

Energy-saving UAV-Assisted Multiuser Communications with Massive MIMO Hybrid Beamforming

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Abstract—In this paper, we consider the hybrid beamforming for the unmanned aerial vehicle (UAV)-assisted communications with massive multiple-input multiple-output (MIMO). Using a popular beamforming design, we derive an approximate closed-form expression of rate and provide a power allocation design which satisfies the rate requirement of each user under the line-of-sight (LoS) channels. It is discovered that the total transmit power should inversely increase with the number of antennas of UAV. Furthermore, we propose the location design of the UAV. In particular, when the channel pathloss exponent is 2, the optimal location is the weighted average location of all users where the weights are signal to interference plus noise (SINR) requirements of all users. It is shown that the weighted average location could be an approximate method to design the UAV location with little performance gap to the optimal location.

Index Terms—Hybrid beamforming, massive MIMO, unmanned aerial vehicle.

I. INTRODUCTION

In current cellular methods, land base stations with fixed locations are deployed to provide seamless coverage and reliable connections for mobile terminals. Due to blockage and environment, however, the communication quality that the cellular network provides can vary dramatically across different environments. As an emerging complementary to existing land stations, unmanned aerial vehicle (UAV)-assisted wireless communications can provide economical wireless access in areas without satisfactory infrastructure coverage [1], [2]. The mobility enables UAVs to dynamically serve users over a wide area. Moreover, line-of-sight (LoS) communication links can be established in most scenarios with the aid of UAVs which potentially leads to better communication channels.

Recently, the investigation of UAVs in three-dimensional space attracts increasing attention which could fully exploit the benefits of the UAV mobility. By treating mobile UAVs as flying base stations, existing studies proposed efficient deployments of UAVs for enhancing wireless coverage [3], [4]. Moreover, power allocation is another challenge because

the UAV's size and weight constraints make the on-board energy practically finite. To address this issue, [5] designed trajectory for UAVs to maximize energy efficiency. In [6], the authors considered to maximize the coverage by using the minimal transmit power. Then, the transmit power and trajectory were jointly optimized to maximize the minimum average throughput within a given time length in [7]. For user-UAV association, [8] investigated the problem of sum power minimization. However, all these studies focused on UAVs equipped with a single antenna. For UAVs equipped with multiple antennas, [9] studied the achievable rate of an uplink MIMO cognitive radio system using a UAV relay. In addition, a 3-D elliptic-cylinder UAV channel model was proposed in [10]. It is necessary to study UAVs equipped with multiple-input multiple-output (MIMO) which requires less power than UAVs using single antenna with a given quality-of-service (QoS). However, to the best of our knowledge, few study has studied the problem of power minimization for UAVs equipped with antenna arrays, especially with large-scale antenna arrays.

In this work, we investigate the UAV base station using multiuser massive MIMO hybrid precoding. Under line-of-sight (LoS) channels, we obtain useful observations and insights on the rate and transmit power of each user. To minimize the total transmit power, we propose a power allocation and location design based on the popular hybrid precoding method. It is interesting to see that the optimal location of UAV can be interpreted as a properly weighted location of all users, particularly for the scenario with a typical pathloss exponent of 2. According to numerical results, the proposed power and location design also obtains great performance even if there is estimation error for pathloss exponent.

The rest of this paper is organized as follows. System and channel models are introduced in Section II. We then propose a power allocation and location design for the UAV base station and analyze the performance of the considered system in Section III. Simulation results are presented in Section IV before concluding remarks in Section V.

Notations throughout this paper are as follows. Upper and lower case bold-face letters are matrices and vectors, respectively. Italicized variables are scalars. $\|\cdot\|_F$ and $(\cdot)^H$ represent the Frobenius norm and Hermitian of a matrix, respectively. $|\cdot|$ represents the absolute value of a complex number. $\mathbf{I}$ stands for the identity matrix. $\mathcal{CN}(\mu, \sigma^2)$ stands for the complex Gaussian distribution with mean μ and variance σ^2 . $\text{diag}(a_1, \dots, a_m)$ refers to a diagonal matrix whose diagonals

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are $a_1, \dots, a_m$.

II. SYSTEM MODEL

We consider a downlink massive MIMO UAV-aided wireless communication system with one UAV equipped with M antennas serving K single-antenna ground users. The UAV is deployed as a flying BS located at (x_0, y_0, H) where H is a constant altitude, while the location of user k is denoted by $(x_k, y_k, 0)$. At a proper altitude, we expect that the channels between the UAV and users are dominantly LoS propagation. To fully describe the characteristics of the wireless channel, we write the multiuser MIMO channel as

$$\mathbf{h}_k = \sqrt{M\beta_k}\mathbf{a}(\theta_k) \quad (1)$$

where β_k reflects the large scale shadowing, $\mathbf{a}(\theta_k)$ denotes the fast fading factor vector which models the propagation condition of the channel and θ_k is the azimuth angle of departure (AOD) of user k . Specifically, the large scale shadowing can be expressed as

$$\beta_k = \beta_0 d_k^{-\alpha} \quad (2)$$

where α is the pathloss exponent, β_0 denotes the channel power gain between the UAV and users at the unit distance, and d_k is the distance between the UAV and user k . Taken the common uniform linear array (ULA) for instance, the LoS channel can be represented by

$$\mathbf{a}(\theta_k) = \frac{1}{\sqrt{M}} \left[1, e^{j2\pi\frac{d}{\lambda}\cos\theta_k}, \dots, e^{j2\pi\frac{(M-1)d}{\lambda}\cos\theta_k} \right]^T. \quad (3)$$

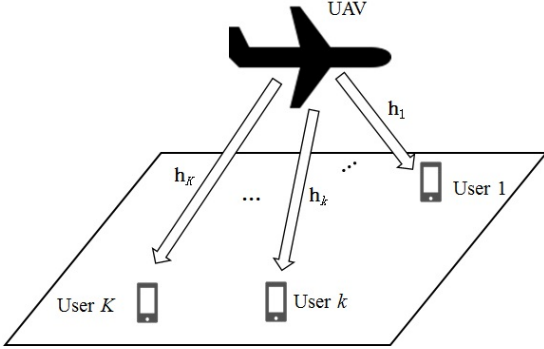


Fig. 1: System model including a UAV and K downlink users.

Due to hardware constraints, the UAV employs hybrid beamforming where the number of RF chains is far less than the number of antennas, i.e., $N_{RF} < M$. To enable multi-stream communications, N_{RF} is assumed to be no smaller than K , i.e., $N_{RF} \geq K$. Since RF chains are responsible for a large amount of power, it is more practical to set $N_{RF} = K$ for the UAV base station which can not afford too much power.

Assuming a block-fading channel model, the received signal at all users is

$$\mathbf{y} = \mathbf{H}^H \mathbf{F} \mathbf{W} \mathbf{P} \mathbf{s} + \mathbf{n} \quad (4)$$

where $\mathbf{P} = \text{diag}[\sqrt{p_1}, \dots, \sqrt{p_K}]$ refers to the power allocation matrix, $\mathbf{F} = [\mathbf{f}_1, \dots, \mathbf{f}_{N_{RF}}] \in \mathbb{C}^{M \times N_{RF}}$ and $\mathbf{W} =$

$[\mathbf{w}_1, \dots, \mathbf{w}_K] \in \mathbb{C}^{N_{RF} \times K}$ are respectively the analog and digital beamforming matrices, $\mathbf{H} = [\mathbf{h}_1, \dots, \mathbf{h}_K] \in \mathbb{C}^{M \times K}$ stands for the channel matrix, $\mathbf{s} = [x_1, \dots, x_K]^T \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ represents the data vector, and $\mathbf{n} = [n_1, \dots, n_K]^T \sim \mathcal{CN}(\mathbf{0}, \sigma_n^2 \mathbf{I})$ is the noise vector. Note that we assume a fully-connected structure where each RF chain is connected to every antenna through a phase shifter. Since the phase shifters can only change the angles of signals, the i -th element of $\mathbf{f}_k$ is normalized as $|f_{ki}| = \frac{1}{\sqrt{M}}$. According to (4), it is not difficult to write the received signal of user k as

$$y_k = \sqrt{p_k} \mathbf{h}_k^H \mathbf{F} \mathbf{w}_k s_k + \sum_{j \neq k} \sqrt{p_j} \mathbf{h}_k^H \mathbf{F} \mathbf{w}_j s_j + n_k \quad (5)$$

where y_k , s_k and n_k respectively denote the k -th element of $\mathbf{y}$, $\mathbf{s}$ and $\mathbf{n}$.

Generally, the hybrid beamforming design is non-trivial due to the constant amplitude constraints of phase shifters. Here, we would like to employ a popular idea to design hybrid beamforming which separates the design into two stages [11]–[14]: (1) The analog beamforming reaps diversity by maximizing the signal power for each user while ignoring the interference among users; (2) The digital beamforming is designed by a linear precoder to manage the resulting multiuser interference. In detail, the UAV first maximizes the signal power by

$$\mathbf{f}_k = \arg\max |\mathbf{h}_k^H \mathbf{f}_k|^2. \quad (6)$$

Then, the digital precoding is designed according to the equivalent channel vector between the UAV and each user which is

$$\mathbf{g} = \mathbf{F}^H \mathbf{h}. \quad (7)$$

With the equivalent channels, we can write the zero-forcing digital precoding as

$$\mathbf{V} = \mathbf{G}(\mathbf{G}^H \mathbf{G})^{-1} \quad (8)$$

where $\mathbf{G} = [\mathbf{g}_1, \dots, \mathbf{g}_K]$. Then, we normalize the digital precoding to guarantee a transmit power constraints. It yields

$$\mathbf{w}_k = \frac{\mathbf{v}_k}{\|\mathbf{F} \mathbf{v}_k\|_F} \quad (9)$$

where $\mathbf{v}_k$ is the k -th column of $\mathbf{V}$.

III. PROBLEM FORMULATION AND SOLUTION

Instead of maximizing the system rate, it might be more practical for the UAV base station to minimize the transmit power under the constraints of rate requirements of users. Note that the location of UAV is related to channels which further has impacts on the rate. Then, the problem is written as

$$\min_{\{p_k\}_{k=1}^K, x_0, y_0} P_{\text{total}} \quad (10)$$

$$\text{s.t.} \quad R_k \geq \tau_k, \forall k \quad (11)$$

$$x_{\min} \leq x_0 \leq x_{\max}, y_{\min} \leq y_0 \leq y_{\max} \quad (12)$$

where $P_{\text{total}} = \sum_{k=1}^K p_k$ refers to the total transmit power, $[x_{\min}, x_{\max}]$ and $[y_{\min}, y_{\max}]$ respectively represents the ranges of x-axis and y-axis of the UAV location, τ_k denotes

the minimal rate requirement of user k and the rate of user k is represented by

$$R_k = B \log_2 \left(\frac{p_k |\mathbf{h}_k^H \mathbf{F} \mathbf{w}_k|^2}{\sum_{j \neq k} p_j |\mathbf{h}_k^H \mathbf{F} \mathbf{w}_j|^2 + \sigma_n^2} \right) \quad (13)$$

where B is the system bandwidth.

To further simplify the problem, we would like to transfer (10) to a problem with fewer optimization variables and constraints. Since the power allocation is only concerned with (11) and the UAV location is related to (11) and ranges of x -axis and y -axis, we first focus on simplifying (10) by deriving a simple expression to characterize the relationship between the rate and $\{p_k\}_{k=1}^K$ in the following proposition.

Proposition 1: For the LoS case in massive MIMO with hybrid beamforming, the rate for user k is approximated by

$$R_k = B \log_2 \left(1 + \frac{M p_k \beta_k}{\sigma_n^2} \right). \quad (14)$$

Proof: See Appendix A.

By substituting (14) into (11), we have the minimum transmit power of user k as:

$$p_k = \frac{(2^{\tau_k} - 1) \sigma_n^2}{M \beta_k} = \frac{(2^{\tau_k} - 1) \sigma_n^2}{M \beta_0} d_k^\alpha. \quad (15)$$

Combining $P_{\text{total}} = \sum_{k=1}^K p_k$ and (15), we have the following observation.

Observation 1: To satisfy the rate requirement of each user, the total transmit power of UAV is concluded as

$$P_{\text{total}} = \frac{\sigma_n^2}{M \beta_0} \sum_{k=1}^K (2^{\tau_k} - 1) d_k^\alpha. \quad (16)$$

Remark 1: From Observation 1, the minimum required total transmit power, i.e., P_{total} , increase linearly at least with $\frac{1}{M}$.

With the beamforming design, we then need to optimize the location of UAV, i.e., (x_0, y_0) . The problem becomes

$$\min_{x_0, y_0} \sum_{k=1}^K \rho_k d_k^\alpha \quad (17)$$

$$\text{s.t. } x_{\min} \leq x_0 \leq x_{\max}, y_{\min} \leq y_0 \leq y_{\max} \quad (18)$$

where $\rho_k \triangleq (2^{\tau_k} - 1)$ is the signal-to-interference-plus-noise ratio (SINR) requirement of user k .

Applying the Karush-Kuhn-Tucker (KKT) conditions, we write the Lagrangian as:

$$L = \sum_{k=1}^K \rho_k d_k^\alpha + \gamma_1 (x_{\min} - x_0) + \gamma_2 (x_0 - x_{\max}) + \gamma_3 (y_{\min} - y_0) + \gamma_4 (y_0 - y_{\max}). \quad (19)$$

Then, the KKT conditions should be

$$\frac{\partial L}{\partial x_0} = 0, \frac{\partial L}{\partial y_0} = 0 \quad (20)$$

$$x_{\min} \leq x_0 \leq x_{\max}, y_{\min} \leq y_0 \leq y_{\max} \quad (21)$$

$$\gamma_i \geq 0 \quad (22)$$

$$\begin{aligned} \gamma_1 (x_{\min} - x_0) &= \gamma_2 (x_0 - x_{\max}) \\ &= \gamma_3 (y_{\min} - y_0) = \gamma_4 (y_0 - y_{\max}) = 0. \end{aligned} \quad (23)$$

Generally, the location of UAV satisfies that $x_{\min} < x_0 < x_{\max}, y_{\min} < y_0 < y_{\max}$ which indicates that $\gamma_i = 0$. Then, we focus on $\frac{\partial L}{\partial x_0}$ which is expressed by

$$\begin{aligned} \frac{\partial L}{\partial x_0} &= \frac{\partial \sum_{k=1}^K \rho_k d_k^\alpha}{\partial x_0} \\ &= \frac{\partial \sum_{k=1}^K \rho_k (d_k^2)^{\frac{\alpha}{2}}}{\partial x_0} \\ &\stackrel{(a)}{=} \alpha \sum_{k=1}^K \rho_k (d_k^2)^{\frac{\alpha}{2}-1} (x_0 - x_k) \end{aligned} \quad (24)$$

where (a) uses $d_k = \sqrt{(x_0 - x_k)^2 + (y_0 - y_k)^2 + H^2}$. Similarly, we can get

$$\frac{\partial L}{\partial y_0} = \alpha \sum_{k=1}^K \rho_k (d_k^2)^{(\frac{\alpha}{2}-1)} (y_0 - y_k). \quad (25)$$

By letting $\frac{\partial L}{\partial x_0} = 0$ and $\frac{\partial L}{\partial y_0} = 0$ and recalling that $\alpha > 0$, we get the necessary conditions:

$$\begin{aligned} \sum_{k=1}^K \rho_k (d_k^2)^{(\frac{\alpha}{2}-1)} (x_0 - x_k) &= 0, \\ \sum_{k=1}^K \rho_k (d_k^2)^{(\frac{\alpha}{2}-1)} (y_0 - y_k) &= 0. \end{aligned} \quad (26)$$

If we define the optimal UAV location as $(x_0^*(\alpha), y_0^*(\alpha))$, it should be the solution of $(x_0^*(\alpha), y_0^*(\alpha))$. It is difficult to obtain a closed-form solution to (26) due to non-integar exponents α . However, (26) can be efficiently solved by existing software tools.

Moreover, we also get a closed-form solution to a special case to (26) in the following observation.

Observation 2: If $\alpha = 2$, the optimal location of the UAV can be represented by

$$x_0^*(2) = \frac{\sum_{k=1}^K \rho_k x_k}{\sum_{k=1}^K \rho_k}, \quad y_0^*(2) = \frac{\sum_{k=1}^K \rho_k y_k}{\sum_{k=1}^K \rho_k} \quad (27)$$

which is the weighted average location of users.

Proof: For $\alpha = 2$, (26) becomes

$$\sum_{k=1}^K \rho_k (x_0 - x_k) = 0, \quad \sum_{k=1}^K \rho_k (y_0 - y_k) = 0 \quad (28)$$

which simply leads to (27). ■

Remark 2: When the pathloss exponent is 2, according to Observation 2, the optimal UAV location could be concluded as the weighted average location of all users where weights are the SINR requirements.

TABLE I: Simulation Parameters

Parameters	Notation	Typical Values
Number of users	K	4
Communication bandwidth	B	1MHz
The noise power density	$\frac{\sigma_n^2}{B}$	-169dBm/Hz
The channel power gain at 1m	β_0	1.42×10^{-4}
The pathloss exponent	α	3.8 (except Fig. 3)
UAV flying height	H	50m
UAV x-axis range	$[x_{\min}, x_{\max}]$	[0,100](m)
UAV y-axis range	$[y_{\min}, y_{\max}]$	[0,100](m)

IV. SIMULATION RESULTS

In this section, we provide some simulation results to verify our derivation results in this paper. We consider UAV base station and several ground users. The location and rate requirement for each user is uniformly random distributed generated. Specifically, the locations of all users are (54.2992, 10.9633), (5.9691, 43.7773), (65.8030, 28.0230), (88.9635, 98.5246) (m,m) and the rate requirements of all users are 8.7875, 1.7832, 4.3063, 5.1230 (Mbits/s). Other simulation parameters are shown in TABLE I.

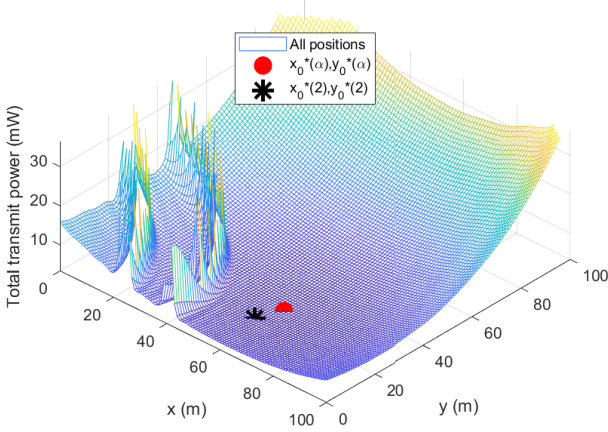


Fig. 2: Power consumption with $M = 64$ at all locations (3.6354 mW at $(x_0^*(\alpha), y_0^*(\alpha)) = (60.0544, 26.4335)$, 3.8428 mW at $(x_0^*(2), y_0^*(2)) = (56.8627, 17.7469)$).

We compare the total transmit power of the UAV base station at all locations in Fig. 2. The minimal power obtained by a exhaustive search (using the step as 1 (m)) is 3.6337 mW. It is discovered from Fig. 1 that the performance of UAV at $(x_0^*(\alpha), y_0^*(\alpha))$ is almost the same with that of optimal location where the difference is $\frac{3.6354 - 3.6337}{3.6337} = 0.0468\%$. Especially, even if α is far larger than 2 ($\alpha = 3.8$), the power cost at $(x_0^*(2), y_0^*(2))$ is also very close to $(x_0^*(\alpha), y_0^*(\alpha))$ with the difference $\frac{3.8428 - 3.6354}{3.6354} = 5.7050\%$. Therefore, it is acceptable to conclude $(x_0^*(\alpha), y_0^*(\alpha))$ as the optimal location of the UAV base station and $(x_0^*(2), y_0^*(2))$ is a good approximate location design with little performance gap to the optimal location.

Fig. 3 demonstrates the total transmit power versus the number of antennas at the UAV. It not only verifies that the

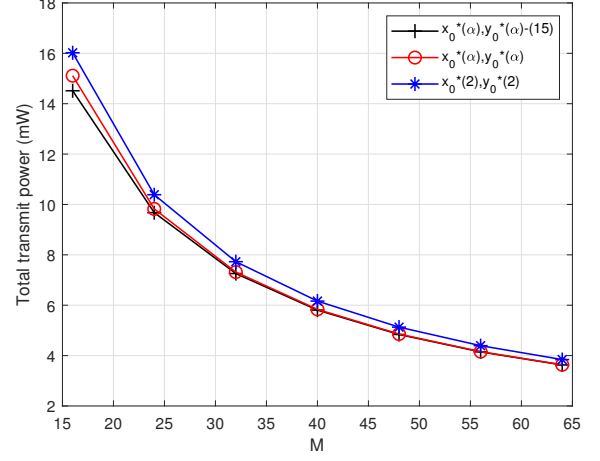


Fig. 3: Power consumption versus M .

performance gap between $(x_0^*(\alpha), y_0^*(\alpha))$ and $(x_0^*(2), y_0^*(2))$ is small, but also shows that the derived (16) is very tight to the exact total power consumption. Note that (16) is still very accurate even if M is not large ($M = 16$). It is due to the fact that the UAV location is chosen to adapt channels. If the UAV location is optimized, the UAV intends to locate at a place with high signal power and small interference where physical channel paths are approximately orthogonal. In this case, it is acceptable and appropriate to assume orthogonal channel paths in (30) even if M is not large.

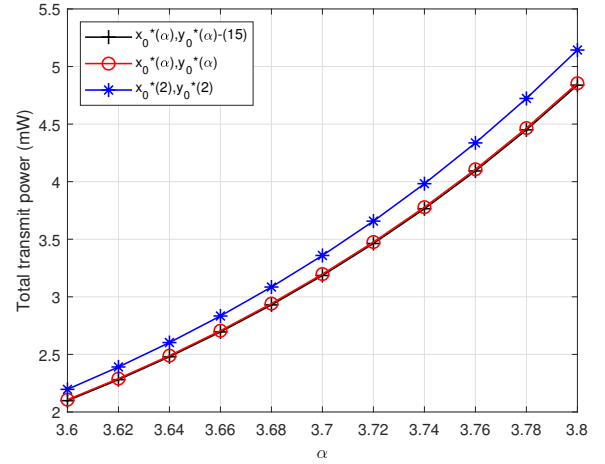


Fig. 4: Power consumption versus α with $M = 48$.

In Fig. 4, we provide the total transmit power of the UAV base station with the varying channel pathloss exponent. It is revealed that the transmit power should increase with α to mitigate the growing signal power loss. Moreover, the performance gap between $(x_0^*(\alpha), y_0^*(\alpha))$ and $(x_0^*(2), y_0^*(2))$ also increases with α . Since $(x_0^*(2), y_0^*(2))$ is optimal when $\alpha = 2$, the performance of $\alpha = 2$ would definitely quite close to $(x_0^*(\alpha), y_0^*(\alpha))$ when α is close to 2. However, when α grows and $\alpha - 2$ becomes larger, the performance gap between $(x_0^*(\alpha), y_0^*(\alpha))$ and $(x_0^*(2), y_0^*(2))$ also becomes larger.

In the derivation part of this paper, we consider LoS channels. However, in a practical system, NLoS (Non-Line-of-Sight) channel paths also exist. In this section, we also provide some simulation results over Rician fading channels where the channel vector between the UAV and user K is expressed as

$$\mathbf{h}_k = \sqrt{\frac{\kappa_k}{1+\kappa_k}} \mathbf{h}_k^{LoS} + \sqrt{\frac{1}{1+\kappa_k}} \mathbf{h}_k^{NLoS} \quad (29)$$

where $\mathbf{h}_k^{LoS}$ is calculated according to (1), $\mathbf{h}_k^{NLoS}$ is randomly distributed as $\mathbf{h}_k^{NLoS} \sim \mathcal{CN}(\mathbf{0}, \frac{\|\mathbf{h}_k^{LoS}\|_F^2}{M} \mathbf{I})$ and κ_k is the Rician K -factor of the k -th user channel. Especially, we assume $\kappa_1 = \dots = \kappa_K = \kappa$. If we only consider LoS channels while designing the precoding and location of the UAV, the rate of each user can not approach the constraints, i.e., $R_k < \tau_k$. We denote $R(\alpha)$ and $R(2)$ as the sum rate for the UAV at $(x_0^*(\alpha), y_0^*(\alpha))$ and $(x_0^*(2), y_0^*(2))$, respectively. τ stands for the sum rate requirements, i.e., $\tau = \sum_{k=1}^K \tau_k$.

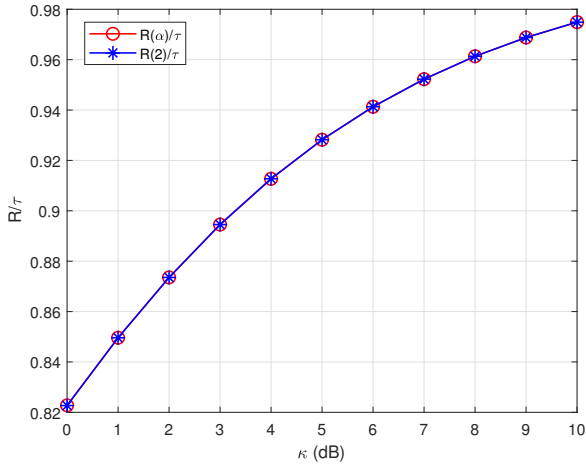


Fig. 5: Sum rate related to sum rate requirements versus κ with $M = 48$.

Fig. 5 illustrates the performance deterioration of the proposed designs over Rician fading channels with varying κ . According to Fig. 5, $\frac{R(\alpha)}{\tau}$ and $\frac{R(2)}{\tau}$ increase with κ and exceed 0.9 when κ is larger than or equal to 4 (dB). It implies that the performance deterioration is not quite large when NLoS channel paths exist. Even when NLoS components are not small and can not be ignored ($\kappa = 3$ dB), the UAV base station could still fulfill around 90% rate requirements. Moreover, $R(\alpha)$ and $R(2)$ are almost the same which indicates that the performance of $(x_0^*(2), y_0^*(2))$ approaches that of $(x_0^*(\alpha), y_0^*(\alpha))$ over Rician channels.

V. CONCLUSIONS

The UAV-assisted communications with multiuser massive MIMO hybrid beamforming is investigated in this work. With a popular beamforming method, power allocation and location designs are proposed to minimize the power while satisfying the rate requirements of all users. Especially, when α is 2, the optimal location could be denoted as the weighted average location of all users.

APPENDIX A PROOF OF PROPOSITION 1

For massive MIMO, the channel model can be well approximated by virtual channel representation [15]

$$\mathbf{h}_k = \sqrt{M\beta_k} \mathbf{t}_k \quad (30)$$

where $\mathbf{t}_k = \mathbf{a}(\hat{\theta}_k)$ in which

$$\hat{\theta}_k = \underset{\hat{\theta}_k \in \{\frac{2\pi}{M}, \frac{4\pi}{M}, \dots, \frac{2\pi(M-1)}{M}\}}{\text{argmin}} |\hat{\theta}_k - \theta_k|. \quad (31)$$

According to (6), the analog precoding for user k should be $\mathbf{f}_k = \mathbf{t}_k$ which further yields $\mathbf{F} = [\mathbf{t}_1, \dots, \mathbf{t}_K]$. From the definition of effective channels in (7), we have $\mathbf{G}^H = \mathbf{H}^H \mathbf{F} = \text{diag}[\sqrt{M}\sqrt{\beta_1}, \dots, \sqrt{M}\sqrt{\beta_K}]$. Using (8) and (9), we calculate $\mathbf{W}$ as $\mathbf{I}$. Substituting above expressions of effective channels, analog and digital precoding into (13), the rate is approximated by (14). ■

REFERENCES

- [1] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36–42, May 2016.
- [2] J. Zhao, F. Gao, G. Ding, T. Zhang, W. Jia, and A. Nallanathan, "Integrating communications and control for UAV systems: Opportunities and challenges," *IEEE Access*, vol. 6, pp. 67519–67527, Nov. 2018.
- [3] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Efficient deployment of multiple unmanned aerial vehicles for optimal wireless coverage," *IEEE Commun. Lett.*, vol. 20, no. 8, pp. 1647–1650, Aug. 2016.
- [4] J. Lyu, Y. Zeng, R. Zhang, and T. J. Lim, "Placement optimization of UAV-mounted mobile base stations," *IEEE Commun. Lett.*, vol. 21, no. 3, pp. 604–607, Mar. 2017.
- [5] Y. Zeng and R. Zhang, "Energy-efficient UAV communication with trajectory optimization," *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 3747–3760, June 2017.
- [6] M. Alzenad, A. El-Keyi, F. Lagum, and H. Yanikomeroglu, "3-D placement of an unmanned aerial vehicle base station (uav-bs) for energy-efficient maximal coverage," *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, pp. 434–437, Aug 2017.
- [7] H. Wang, G. Ren, J. Chen, G. Ding, and Y. Yang, "Unmanned aerial vehicle-aided communications: Joint transmit power and trajectory optimization," *IEEE Wireless Commun. Lett.*, vol. 7, no. 4, pp. 522–525, Aug 2018.
- [8] M. Chen, M. Mozaffari, W. Saad, C. Yin, M. Debbah, and C. S. Hong, "Caching in the sky: Proactive deployment of cache-enabled unmanned aerial vehicles for optimized quality-of-experience," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 5, pp. 1046–1061, May 2017.
- [9] L. Sboui, H. Ghazzai, Z. Rezki, and M. Alouini, "Achievable rates of UAV-relayed cooperative cognitive radio MIMO systems," *IEEE Access*, vol. 5, pp. 5190–5204, 2017.
- [10] H. Jiang, Z. Zhang, L. Wu, and J. Dang, "Three-dimensional geometry-based UAV-MIMO channel modeling for A2G communication environments," *IEEE Commun. Lett.*, vol. 22, no. 7, pp. 1438–1441, July 2018.
- [11] L. Liang, W. Xu, and X. Dong, "Low-complexity hybrid precoding in massive multiuser MIMO systems," *IEEE Wireless Commun. Lett.*, vol. 3, no. 6, pp. 653–656, Dec. 2014.
- [12] A. Alkhateeb, G. Leus, and R. W. Heath, "Limited feedback hybrid precoding for multi-user millimeter wave systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 11, pp. 6481–6494, Nov. 2015.
- [13] W. Xu, J. Liu, S. Jin, and X. Dong, "Spectral and energy efficiency of multi-pair massive MIMO relay network with hybrid processing," *IEEE Trans. Commun.*, vol. 65, no. 9, pp. 3794–3809, Sept. 2017.
- [14] J. Du, W. Xu, H. Shen, X. Dong, and C. Zhao, "Hybrid precoding architecture for massive multiuser MIMO with dissipation: Sub-connected or fully-connected structures?" *IEEE Trans. Wireless Commun.*, vol. 17, no. 8, pp. 5465–5479, Aug. 2018.
- [15] A. M. Sayeed, "Deconstructing multiantenna fading channels," *IEEE Trans. Signal Process.*, vol. 50, no. 10, pp. 2563–2579, Oct. 2002.