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Performance and User Association Optimization for UAV Relay-assisted mm-Wave Massive MIMO Systems

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ABSTRACT Unmanned aerial vehicle (UAV) relaying is deemed as a promising solution to enhance the achievable rate and widespread connectivity in millimeter-Wave (mm-Wave) systems for tomorrow's 6G wireless networks. In this paper, we study both the performance and user association optimization for the UAV relay-assisted mm-Wave massive multiple-input multiple-output (MIMO) communication system, where multiple base stations (BSs) serve their respective users with the help of one beamforming UAV relay. Both the beamforming and the UAV relay have essential impact on the achievable sum-rate of the system. Thus, a multi-user hybrid beamforming scheme is designed to mitigate the inter-user interference issues and achieve a better trade-off between performance and complexity in UAV-enabled communications. Also, to exploit UAV relay based architecture in serving different ground BS-user pairs, we propose a UAV relay-assisted multi-BS mm-Wave massive MIMO system with hybrid beamforming architecture, which prevent sudden link disconnections caused by high path loss and line-of-sight (LOS) blockage in mm-Wave frequency band. Then, we formulate a user association problem with multiple constraints so that the sum-rate of the overall UAV relay assisted-mm-Wave massive MIMO system is maximized. Simulation results are provided to show the effectiveness of the proposed UAV relay-enabled architecture.

INDEX TERMS Unmanned aerial vehicle (UAV) relay, mm-Wave communications, massive MIMO, 6G, hybrid Beamforming, user association, sum rate maximization.

I. INTRODUCTION

MILLIMITER-WAVE (mm-Wave) communications have been envisioned as a dominant candidate for enhancing the data rate, while supporting a wide variety of applications of beyond 5G wireless networks [1]. These benefits are mainly due to the huge bandwidth availability in their frequency bands, and the great potential they offer for antennas miniaturization [2]. However, the biggest challenging factor with these high frequencies is the severe path loss and the easy blockage by obstacles, especially considering the very long transmission distances involved [3], [4]. This results in substantial system performance losses if the network is not configured properly. To combat the aforementioned issues, researchers have proposed multiple key enabling technologies, e.g., massive multiple-input multiple-output (MIMO) technology, networks densification, the use of the unmanned aerial vehicles (UAVs), etc [5]. Another powerful solution to establish high-quality communication links and extend coverage of outdoor mm-Wave systems is through relay-based beamforming approach [6].

With regard to its great potential in 5G wireless networks, massive MIMO with hybrid beamforming structure is considered as an innovative research direction of 5G wireless communication, where hybrid beamforming plays a paramount role [7], [8]. This latter has been recently proposed as a practical solution for mm-Wave MIMO communications through striking a trade-off between system performance and hardware efficiency. Hybrid beamforming approaches generally employ few radio frequency (RF) chains to realize low dimensional digital beamformers followed by a large number of cost-efficient phase shifters to implement high dimensional analog beamformers. As a result, the analog beamformers can provide a sufficient beamforming gain to compensate for the huge path loss in mm-Wave frequency bands, and the digital beamformers can offer the flexibility to realize multiplexing techniques [9].

In addition, communications via UAVs, popularly referred to as drones, are one of the most crucial enabling technologies for 6G wireless networks to realize a massive amount of connections. Recently, UAV communications have attracted lots of attention in both industry and academia [10], [11]. This interest is motivated by their flexibility, low acquisition and cost efficiency, and their targeting of potential applications such as device to-device (D2D) communications, smart city construction, Internet of Things (IoT), public safety, and so forth [12]–[14]. In fact, UAV-aided wireless communication becomes one promising solution to provide temporary wireless connectivity, extended coverage range, and long transmission distances for ground users [15].

A very appealing solution for enhancing the propagation performance of the mm-Wave systems and realizing the ambitious goals of future 6G wireless networks, is to use UAVs equipped with massive MIMO beamforming [16]. On the one hand, UAVs can fly out of blockage zone to establish LOS links, which results in overcoming the aforementioned penetration losses, and hence the low latency communications is satisfied [17]. On the other hand, the short wavelength of mm-Wave permits massive antennas to be placed into a small UAV so that beamforming structure can be carefully designed to overcome the drawbacks of mm-Wave communications [18], [19]. For instance, in [18], a three-dimensional (3D) beamforming approach is explored to achieve flexible coverage for target areas by designing wide beams in mm-Wave-UAV communications. In [19], massive MIMO schemes have been integrated in mm-Wave-UAV communication systems to enhance network coverage and the system spectrum efficiency by exploiting the beamforming gains.

Recently, there has been a growing interest in developing UAV relays in the 6G wireless networks aiming for the improvement of the connectivity and the coverage of ground wireless devices [20]. Compared to the deployment of conventional terrestrial infrastructures, such as ground relays, aerial relay-assisted communications provide effective ways to prolong the mm-Wave transmission range, offer a better signal quality, and increase the data rate between two or multiple terrestrial nodes in the mm-Wave bands [21]. This is simply due to the fact that the placement of UAVs at elevated altitudes could effectively bypass the obstacles on the ground, and which are more likely to have LOS links, and consequently a better channel gain. On the other side, UAVs can move freely in the 3D space to adapt to the network mobility and enhance the system performance [6]. Naturally, employing large MIMO antennas in UAV relay-assisted mm-Wave networks brings additional challenges in designing 6G system architecture, more particularly the ones pertaining to the limited power issue, which results in a strict constraint on their energy consumption [22]. Theoretically speaking, an analog beamforming structure represents the most preferable solution to achieve low power consumption for the UAV, since it adopts the simplest electronic components and requires a single RF chain [23]. However, and only because of the limited flexibility of analog beamforming, multiple UAVs were suggested to provide ubiquitous network coverage to ground users, which may incur significant energy consumption for propulsion. Beside, opting for multiple UAVs could be quite challenging in practice since it involves aspects pertaining to complex synchronization, altitude control, cost, and power optimization, …etc [22], [24]. In view of this issue, the research community is leaning towards the development of hybrid beamforming configuration for massive MIMO system, which enables simultaneous transmission of multiple data streams from the same UAV station, and makes it possible to reduce the UAV swarm size and its relative cost compared to the analog beamforming counterpart [25]. Inspite of these viable advantages, quite few research works have been devoted to incorporation of hybrid beamforming in the hot topic of UAV-based relaying communication system.

In light of these aforementioned benefits of mm-Wave communications and UAV relay networks, in this paper we consider a mm-Wave massive MIMO network employing multiple BSs to serve multiple ground users with the help of UAV relay-based hybrid beamforming structure to enhance the achievable rate and widespread connectivity in mm-Wave communications.

A. RELATED WORK AND MOTIVATION

There is a growing number of works that integrates UAV into mm-Wave networks due to its promising merits. In [26], the authors provided a comprehensive survey on UAV-assisted mm-Wave communications and summarized their main challenges. In [27], the performance evaluation of UAV-assisted mm-Wave networks is investigated, where UAVs were deployed as mm-Wave access points communicating with ground users. In [28], the authors studied the quality of service (QoS)-based performance analysis for a coexisting network of sub-6 GHz and mm-Wave UAV-based communication. In [29] the outage performance of the mm-Wave UAV swarm network is studied, where a multiple UAV BSs provide connectivity to a far-distance user in the presence of blockages. In [30], a position and attitude prediction-based learning algorithm for mm-Wave UAV-to-UAV communication is proposed using conventional uniform planar arrays (UPA). In [31] the problem of maximizing the achievable sum rate of all users in mm-Wave UAV system is investigated, where the UAV serves as a BS. The authors of [32] focused on network coverage and the performance optimization problem in UAV-assisted powered mm-Wave networks. Indeed, we only increase the number of BS antennas to become massive and exploit hybrid beamforming techniques.

Different from the previous works, this paper considers UAV relay-assisted mm-Wave networks to further improve the achievable rate performance and widespread connectivity in mm-Wave communications. The potential benefits of deploying UAV-based relay in mm-Wave networks have been studied by many works [23], [33]–[37]. In [33] a novel UAV-relaying method for mm-Wave system is proposed in order to overcome shadowing and NLOS conditions by adjusting their optimal location automatically. In [34], a new energy-efficient modulation scheme associated with free space optical (FSO) communications is developed for the UAV relay in order to improve its battery life. The authors in [35] deployed a UAV as an Amplify-and-Forward (AF) relay using mm-Wave concurrently in backhaul and access links. Authors in [36] proposed to deploy UAVs as aerial relay nodes to enable dynamic routing in mm-Wave backhaul links, thereby mitigating blockage due to random mobility of blocking users. Very recently, the authors in [37] proposed a hybrid beamforming-NOMA approach to improve the achievable rate of downlink mm-Wave half-duplex UAV relay-assisted massive multi-user MIMO networks. Additionally, in [23], the full duplex UAV relay is employed to improve the achievable rate performance of mm-Wave communications, in which an analog beamforming is utilized to mitigate the self interference.

The research works in [23], [33]–[37] can provide us with a good picture about employing UAV relaying to enhance the performance of mm-Wave networks. Nonetheless, some crucial points in the prior works are not yet adequately addressed in the more recent studies. For example, most of them mainly focus on single-antenna UAV relay-assisted mm-Wave communications except in the mentioned contributions in [23], [37]. Moreover, the UAV relay-enabled mm-Wave networks for multiple BSs, which is investigated in this paper, has not yet been considered. Also, all the prior works on UAV networks using the mm-Wave band are still minimal and there seem to be no prior works focusing on the users association problem in UAV mm-Wave relaying networks with hybrid beamforming architecture.

Considering the scope of our work, the process of associating users and BSs is another critical issue for mm-Wave networks. This issue becomes more challenging for multi-BS massive MIMO systems since each user receives not only the desired signal but also interference from many antennas of several BSs at different locations. The problem of users' association in mm-Wave networks and massive MIMO deployment has been widely investigated [38]–[46]. In the context of HetNets, with the goal of maximizing the sum backhaul rate, an efficient association and placement of the backhaul hubs have been studied in [38], [39], where the UAVs are used as backhaul aerial hubs between small-cells and core network and are connected via FSO links. Similarly in [40], a genetic algorithm for the joint optimal placement of UAV-hubs and the association of small-cell base stations (SCBSs) is proposed such that the sum-rate of the overall system can be maximized. In [41], authors used the idea of employing UAVs using the unsupervised learning based k-means clustering algorithm and then the association of SCBSs with UAVs is performed, which resulted in consuming less bandwidth while achieving high sum-rate. In the context of mm-Wave networks, several studies have been proposed [42]–[46]. In [42], the BS placement and user association problem with the objective of minimizing the outage probability in mm-Wave networks are analyzed. In [43], a user association problem in mm-Wave backhaul small cell networks with the objective of maximizing the network energy and spectrum efficiency is investigated. In [44], a joint coordinated user association and spectrum allocation problem in 5G HetNets that use mm-Wave bands is studied. In [45], a joint beamforming and cell association optimization problem in mm-Wave cellular networks is investigated with the objective of maximizing the throughput of the users. In [46], an association problem in a two tier network with massive MIMO deployment both at the macro and femto tiers is investigated. Besides, the work addressed in [38]–[46], the user association in UAV relay-assisted mm-Wave massive MIMO systems, which is investigated in this paper, has not yet been considered. To the best of our knowledge, despite the orientation towards the exploitation of the mm-Wave bands, this is the first article which provides both the achievable rate performance and user association optimization problem while maximizing the sum-rate of the overall UAV relay assisted mm-Wave massive MIMO communication systems. In addition, the positive impact of UAV relay-based hybrid beamforming structure on both user association and sum-rate performance has not been considered in prior work for any user association scheme for mm-Wave networks. Nonetheless, the benefit of massive MIMO for sub-6 GHz was a result of channel hardening and favorable propagation properties [47]. However, the mm-Wave and Terahertz (THz) frequency bands are characterized by sparse and low rank channels, where the number of NLoS links decreases as we increase the carrier frequency of operation [17], [48]. Recall that the work in [17] addressed the open issues of UAV mm-Wave channels and their specific characteristics, scenarios, and challenges. Hence, as a result of the specific UAV channels at high frequency bands, our ability to leverage the channel hardening and favorable propagation condition of massive MIMO is still questionable [47], [48]. Therefore, no channel hardening and favorable propagation properties have been used.

B. CONTRIBUTIONS

In this paper, we consider a UAV relay-assisted multi-BS multi-user mm-Wave massive MIMO system through hybrid beamforming structure, wherein the source is a set of multiple distributed BSs and the destination is a set of multiple single-antenna users. The key feature of the considered system is to equip the UAV relay with massive MIMO antennas to overcome the severe propagation loss of mm-Wave signals and exploit the hybrid beamforming design, with the goal of achieving a performance comparable to fully digital beamforming, but with much reduced complexity and power consumption. Moreover, we define the association problem of users and BSs, and present its performance. To summarize, our contributions can be described as follows:

- To fully exploit the advantages of distributed BSs and improve communication quality under severe path loss and blockage drawbacks usually occurring in mm-Wave communications, we consider a UAV relay-assisted mm-Wave massive MIMO system with hybrid beamforming architecture. Specifically, UAV based relaying can significantly improve the sum rate performance as well as extend the coverage area. Simulation results demonstrate that UAV relay-based architecture can significantly enhance the achievable sum data rate over the alternative one without UAV relaying for mm-Wave communications.

- To achieve a better trade-off between performance and complexity in UAV enabled communications, a multi-user hybrid beamforming scheme is designed, which significantly reduces the implementation overhead, and effectively mitigates the inter-user interference. The corresponding performance is very close to that obtained by the full digital beamforming, and outperforms the existing scheme proposed in [49].
- To formulate an optimization problem that find the best user association scenario such that the sum-rate of the overall UAV relay assisted mm-Wave massive MIMO system can be maximized under a multiple communication-related constraints, i.e., quality of service, maximum available bandwidth that each BS can support, maximum number of links, power limit at which a BS can transmit the initialization signal and maximum data rate constraints are considered. We show through simulations that our proposed solution perform nearly optimal.

The rest of the paper is organized as follows. Section II introduces the system and channel models. The multi-user hybrid beamforming design is described in Section III. By considering different communication constraints, the optimization problem formulation is derived in Section IV. In Section V, we present some results to validate the effectiveness of the UAV relay-enabled architecture. Finally, we conclude the paper in Section VI.

II. SYSTEM AND CHANNEL MODELS

In this section, we first introduce the UAV relay-assisted multi-user mm-Wave massive MIMO system model followed by the 3D geometry based-UAV mm-Wave channel model.

A. THE SYSTEM MODEL

As shown in Fig. 1, we consider a UAV relay assisted-mm-Wave massive MIMO network consisting of N_{BS} BSs, U single antenna users, and one UAV relay working in a half-duplex mode. In this system, there is no direct link between the source nodes (BSs) and their destinations (users) since mm-Wave signals are sensitive to severe blockages. To ensure a wide coverage area, we assume massive MIMO deployment both at the BSs and UAV relay with N_t and N_{re} antennas, respectively. It should be noted that while allowing a user to be served by multiple BSs may require more overhead to implement, and hence it is more difficult to implement multiple-BS association than single-BS association [50], [51]. Therefore, even though the performances of multiple BSs association schemes are close to optimal [52], we have chosen to focus on one BS at a time where all BSs have to be associated in the end of the association cycle and leave the case of multi-BS association scheme to future work. This assumption is supported by it practical purposes, thus it simplifies the beamforming /combining procedure at the UAV relay and user association. In this paper, we assume that All BSs are connected to a central controller, able to decide which particular BS serve their associated users based on the information provided by the users. Upon receiving the association information from the central controller, all BSs will transmit information data to their associated users.

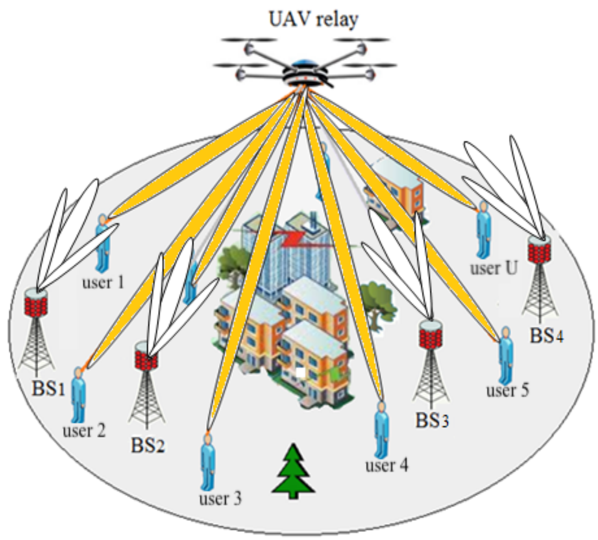


FIGURE 1. Graphical illustration of UAV relay-enabled architecture for multi-BS mm-Wave massive MIMO multi-user system.

In order to reduce the hardware cost of the massive antennas deployment in UAV relay-enabled architecture, hybrid beamforming structure is applied between the multiple BSs, the UAV relay, and the ground users as illustrated in Fig. 2. Specifically, both BSs and the UAV hold the same number of RF chains, denoted as N_{RF}, where $N_t \geq N_{\text{re}} \gg N_{\text{RF}}$, and to achieve full multiplexing gains, we assume $N_{\text{RF}} = U$ [53]. Similarly, the total number of transmitted streams are $N_s = U$. Furthermore, each user is equipped with one RF chain, which can reduce the processing complexity of the destination. Without loss of generality, we assume that the channel state information (CSI) is perfectly known at the BSs and UAV relay, which corroborates the assumptions in (as done in many related references such as) [31], [54]. CSI acquisition at UAV-aided mm-Wave systems is currently a topic of active research. Recently, imperfect CSI has been brought into the context of mm-Wave systems by exploiting the sparsity of mm-Wave channels to embed compressed sensing (CS) techniques for the estimation of the these channels [55]–[57].

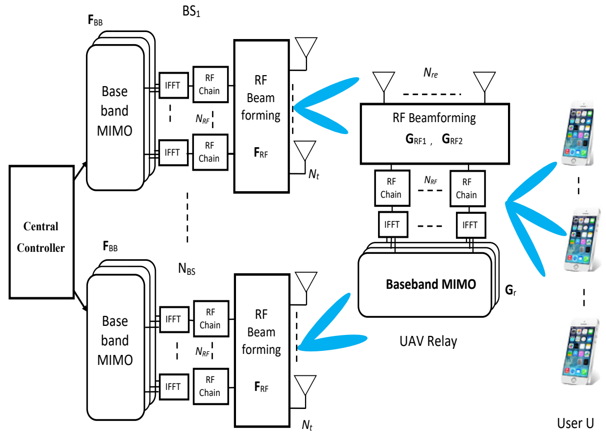


FIGURE 2. UAV relay based-hybrid beamforming architecture.

To deal with the frequency selective fading, the mm-Wave massive MIMO system normally uses orthogonal frequency-division multiplexing (OFDM) scheme. We assume that the number of OFDM sub-carriers is K. It is important to emphasize here that the RF beamforming matrix is the same for all sub-carriers, because the RF beamformer cannot be implemented separately for each sub-carrier [6]. The transmission process from the sources to the destinations takes place during two sequential phases.

During phase-I, each BS node applies a $N_t \times U$ beamforming $\boldsymbol{F}^j$ to transmit a symbol for each user. The transmitted signal from the j^{th} BS using the k^{th} sub-carrier can be expressed as:

$$\boldsymbol{x}^j(k) = \boldsymbol{F}^j(k)\boldsymbol{s}^j(k), \tag{1}$$

where $\boldsymbol{F}^j(k) = \boldsymbol{F}_{\text{RF}}^j\boldsymbol{F}_{\text{BB}}^j(k)$ is the hybrid beamforming matrix for the j^{th} BS, with $\boldsymbol{F}_{\text{RF}}^{(j)} \in \mathbb{C}^{N_t\times N_{\text{RF}}}$ being the analog RF with constant magnitudes while $\boldsymbol{F}_{\text{BB}}^j(k)$=[$\boldsymbol{f}_{\text{BB}}^{(1,j)}(k), ..., \boldsymbol{f}_{\text{BB}}^{(U,j)}(k)] \in \mathbb{C}^{N_{\text{RF}}\times U}$ is the baseband beamforming matrix, and $\boldsymbol{s}^j(k) = [s^{(1,j)}(k), ..., s^{(U,j)}(k)]^T$ represents the transmitted symbols from the j^{th} BS node, such that E[$\boldsymbol{s}^j(k)(\boldsymbol{s}^j(k))^H$]=I$_U$. The received signal at the UAV relay in the k^{th} sub-carrier could then be represented as:

$$\boldsymbol{y}(k) = \sum_{j=1}^{N_{\text{BS}}} \boldsymbol{H}_1^j(k) \sum_{i=1}^{U} \boldsymbol{F}_{\text{RF}}^j\boldsymbol{f}_{\text{BB}}^{(i,j)}(k)\text{s}^{(i,j)}(k) + \boldsymbol{w}(k), \tag{2}$$

where $\text{s}^{(i,j)}$ is the transmit symbol which BS j intends to transmit to user i, $\boldsymbol{H}_1^j(k) \in \mathbb{C}^{N_{re}\times N_t}$ is the frequency domain channel matrix between the j^{th} BS and the UAV relay, and $\boldsymbol{w}(k)$ is the additive noise vector at the UAV relay with $(0, \sigma_r^2)$ elements.

In phase-II, the transmitted signal from the BSs travels through the $U \times N_{\text{re}}$ analog receive matrix $\boldsymbol{G}_{\text{RF2}}$ at the relay, then is amplified by the $N_{\text{RF}}\times U$ baseband matrix $\boldsymbol{G}_{\text{r}}(k)$, and is subsequently forwarded to all users through the $N_{\text{re}} \times N_{\text{RF}}$ analog transmit matrix $\boldsymbol{G}_{\text{RF1}}$. The received signal at the i^{th} user can be modeled as:

$$\text{Y}_i(k) = \boldsymbol{H}_{2,i}^H(k)\sum_{j=1}^{N_{\text{BS}}} \boldsymbol{G}(k)\boldsymbol{H}_1^j(k)\boldsymbol{F}_{\text{RF}}^j\boldsymbol{f}_{\text{BB}}^{(i,j)}(k)\text{s}^{(i,j)}(k) +$$
$$\sum_{i'\neq i}^{U}\sum_{j=1}^{N_{\text{BS}}} \boldsymbol{H}_{2,i}^H(k)\boldsymbol{G}(k)\boldsymbol{H}_1^j(k)\boldsymbol{F}_{\text{RF}}^j\boldsymbol{f}_{\text{BB}}^{(i',j)}(k)\text{s}^{(i',j)}(k) + \text{W}_i(k),$$

where $\sum_{j=1}^{N_{\text{BS}}} \boldsymbol{G}(k)\boldsymbol{H}_1^j(k)\boldsymbol{F}_{\text{RF}}^j\boldsymbol{f}_{\text{BB}}^{(i,j)}(k)\text{s}^{(i,j)}(k)$ is the superposition of desired signals that user i receives from the BSs, $\boldsymbol{H}_{2,i}(k)$ is the frequency domain channel between the UAV relay and the i^{th} user, $\boldsymbol{G}(k)$=$\boldsymbol{G}_{\text{RF1}}\boldsymbol{G}_{\text{r}}(k)\boldsymbol{G}_{\text{RF2}}$ represents the overall relay processing matrix, and $\text{W}_i(k)$=$\boldsymbol{H}_{2,i}^H(k)\boldsymbol{G}(k)\boldsymbol{w}(k)$ encompasses the equivalent noise vector. For the UAV relay-assisted mm-Wave communications involved herein, both channels $\boldsymbol{H}_1^j$ and $\boldsymbol{H}_{2,i}$ are the Fourier transforms of temporal channels, which are represented using a 3D geometric model.

B. THE CHANNEL MODEL

In the considered scenario, we assume that the BSs and the ground users are distributed randomly using stochastic geometry approach and following a $Matern$ type-I hard-core process over the same geographical area, with an intensity of λ_s per m^2, and a minimum separation of $d_{\text{BS}}^{\text{min}}$ and d_U^{min} from the neighbours, respectively [58]. Without loss of generality, we define the 3D coordinates vectors of the UAV relay by (x_u,y_u,h_u). Equivalently, we refer by (x_j,y_j,z_j) to the 3D position of the j^{th} BS, and with (x_i, y_i) to the 2D location of the i^{th} user. Herein, we describe the UAV relay-assisted mm-Wave communications channel model between the j^{th} BS node and the UAV relay. This model assumes that there are multiple paths between the BSs nodes and the UAV relay node, and each of these paths have different angles of departure (AoDs) and angles of arrival (AoAs). In frequency domain, the channel $\boldsymbol{H}_1^j$ can be expressed as:

$$\boldsymbol{H}_1^j(k) = \sum_{t=0}^{N-1}\sum_{l=1}^{L} \frac{\alpha_l^j}{[D^j]^\nu} e^{(-j2\pi f_d T_s \cos\varphi_l^j + \gamma_l^j)} \boldsymbol{a}_t^j(\phi_l^{j,t}, \theta_l^{j,t})$$
$$\boldsymbol{a}_r(\phi_l^r, \theta_l^r) e^{-j\frac{2\pi kt}{K}}, \qquad k = 1, ..., K \tag{3}$$

where α_l^j is the small-scale fading coefficient associated with the l^{th} propagation path of the j^{th} BS, D^j is the distance between the j^{th} BS and the UAV relay, L is the number of multi-paths, ν is the path-loss exponent, f_d is the maximum Doppler frequency, T_s is the system sampling period, φ_l^j is the angle between the transmitted signal and the motion direction of the UAV relay, and γ_l^j refers to the initial phase. Moreover, $\phi_l^{j,t}$, $\theta_l^{j,t}$, ϕ_l^r, θ_l^r represent the azimuth AoD, the elevation AoD, the azimut AoA, and the elevation AoA of the j^{th} BS and the UAV relay, respectively.

The vectors $\boldsymbol{a}_t^j \in \mathbb{C}^{N_t \times 1}$ and $\boldsymbol{a}_r \in \mathbb{C}^{N_{re} \times 1}$ are the array response vectors at the j^{th} BS source and the receiving UAV relay respectively. For a uniform square planar array (USPA) with $\sqrt{N_x} \times \sqrt{N_x}(x \in \text{BSs or relay})$ antenna elements, the reponse vector can be defined as:

$$\boldsymbol{a}_x^j = [1, ..., e^{j\frac{2\pi\delta_j}{\lambda_c}(p-1)\sin(\theta_l^{j,x})\sin(\phi_l^{j,x})+q\cos(\phi_l^{j,x})}]^T, \quad (4)$$

where x may be either t or r indicating the transmit or the receive sides, d represents the antenna elements spacing, λ_c is the carrier wavelength, and $0 \leq p, q \leq \sqrt{N_x}$ are the antenna indices in the 2D plane where $\sqrt{N_x}$ is the number of antennas. According to basic geometry, we obtain the distance between the UAV relay and the j^{th} BS as:

$$D^j = \sqrt{(x_j - x_u)^2 + (y_j - y_u)^2 + (z_j - h_u)^2}, \quad (5)$$

The corresponding angles pertaining to the LOS path in (4) are retrieved as:

$$\varphi_0^j = \arccos\sqrt{\frac{(x_j - x_u)^2 + (z_j - h_u)^2}{D^j}}, \quad (6)$$

and

$$\theta_0^j = \arcsin\sqrt{(y_j - y_u)^2}/D^j, \quad (7)$$

$$\phi_0^j = \arccos(\frac{h_u}{D^j}), \quad (8)$$

The channel from the UAV relay to the i^{th} user can also be generated in a similar way. According to the system model introduced in (3), the signal to interference-and-noise ratio (SINR) of user i is evaluated as follows:

$$\text{SINR}_i = \frac{\left|\sum_{j=1}^{N_{\text{BS}}} \boldsymbol{H}_{2,i}^H(k)\boldsymbol{G}(k)\boldsymbol{H}_1^j(k)\boldsymbol{F}_{\text{RF}}^j\boldsymbol{f}_{\text{BB}}^{(i,j)}(k)\right|^2}{\sum_{i' \neq i}^{U}\left|\boldsymbol{Is}\right|^2 + \sigma_i^2(k)}, \quad (9)$$

where we define $\left|\sum_{j=1}^{N_{\text{BS}}} \boldsymbol{H}_{2,i}^H(k)\boldsymbol{G}(k)\boldsymbol{H}_1^j(k)\boldsymbol{F}_{\text{RF}}^j\boldsymbol{f}_{\text{BB}}^{(i,j)}(k)\right|^2$ as the summation of desired signal powers sent to user i via the UAV relay, $\sigma_i^2(k)$ is the noise power at the i^{th} user, and $\boldsymbol{Is}$=$\sum_{j=1}^{N_{\text{BS}}} \boldsymbol{H}_{2,i}^H(k)\boldsymbol{G}(k)\boldsymbol{H}_1^j(k)\boldsymbol{F}_{\text{RF}}^j\boldsymbol{f}_{\text{BB}}^{(i',j)}(k)$ denotes the total interference to user i from all BSs via UAV relay. In the considred system model, the hybrid beamforming will be designed at each BS to cancel out the multi-user interference. Let SINR_{ij} be the SINR of the i^{th} user, when potentially associated with BS j. Its formulation can be written as:

$$\text{SINR}_{ij} = \frac{\left|\boldsymbol{H}_{2,i}^H(k)\boldsymbol{G}(k)\boldsymbol{H}_1^j(k)\boldsymbol{F}_{\text{RF}}^j\boldsymbol{f}_{\text{BB}}^{(i,j)}(k)\right|^2}{\sum_{i' \neq i}^{U}\left|\boldsymbol{Iu}\right|^2 + \sigma_i^2(k)} \quad (10)$$

where $\sum_{i' \neq i}^{U} \boldsymbol{Iu}$=$\sum_{i' \neq i}^{U} \boldsymbol{H}_{2,i}^H(k)\boldsymbol{G}(k)\boldsymbol{H}_1^j(k)\boldsymbol{F}_{\text{RF}}^j\boldsymbol{f}_{\text{BB}}^{(i',j)}(k)$ denotes the inter-user interference component. According to (10), the achievable rate of user i receiving from BS j via a channel with a bandwidth b_{ij} is given as:

$$R_{ij} = b_{ij}[\log_2(1 + \text{SINR}_{ij})], \quad (11)$$

Let introduce $a_{ij} \in \{0, 1\}$ as the entries of association matrix $\boldsymbol{A}$, which is equal to 1 when the association between BS j and user i is active and 0 otherwise, $\forall i \in U, \forall j \in N_{\text{BS}}$. Based on this, the total data rate of all users in the mm-Wave network can be expressed as follows:

$$r = \sum_{i=1}^{\text{U}}\sum_{j=1}^{N_{\text{BS}}} a_{ij}R_{ij} \quad (12)$$

The major goal of this work is to maximize the sum-data rate of the overall network by controlling the user association and different communication constraints.

III. MULTI-USER HYBRID BEAMFORMING DESIGN

For the considered UAV relay-assisted multi-user mm-Wave massive MIMO system, it is costly to connect each antenna to a separate RF chain, more particularly at a relay level. This is mainly due to the limited power, low profile and intended cost of the UAV relay. Thus, hybrid beamforming scheme is suitable for the UAV-enabled mm-Wave network since it allows to meet the power consumption and hardware complexity requirements [16]. Throughout this section, a multi-user hybrid beamforming algorithm is designed to suppress the interference of the users at the destination. The main idea of the hybrid beamforming algorithm is to divide the calculation of the beamformers into two phases. In the first phase, we aim to design the analog RF beamforming and combining matrices $\boldsymbol{F}_{\text{RF}}^j$, $\boldsymbol{G}_{\text{RF2}}$, and $\boldsymbol{G}_{\text{RF1}}$ in order to maximize the desired signal power and the digital beamforming $\boldsymbol{G}_{\text{BB}}(k)$ to manage the interference between BSs, while in the second phase, the digital beamforming of the UAV relay $\boldsymbol{G}_r(k)$ is designed to manage the resulting multi-user interference.

- During phase I, each BS and the UAV relay find the analog beamforming and combining vectors $\boldsymbol{g}_{\text{m}}^\star$ and $(\boldsymbol{f}_{\text{m}}^j)^\star$ that solve the following optimization problem:

$$\left\{\boldsymbol{g}_{\text{m}}^\star, (\boldsymbol{f}_{\text{m}}^j)^\star\right\} = \underset{\boldsymbol{g}_{\text{m}} \in \boldsymbol{S}_{r-rel}, \boldsymbol{f}_{\text{m}}^j \in \boldsymbol{S}_t^j}{\arg\max} \left\|\boldsymbol{g}_{\text{m}}^H \boldsymbol{H}_1^j(k)\boldsymbol{f}_{\text{m}}^j\right\|, \text{m} = 1, ..., N_{\text{RF}}, \quad (13)$$

where $\boldsymbol{g}_{\text{m}}$ and $\boldsymbol{f}_{\text{m}}^j$ denote the m^{th} row of $\boldsymbol{S}_{r-rel}$ and the m^{th} column of $\boldsymbol{S}_t^j$, respectively. Here $\boldsymbol{S}_{r-rel} \in \mathbb{C}^{N_{\text{RF}} \times N_{re}}$ and $\boldsymbol{S}_t^j \in \mathbb{C}^{N_t \times N_{\text{RF}}}$ are the sets of all N_{RF} array response vectors with the highest power (LoS path), which can be expressed as:

$$\begin{cases} \boldsymbol{S}_{r-rel} = [\boldsymbol{a}_r^1(\phi_0^r, \theta_0^r), ..., \boldsymbol{a}_r^{N_{\text{RF}}}(\phi_0^r, \theta_0^r)]^T, \\ \boldsymbol{S}_t^j = [\boldsymbol{a}_t^{j,1}(\phi_0^{j,t}, \theta_0^{j,t}), ..., \boldsymbol{a}_t^{j,N_{\text{RF}}}(\phi_0^{j,t}, \theta_0^{j,t})], \end{cases} \quad (14)$$

We can then assign $\boldsymbol{g}_{\text{m}}^\star$ and $(\boldsymbol{f}_{\text{m}}^j)^\star$ to the analog matrices as:

$$\begin{cases} \boldsymbol{G}_{\text{RF2}}(m, :) = \boldsymbol{g}_{\text{m}}^\star, & \text{m} = 1, ..., N_{\text{RF}} \\ (\boldsymbol{F}_{\text{RF}}^j)(:, m) = (\boldsymbol{f}_{\text{m}}^j)^\star, & \text{m} = 1, ..., N_{\text{RF}} \end{cases} \quad (15)$$

Algorithm 1 Hybrid beamforming relaying design

Inputs: $\boldsymbol{S}_{t-rel}$, $\boldsymbol{S}_{r-rel}$, $\boldsymbol{S}_t^j$

Phase 1

The j^{th} BS and the UAV relay select $\boldsymbol{g}_{\mathrm{m}}^{\star}$ and $(\boldsymbol{f}_{\mathrm{m}}^{j})^{\star}$ that solve:

$$\left\{\boldsymbol{g}_{\mathrm{m}}^{\star}, (\boldsymbol{f}_{\mathrm{m}}^{j})^{\star}\right\} = \underset{\boldsymbol{g}_{\mathrm{m}} \in \boldsymbol{S}_{r-rel}, \boldsymbol{f}_{\mathrm{m}}^{j} \in \boldsymbol{S}_t^j}{\arg\max} \left\|\boldsymbol{g}_{\mathrm{m}}^{H} \boldsymbol{H}_1^j(k) \boldsymbol{f}_{\mathrm{m}}^{j}\right\|,$$

$\mathrm{m} = 1, ..., N_{\mathrm{RF}}$,

BS sets $\boldsymbol{F}_{\mathrm{RF}}^{j} = [(\boldsymbol{f}_1^j)^{\star}, (\boldsymbol{f}_m^j 2)^{\star}, ..., (\boldsymbol{f}_{N_{\mathrm{RF}}}^{j})^{\star}]$,

UAV relay sets $\boldsymbol{G}_{\mathrm{RF2}} = [(\boldsymbol{g}_1)^{\star}, (\boldsymbol{g}_2)^{\star}, ..., (\boldsymbol{g}_{N_{\mathrm{RF}}})^{\star}]$,

The UAV relay feeds $\boldsymbol{H}_e^j(k) = \boldsymbol{G}_{\mathrm{RF2}} \boldsymbol{H}_1^j(k) \boldsymbol{F}_{\mathrm{RF}}^{j}$ back to each BS node

The j^{th} BS designs $\boldsymbol{F}_{\mathrm{BB}}^{j}(k) = \boldsymbol{H}_e^j(k)^H (\boldsymbol{H}_e^j(k) \boldsymbol{H}_e^j(k)^H)^{-1}$ and normalizes $\boldsymbol{F}_{\mathrm{BB}}^{j}(k) = \frac{\boldsymbol{F}_{\mathrm{BB}}^{j}(k)}{\|\boldsymbol{F}_{\mathrm{RF}}^{j} \boldsymbol{F}_{\mathrm{BB}}^{j}(k)\|_F}$

Phase 2

For each user, the UAV relay select $\boldsymbol{g}_{\mathrm{t}}^{\star}$ that solve:

$$\boldsymbol{g}_{\mathrm{t}}^{\star} = \underset{\boldsymbol{g}_{\mathrm{t}} \in \boldsymbol{S}_{t-rel}}{\arg\max} \left\|\boldsymbol{H}_{2,i}(k) \boldsymbol{g}_{\mathrm{t}}\right\|, \quad \mathrm{t} = 1, ..., U,$$

UAV relay sets $\boldsymbol{G}_{\mathrm{RF1}} = [(\boldsymbol{g}_1)^{\star}, (\boldsymbol{g}_2)^{\star}, ..., (\boldsymbol{g}_{\mathrm{U}})^{\star}]$,

For each user i, the user feeds $\boldsymbol{H}_{ef}(k) = \boldsymbol{H}_{2,i}(k) \boldsymbol{G}_{\mathrm{RF1}}$ back to the UAV relay

The relay designs $\boldsymbol{G}_r(k) = \boldsymbol{H}_{ef}(k)^H (\boldsymbol{H}_{ef}(k) \boldsymbol{H}_{ef}(k)^H)^{-1}$, finally normalizes $\boldsymbol{G}_r(k) = \frac{\boldsymbol{G}_r(k)}{\|\boldsymbol{G}_{\mathrm{RF1}} \boldsymbol{G}_r(k)\|_F}$

The effective channel can be utilized to mitigate the interference among BS, and is defined as:

$$\boldsymbol{H}_e^j(k) = \boldsymbol{G}_{\mathrm{RF2}} \boldsymbol{H}_1^j(k) \boldsymbol{F}_{\mathrm{RF}}^{j} \tag{16}$$

Then, the zero-forcing (ZF) digital beamforming is computed based on the effective channel $\boldsymbol{H}_e^j(k)$, which has a form of:

$$\boldsymbol{F}_{\mathrm{BB}}^{j}(k) = \boldsymbol{H}_e^j(k)^H (\boldsymbol{H}_e^j(k) \boldsymbol{H}_e^j(k)^H)^{-1} \tag{17}$$

• In phase II, we design the RF beamforming $\boldsymbol{G}_{\mathrm{RF1}}$ to maximize the desired signal power for user i, while neglecting the other users' interference, the problem can be expressed as:

$$\boldsymbol{g}_{\mathrm{t}}^{\star} = \underset{\boldsymbol{g}_{\mathrm{t}} \in \boldsymbol{S}_{t-rel}}{\arg\max} \left\|\boldsymbol{H}_{2,i}(k) \boldsymbol{g}_{\mathrm{t}}\right\|, \quad \mathrm{t} = 1, ..., U \tag{18}$$

where $\boldsymbol{g}_{\mathrm{t}}$ is the t^{th} column of $\boldsymbol{S}_{t-rel}$, which is also selected from the set of all array response vectors of the U users as:

$$\boldsymbol{S}_{t-rel} = [\boldsymbol{a}_t^1(\phi_0^t, \theta_0^t), ..., \boldsymbol{a}_t^U(\phi_0^t, \theta_0^t)] \tag{19}$$

Subsequently, the analog beamforming matrix $\boldsymbol{G}_{\mathrm{RF1}}$ can be expressed as:

$$\boldsymbol{G}_{\mathrm{RF1}}(:, t) = \boldsymbol{g}_{\mathrm{t}}^{\star}, \qquad \mathrm{t} = 1, ..., U \tag{20}$$

The effective channel of the i^{th} user is then given as:

$$\boldsymbol{H}_{ef}(k) = \boldsymbol{H}_{2,i}(k) \boldsymbol{G}_{\mathrm{RF1}} \tag{21}$$

Finally, we utilize the ZF digital beamforming, $\boldsymbol{G}_{\mathrm{r}}$, to suppress the inter-user interference, which can be expressed as:

$$\boldsymbol{G}_{\mathrm{r}}(k) = \boldsymbol{H}_{ef}(k)^H (\boldsymbol{H}_{ef}(k) \boldsymbol{H}_{ef}(k)^H)^{-1} \tag{22}$$

Then, we normalize the digital beamforming to guarantee transmit power constraints. It is worth mentioning that in the case of full digital beamforming design, the $\boldsymbol{F}_{\mathrm{BB}}^{j}(k)$ and $\boldsymbol{G}_{\mathrm{r}}(k)$ are calculated directly from the propagation channels $\boldsymbol{H}_1^j(k)$ and $\boldsymbol{H}_{2,i}^H(k)$, respectively. The multi-user hybrid beamforming relaying design for the considered system is summarized in **Algorithm 1**.

IV. PROBLEM FORMULATION

In the considered UAV relay assisted mm-Wave massive MIMO architecture, the 3D location of the UAV relay is fixed and both the users and BSs are randomly distributed in the same area following $Matern$ type-I hard-core process [58]. Our objective is to find the best association of the users to the BSs in order to maximize the sum rate of the entire network. Clearly, the optimization problem (26) is a Binary Integer Linear Program (BILP) that is NP-hard. To tackle this difficulty, a greedy solution based iterative method is designed for solving the user-BS association problem, including a number of factors such as, maximum bandwidth B_j of each BS, number of links N_l that every BS can support, minimum SINR, maximum transmit power, and data rate limit constraints. It is worth mentioning that, to deliver a promised QoS to the users, while consuming as little power as possible, the beamforming constraint is included in the optimization problem. Here, it is considered that the UAV relay position remains unchanged (or that the UAV speed is sufficiently low) during a certain time interval in order to serve the ground users. Nevertheless, power-limited constraint, which affects the flight time can be taken into account for futur studies, and there are some related works can be found in [59], [60]. Throughout this paper, we assume that problem (26) is always feasible when the QoS requirement of each user will be satisfied if $a_{ij} = 1$. To simplify the hybrid beamforming design-based UAV relay and user association process in practical systems, we assume that each user can only be associated with only one BS at a time [51]. Before modeling the association problem, let us introduce the following communication constraints:

- User scheduling constraint: each user can only associate with one BS at a time. Thus, we have:

$$\sum_{j=1}^{N_{\mathrm{BS}}} a_{ij} \leq 1, i \in U \tag{23}$$

- Power constraint: we assume that there exists a maximum transmit power for each BS j, which is given by:

$$\sum_{i=1}^{U} \|\boldsymbol{F}^j(k)\|_2^2 \leq P_j, \qquad \forall j, \tag{24}$$

This constraint is satisfied for every BS, where P_j is the maximum transmit power on the j^{th} BS.

- QoS constraint for users:

$$\text{SINR}_{ij} a_{ij} \geq \text{SINR}_{\text{min}}, \qquad \forall i, j, \tag{25}$$

where SINR_{min} denotes the minimum received SINR of the system, which can play an important role in the distribution of bandwidth, and it is assumed to be given. Aiming at maximizing the total sum data rate, the user association problem can be formulated as:

$$\max_{\{a_{ij}\}\in\{0,1\}} \quad \sum_{i=1}^{U}\sum_{j=1}^{N_{\text{BS}}} R_{ij}.a_{ij} \tag{26a}$$

Subject to

$$\sum_{i=1}^{\text{U}} a_{ij}.b_{ij} \leq B_j, \qquad \forall j, \tag{26b}$$

$$\text{SINR}_{ij}.a_{ij} \geq \text{SINR}_{\text{min}}, \qquad \forall i, j, \tag{26c}$$

$$\sum_{i=1}^{U} \|\boldsymbol{F}^j(k)\|_2^2 \leq P_j, \forall j \tag{26d}$$

$$\| \|\boldsymbol{G}_{\text{r}}(k)\|_2^2 \|_0 \leq a_{ij}.U, \tag{26e}$$

$$\sum_{i=1}^{\text{U}} a_{ij} \leq N_l, \qquad \forall j, \tag{26f}$$

$$\sum_{j=1}^{N_{\text{BS}}} a_{ij} \leq 1, \qquad \forall i, \tag{26g}$$

$$\sum_{i=1}^{U}\sum_{j=1}^{N_{\text{BS}}} R_{ij} a_{ij} \leq R, \tag{26h}$$

The function in (26a) represents the total achieved sum-rate from the overall network, with the objective of maximizing the user-BS association and their data rate. Note that constraint (26b) limits the bandwidth resource of each BS, constraint (26c) satisfies a minimum SINR requirement between each BS-user pair, and (26d) shows the power constraint of each BS. Moreover, the constraint (26e) represents the power amplifier at the UAV relay to several users in the system. In such constraint, setting the power allocated, $\|\boldsymbol{G}_{\text{r}}(k)\|_2^2$, to the non associated users (if a_{ij} = 0) equal to zero means that the other BSs $j' \neq j$ are not equipped with UAV relay. However, if there is an association between the BS j and the user i then power amplifier of UAV relay supports U users. We make use of (26e) to enforce the impact of the association variable on the beamforming-based UAV relay. Constraint (26f) assures that each BS can serve at most N_l users, and constraint (26g) restricts each user to be

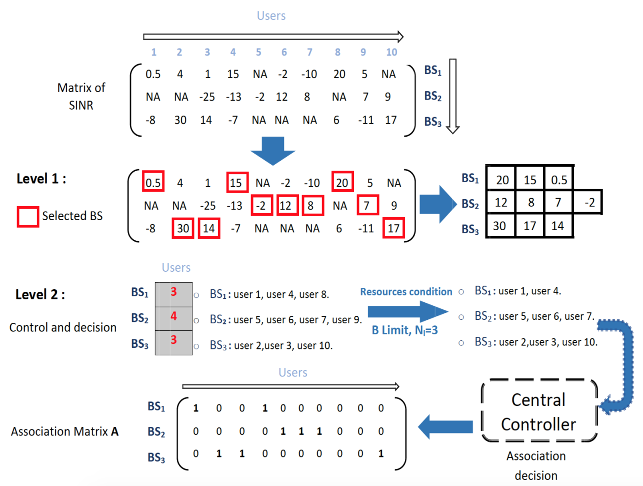


FIGURE 3. An example of our proposed association scheme in the case with 3 BSs and 10 users, NA not available links, $N_l = 3$.

associated with one particular BS. Additionally, constraint (26h) ensures that the sum of the data rate provided to the associated users is limited by the maximum data rate of the entire network, thereby including the total communication traffic from the users or the BSs. To solve the problem in (26), an efficient two-level association approach is summarized in **Algorithm 2**. This algorithm is based on the maximum SINR criterion for the user associated with each BS, which is designed among two network nodes including users and BSs, communicating through one UAV relay link. In the first-level, the user selects the LOS BS which provides the highest SINR without taking into consideration the interference factor due the multi-user hybrid beamforming scheme, and at the second-level, each BS controls their users with an admission control based on the spectrum resource conditions. Finally an association decision is computed at a central controller which is connected to all BSs using wireless links. An example of our association solution scheme is illustrated in Fig. 3.

- **First-level: users selection procedure:** this level is performed for each user individually, in which the users select the corresponding BSs one-to-one. During this level, the BSs send a broadcast initialization signal using hybrid beamforming, along with the information regarding the transmit power of the BSs satisfying constraint (26d), and following the "max SINR" rule, the i^{th} user pre-selects the LOS BS which provides the highest SINR by calculating the SINR with all available BSs according to Eq. (10) (e.g. user 1 with BS1 in the example in Fig. 3). Next, a user verifies the constraint (26c) by comparing their SINR with the minimum SINR. Based on the obtained temporal association, we define the set of vectors as:

$$\boldsymbol{\mathcal{V}} = [\mathcal{V}_1, ..., \mathcal{V}_j, ..., \mathcal{V}_{N_{\text{BS}}}], \tag{27}$$

where $\boldsymbol{\mathcal{V}}$ denotes the set of all possible users-BSs assignments, whereas each vector $\mathcal{V}_j$ from $\boldsymbol{\mathcal{V}}$ represents

Algorithm 2 Two-level association algorithm

Inputs: N_{BS}, U, b_{ij} , R_{ij} , B, N_l, SINR_{ij}, R, P_j, SINR_{min}
Output: Association matrix $\boldsymbol{A}$.
Initialization : $A = \emptyset$;
First-level: Selection process
for i from 1 to U, **do**
  idx = argmax$\{\text{SINR}_{ij}\}$;
  validates if it satisfies the constraint (26c);
  $\boldsymbol{\mathcal{V}}_{\text{idx}} = \boldsymbol{\mathcal{V}}_{\text{idx}} \bigcup i$; indices of $\boldsymbol{\mathcal{V}}_{\text{idx}}$ sorted in decreasing order.
end for
Second-level: Control condition
for $j = 1 : \text{N}_{\text{BS}}$ **do**
  Initialize counters: C_{N_l}= 0, C_B = 0
  while $C_{N_l} < N_l \wedge C_B <$ B **do**
    Find min. b_{ij} with max. R_{ij},
    if $C_B + b_{ij} \leq$ B **then**
      update $a_{ij} = 1$, C_{N_l}=$C_{N_l}-1$ and $C_B = C_B + b_{ij}$
    end if
  end while
end for
Decision process
Initialize: T_a as total sum-rate of associated users;
while $T_a < R$ limit **do**
  Select users with max data rate,
  Associates the request BS-user pair as $a_{ij} = 1$
  Update total data rate $T_a = T_a + R_{ij}$
end while

a list of the users associated with only one BS; thus, satisfying constraint (26g). The list of users is created by adding the i^{th} user to the vector $\mathcal{V}_j$ corresponding to the serving BS j. Then, we generate indices for every vector from $\boldsymbol{\mathcal{V}}$ and arrange them in a descending order according to their corresponding SINR value (i.e., the user with the highest SINR is selected first as shown in the example of Fig. 3; $\mathcal{V}_1$ = {user 1, user 4, user 8}). Later on, a user sends the feedback 1 to the selected BS corresponding to the maximum SINR, and null vector to the remaining BSs (which corresponds to non-selected BS). Otherwise, it sends a feedback of 0 to all the BSs by considering constraint (26e). Then, based on the association, we decide which BSs should be turned off, as those BSs do not satisfy the users requirement. It is noted that for our association scenario, the number of RF chains of both BS and UAV relay limit the number of users it can serve in practice.

- **Second-level: control and decision:** based on the users selection procedure, each BS receives a number of association requests from a list of users. However, due to the limited spectrum resources, not all of them can eventually get associated with the BSs, so an admission control is required. To do that, each BS j, on its turn, chooses among the requesting users, the ones with minimum bandwidth b_{ij} that results in maximum sum-rate and rejects the remaining users by modifying their requests to zero, since they do not satisfy the constraint (26c). In this case, each rejected user attempts to connect to his second most preferred BS (based on the ordered set of indices), if no more bandwidth is left on this BS. It is important to note that BS j firstly allocates bandwidth to the user with the highest data rate. Before associating the retained users, the user should connect to the BSs that maintains only N_l links which is included in constraint (26f) then the association matrix $\boldsymbol{A}$ is updated.
  Since the objective function aims at maximizing the sum-rate of the overall mm-Wave network, each BS searches for users with maximum demanded rate and associates its request. This means that the user calculates the resultant data rate with each BS pair, and verifies if the achieved sum-rate is within the rate limit or not (constraint 26h), then the association algorithm completes. Once the association is computed at the centralised controller, BSs then start in the data transmission phase.

V. SIMULATION RESULTS

In this section, simulation results are presented and discussed to demonstrate the effectiveness of the UAV relay-assisted multi-BS massive MIMO multi-user mm-Wave communication system by comparing its performance with the alternative system where there is no UAV relay. The studied scenario consists of three BSs, $U = 28$ users, and one UAV relay working at mm-Wave frequencies with a carrier frequency of 28 GHz. In particular, we consider a 4 $\times$ 4 km^2 area, where both BSs and users are randomly distributed over a square region using $Matern$ type-I hardcore process, with a density of $\lambda_a = 2 \times 10^{-6}$ per m^2, such that the distance between any two BSs and users is at least $d_{\text{BS}}^{\text{min}}$= 300 m and d_{U}^{min}=100 m, respectively. Also, each BS is assumed to hold $N_t = 64$ antennas and 28 RF chains while there is only one RF chain at each user. All BSs are assumed to transmit $N_s = 28$ data streams to the destination via the assistance of the UAV relay, which is equipped with N_{re} = 32 antennas and N_{RF} = 28 RF chains. The height of each BS is set to z_j = 10 m, while that of UAV relay is set to h_{min}=100 m. Additional simulation parameters are listed in Table 1. All results are averaged over N runs of Monte-Carlo simulations and at each run both BSs and users' positions are randomly reset. The achievable sum-rate has been formulated in the case of perfect channel estimation process.

In Fig. 4, we investigate the total achieved sum-rate performance of UAV relay-assisted mm-Wave massive MIMO system when using the analog, the hybrid, and the full digital beamforming structures, along with the impingement of the incorporation of UAV relay on its performance. To confirm the effectiveness of our hybrid beamforming (**Algorithm 1**), the performance of hybrid beamforming proposed in [49] is also portrayed in the simulation. From this figure, it appears clearly that our hybrid beamforming scheme can perform much better than both the analog beamforming and

TABLE 1. SIMULATIONS PARAMETERS

Parameter	Value
Bandwidth	500 MHz
Data rate limit	6 Gbps
Power transmission	20 dBm
N_l	7
z_j	10 m
SINR_{min}	-5 dB
Multi-paths L	2
Sub-carriers K	64
Number of Monte-Carlo simulations N	500

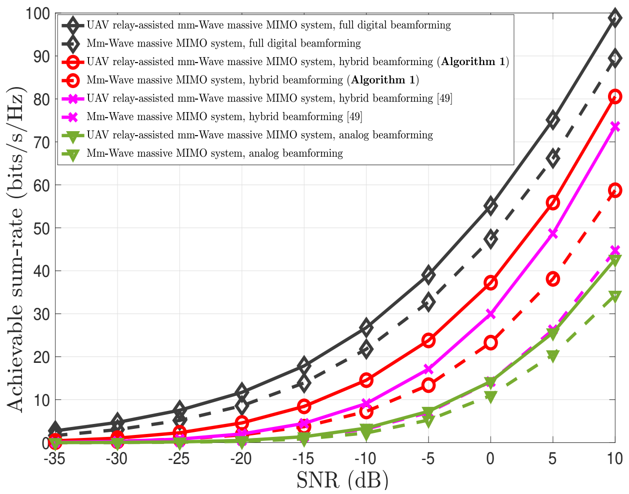


FIGURE 4. Achievable rates performance using the analog beamforming, the hybrid beamforming in [49], the hybrid beamforming (**Algorithm 1**), and the optimal full digital beamforming for the considered UAV relay-assisted mm-Wave massive MIMO and the conventional systems, when the UAV relay altitude is h_u= 100 m.

the existing hybrid beamforming scheme [49] over the whole SNR range in consideration. Besides, the achievable rate of the proposed hybrid beamforming is very close to the fully digital beamforming case. On the other hand, when analog beamforming scheme based system is used, the penalty of the path losses on the considered system is significant such that the cooperative diversity system becomes inferior in performance to the one of the counterpart without a relaying device. At the same time, we observe that the benefit of the relying enriched with the UAV relay based architecture scheme finds its great efficiency at quite reasonable SNR values, since 20 bits/s/Hz performance gain is noted over the alternative system with no relaying, when SNR is 10 dB.

Fig. 5 illustrates the effect of the UAV relay altitude on the achievable sum rates calculated by three different beamforming designs, when SNR =- 5 dB. It can be seen clearly that the achievable sum-rate performance of the different beamforming design schemes increases when the UAV's altitude increases from the ground to 100 m. This might be due to the dual effects of higher LOS probability in the network when the altitude increases and to the efficient beamforming performed between the BSs and the UAV relay to a certain value of the altitude. Beyond those altitudes, the achievable

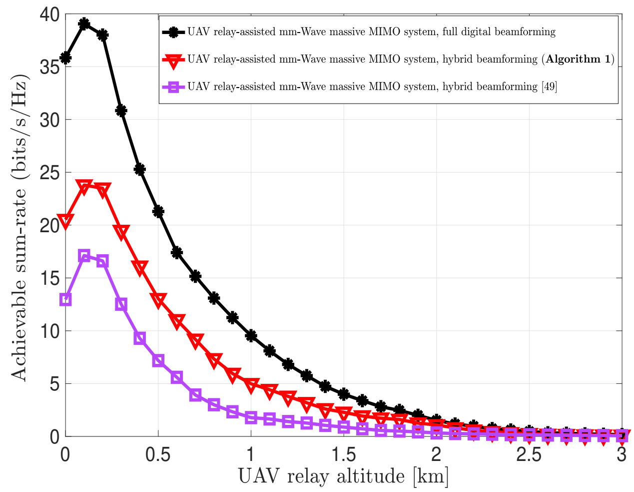
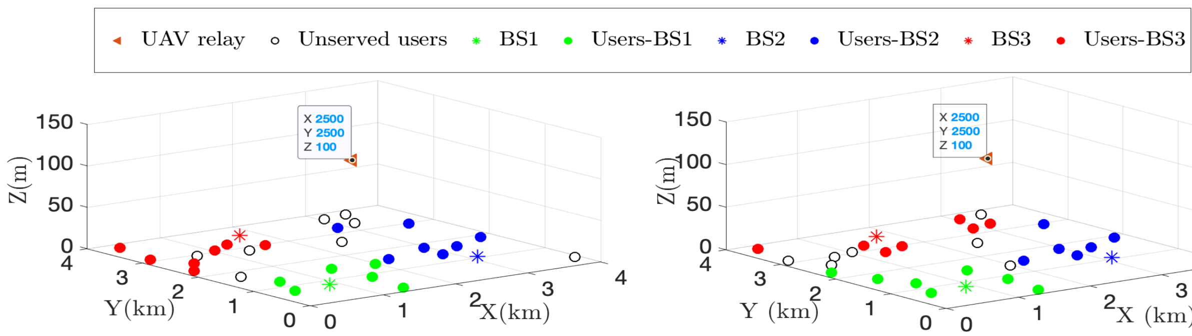


FIGURE 5. Achievable rate performance versus the altitude of the UAV relay in the mm-Wave massive MIMO system under different beamforming structures.

sum-rate starts to decrease, due to the path loss effect related to the increasing distance between the UAV and the BSs. This means that, at a sufficient altitude, beamforming signals are propagated far away from their BSs, thereby causing serious performance losses. The performance of hybrid beamforming in [49] is worse than those of the other two approaches by about 6.67 dB bits/s/Hz compared to the proposed hybrid beamforming scheme. This is because beam gains may not concentrate on user directions of the strongest multipath components. The UAV relay altitude is set as 100 m in the remaining simulations.

Fig. 6 shows the users' association results at a particular iteration, as an example. The relay is assumed to be located at a horizontal position of x_u= y_u = 2.5 km. For comparison, we use Branch and Bound (B&B) method [61], as an optimal benchmark solution as shown in Fig. 6b. Each user is marked with the same color as its associated BS. For the same scenario, it can be observed by comparing Fig. 6a and Fig. 6b that B&B and the proposed solution scheme (**Algorithm 2**) associate 21 and 20 users, respectively. The performance is close but the difference is mainly because of the data rate constraint. In this case, the UAV relay is mainly used to enhance the quality of the direct links between the users and their respective serving BSs.

Fig. 7 presents the impact of the proposed association solution on mm-Wave massive MIMO system without UAV relay, in which the hybrid beamforming is designed between the BSs and multiple user nodes (**Algorithm 1**). We first note that the proposed association solution is unable to associate all users with the their BSs, which is due to the stringent mm-Wave communication constraints. In particular, in the surroundings of BS 3, only 4 users are associated due to its adverse channel conditions (low SINR criteria (constraint (26c)). Also, the unassociated users are not served by other BSs due to bandwidth limitations (constraint (26b)). Further,



(a) Proposed assosication (with UAV relay) (b) B&B association (with UAV relay)

FIGURE 6. Comparison of user association schemes in UAV relay assisted-mm-Wave massive MIMO system.

by comparing Fig. 7 and Fig. 6, it can be concluded that the UAV relay-based architecture allows to serve a higher number of associated users for all BSs. In particular, 20 users are served in the considered scenario with the proposed association solution, whereas only 14 users are connected in the alternative system without relay. Furthermore, it is observed from Fig. 6 that all BSs serve the users that are closest to them. This is because the SINR of each user is mainly determined by its direct links with BSs (i.e., users-BS2 in Fig. 7a). In contrast, thanks to the UAV relay based hybrid beamforming deployment, it is observed that BSs 2 and 3 serve users that obtain better signal quality instead of the nearest users as in Fig. 6(a). In this way, the effective link between BS and users can be stronger than the direct link between them.

With the same distribution and parameters as in the previous simulation, Fig. 8 compares the total sum data rate versus the number of associated users of the proposed association solution with the one achieved by the optimal B&B method, to provide more straightforward results and demonstrate the performance of mm-Wave massive MIMO system with and without UAV relay. It is worth mentioning that due to the UAV relay, the proposed association solution and B&B schemes both achieve a higher communication rate gain, and also provide the same sum data rate and thus have the same performance. In contrast, the total sum rate in the alternative system without UAV relay result in lower rates due to the communication between users and BSs which is greatly affected by obstacles in mm-Wave bands. For instance, our algorithm achieves a sum-rate of 22.8 Mbps for maximum number of sources. Note that the number of connections in each BS also plays an important role in the sum data rate performance.

VI. CONCLUSION

In this paper, we have developed an efficient design of UAV deployment in which UAV operates as a beamforming relay in mm-Wave massive MIMO communication context, thereby mitigating the drawbacks of link blockage encountered in mm-Wave networks. Subsequently, a good link reliability between every BS and multiple ground users is maintained. In particular, by considering the impact of UAV relay based beamforming aproach, an association of users problem is formulated so that the sum-rate of the overall UAV relay-assisted mm-Wave massive MIMO system can be maximized. Furthermore, in order to mitigate the interference impediment and decrease the massive MIMO hardware complexity, hybrid beamforming relay scheme is designed between the multiple BSs, the relay, and the ground users, merging the spatial processing and the amplify-forward operation. Simulation results demonstrated the substantial performance gains achieved by the deployment of UAV relay assisted mm-Wave massive MIMO system with our hybrid beamforming design as compared to the conventional system, and highlight the effect of the UAV altitude on the achievable rates performance. It is also revealed that the user-BS association achieve satisfactory utility performance compared to B&B method in terms of associated users and achieve the same sum-rate performance. More importantly, the performance achieved by this approach is significantly higher with the presence of the UAV relay. In future work, we will investigate possible UAV relaying schemes with the impact of channel estimation, while taking care of the computational complexity issue.

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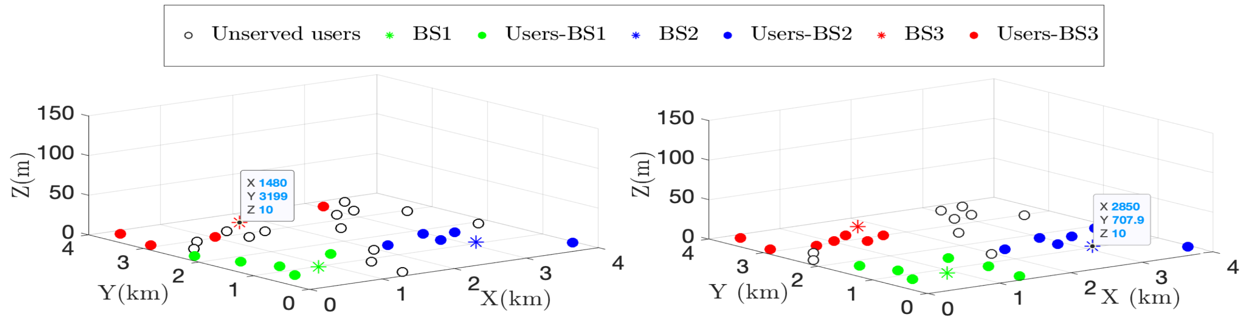

(a) Proposed assosication (without UAV relay)

(b) B&B association (without UAV relay)

FIGURE 7. Comparison of user association schemes in mm-Wave massive MIMO system without UAV relay.

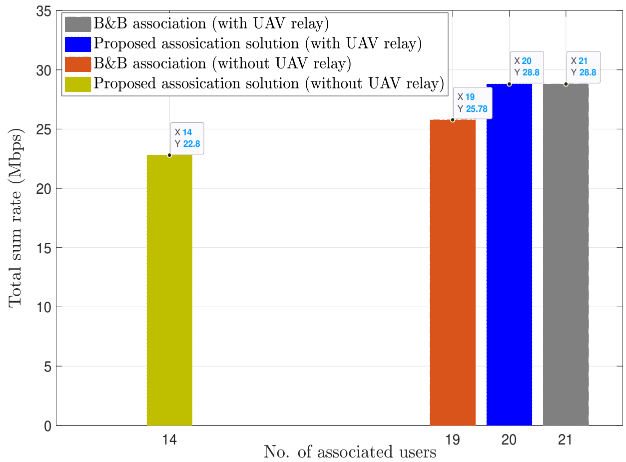

FIGURE 8. Total sum data rate vs. the number of associated users for B&B method and proposed association algorithm.

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