan, V. Handziski, R. Brodersen, G. Fettweis, A. Wolisz, and J. Wawrzynek, "Localization as a feature of mmWave communication," in *Proc. Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Sep. 2016, pp. 1033–1038.

[24] G. Bu and J. Jiang, "Reinforcement learning-based user scheduling and resource allocation for massive MU-MIMO system," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Aug. 2019, pp. 641–646.

[25] Y. Heng, J. G. Andrews, J. Mo, V. Va, A. Ali, B. L. Ng, and J. C. Zhang, "Six key challenges for beam management in 5.5G and 6G systems," *IEEE Commun. Mag.*, vol. 59, no. 7, pp. 74–79, Jul. 2021.

[26] B. P. Zhou, A. Liu, and V. Lau, "Successive localization and beamforming in 5G mmWave MIMO communication systems," *IEEE Trans. Signal Process.*, vol. 67, no. 6, pp. 1620–1635, Mar. 2019.

[27] X. Wu, Z. Ma, X. Chen, F. Labeau, and S. Han, "Energy efficiency-aware joint resource allocation and power allocation in multi-user beamforming," *IEEE Trans. Veh. Technol.*, vol. 68, no. 5, pp. 4824–4833, May 2019.

[28] S. Buzzi, C. D'Andrea, and M. Lops, "Using massive MIMO arrays for joint communication and sensing," in *Proc. 53rd Asilomar Conf. Signals, Syst., Comput.*, Nov. 2019, pp. 5–9.

[29] O. B. Akan and M. Arik, "Internet of radars: Sensing versus sending with joint radar-communications," *IEEE Commun. Mag.*, vol. 58, no. 9, pp. 13–19, Sep. 2020.

[30] C. Xu, B. Clerckx, S. Chen, Y. Mao, and J. Zhang, "Rate-splitting multiple access for multi-antenna joint radar and communications," *IEEE J. Sel. Topics Signal Process.*, vol. 15, no. 6, pp. 1332–1347, Nov. 2021.

[31] X. Tong, Z. Zhang, J. Wang, C. Huang, and M. Debbah, "Joint multi-user communication and sensing exploiting both signal and environment sparsity," *IEEE J. Sel. Topics Signal Process.*, vol. 15, no. 6, pp. 1409–1422, Nov. 2021.

[32] N. Zhao, Y. Wang, Z. Zhang, Q. Chang, and Y. Shen, "Joint transmit and receive beamforming design for integrated sensing and communication," *IEEE Commun. Lett.*, vol. 26, no. 3, pp. 662–666, Mar. 2022.

[33] Z. Ni, J. A. Zhang, K. Yang, X. Huang, and T. A. Tsiftsis, "Multi-metric waveform optimization for multiple-input single-output joint communication and radar sensing," *IEEE Trans. Commun.*, vol. 70, no. 2, pp. 1276–1289, Feb. 2022.

[34] S. Piersanti, L. A. Annoni, and D. Cassioli, ''Millimeter waves channel measurements and path loss models,'' in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2012, pp. 4552–4556.
[35] J. Wang, H. Zhu, L. Dai, N. J. Gomes, and J. Wang, ''Low-complexity beam allocation for switched-beam based multiuser massive MIMO systems,'' *IEEE Trans. Wireless Commun.*, vol. 15, no. 12, pp. 8236–8248, Dec. 2016.

YACHUAN BAO is currently an Engineer with the State Key Laboratory of Satellite Navigation System and Equipment Technology (CEPNT). He is mainly engaged in satellite navigation, communication, and navigation integration technology research. He is a Reviewer of *IET Generation, Transmission and Distribution* and *Tactical Missile Technology*.

BAOGUO YU is currently a Professor and a Doctoral Supervisor. He is the Director of the State Key Laboratory of Satellite Navigation System and Equipment Technology (CEPNT). He is the Chief Scientist of CETC. He is a member of the National BD Standardization Technical Committee. He is a member of the Technology Committee, National Administration of Surveying, Mapping and Geoinformation. He is the Chairperson of Navigation and Location Service Session of China Satellite Navigation Conference.

BENQUAN YIN was born in Anhui, China. He received the B.Sc. degree in optoelectronic information science and technology from Xidian University, Xi'an, China, in 2020, where he is currently pursuing the M.Sc. degree in communication and information system with the State Key Laboratory of Integrated Service Networks. His research interests include millimeter wave, virtual MIMO, and resource allocation of wireless communications.

XUENI LUO was born in Hunan, China. She received the B.Sc. degree in communication engineering from Xidian University, Xi'an, China, in 2021, where she is currently pursuing the M.Sc. degree in communication and information system with the State Key Laboratory of Integrated Service Networks. Her research interests include OFDM, mmWave, and resource allocation of wireless communications.

XIAOFENG LU received the B.Sc. degree from Sichuan University, Chengdu, China, in 1996, the M.Sc. degree from Hunan University, Changsha, China, in 1999, and the Ph.D. degree from the Huazhong University of Science and Technology, Wuhan, China, in 2006. From 1999 to 2003, he was a Research and Development Engineer with the Wuhan Research Institute of Post and Telecommunications. He is currently a Full Professor with the State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an, China. His main research interests include broadband wireless communications, covering topics, such as resource allocation and virtualization, MU-MIMO, and OFDMA.