

文章编号:1007-5321(2019)03-0120-07

DOI:10.13190/j.jbupt.2018-277

# 一种基于无人机毫米波通信的波束选择方法

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**摘要:** 在无人机毫米波多用户通信网络中,基于波束空间多输入多输出系统提出了一种利用无人机移动特性的波束选择方法. 首先,以减少用户间的能量泄漏为目标设计了无人机基站的最优部署位置;然后,为避免不同用户选择同一波束造成射频链路浪费的情况,提出了一种通过用户接收能量衡量的波束重新选择准则. 仿真结果表明,相比传统的波束选择方法,所提方法可以实现接近最优的系统和速率性能以及更高的能量效率.

**关键词:** 毫米波通信; 无人机; 波束选择; 波束空间多输入多输出

中图分类号: TN929.53

文献标志码: A

## A Beam Selection Method Based on Unmanned Aerial Vehicle Millimeter Wave Communication

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**Abstract:** A millimeter-wave unmanned aerial vehicle (UAV) cellular multiuser network is investigated based on beamspace multiple-input and multiple-output. A beam selection scheme assisted by UAV mobility is proposed. At first, an optimal deployment position of UAV base station is identified with the aim of reducing power leakage problem among users. Afterwards, a simple power focused beam selection criterion called beam reselection is introduced to avoid the problem that the same beam is selected by different users, which will cause the waste of radio-frequency chains. Numerical simulation results show that the proposed scheme achieves near optimal achievable sum rate performance and higher power efficiency compared with conventional beam selection scheme.

**Key words:** millimeter-wave communication; unmanned aerial vehicle; beam selection; beamspace multiple-input and multiple-output

Millimeter-wave (mm-wave) communication has been considered as one of key enabling technologies in fifth generation of mobile communications system (5G) wireless communication system<sup>[1]</sup>. Mm-wave multiple-input and multiple-output (MIMO) communication

could achieve multi-Gbit/s data rates due to its large amount of available spectrum resource (30 ~ 300 GHz)<sup>[2]</sup>. Another potential technology for 5G communication is unmanned aerial vehicles (UAVs) aided wireless communication<sup>[3]</sup> with the benefit of low cost

收稿日期: 2018-11-07

基金项目: 国家自然科学基金项目(61271178)

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and high maneuverability. UAVs equipped with communication devices could be deployed as aerial base station (BS) and provide communication services for ground users when there is a temporary event or the communication infrastructure is destroyed after a natural disaster<sup>[4]</sup>. Combining mm-wave communication with UAV cellular is considered as a promising method to efficiently support high data rate<sup>[5]</sup>.

In order to compensate the severe path loss in mm-wave communication, a large number of antenna arrays are needed to form narrow directional beams and high array gains<sup>[6]</sup>. In the conventional MIMO communication system, each antenna is connected with a radio-frequency (RF) chain<sup>[7]</sup>, which becomes impossible to realize in mm-wave communication system because of the high power consumption and high cost. The concepts of beamspace MIMO (B-MIMO) are proposed in Ref. [7] based on the sparsity of mm-wave channels to reduce the hardware complexity. The channels are transformed into beamspace channel by utilizing discrete Fourier transform (DFT) and only a small number of beams are selected<sup>[8-9]</sup>. The conventional beam selection scheme proposed in Ref. [8] selects beams which contain most channel power. But the same beam may be selected by different users, which will cause the waste of RF chains and power leakage problem<sup>[10]</sup>.

In this paper, a beam selection scheme assisted by UAV mobility called BRS-UMis designed for an mm-wave UAV cellular multiuser network. By exploiting the mobility of the UAV BS, the optimal deployment position is identified to reduce the power leakage problem. And a power focused beam reselection scheme is proposed to avoid that the same beam is selected by different users. Numerical results indicate the proposed scheme achieves near optimal achievable sum rate performance and higher power efficiency compared with conventional fixed BS beam selection scheme.

## 1 System Model

Fig. 1 shows an mm-wave UAV cellular multiuser network. A UAV control station is located in the cell center. The radius of the cell is  $R_{\text{cell}}$ . And a rotary

wing UAV such as a quadcopter, which is able to stay stationary in the air or move in any direction<sup>[3]</sup>, is deployed as UAV BS. The height of UAV BS  $h_u$  is fixed and the UAV BS could only adjust its position in the red inner circular region whose radius is  $R_{\text{in}}$ .  $R_{\text{in}}$  is determined with the control range of the UAV control station. A uniform planar array (UPA) is equipped on the UAV BS,  $N_h$  and  $N_v$  is the number of antenna elements in rows and columns.  $N = N_h N_v$  is the total number of antenna elements. And there are  $K$  single antenna ground users located in the cell, who are served by the UAV BS simultaneously. The locations of ground users are assumed to be known and remain unchanged at UAV BS through global positioning system (GPS). The scenario in this paper can be a sports events or a vocal concert, people who attend the events usually have a fixed seat. Their locations can remain unchanged during the period of the events and UAVs are deployed to offload the traditional communication service or enhance the quality of communication in such a hot spot area<sup>[3]</sup>.

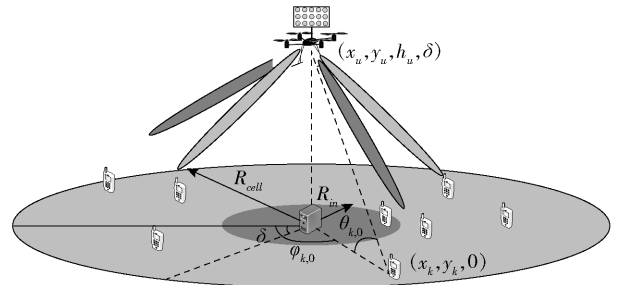


Fig. 1 Illustration of a mm-wave UAV cellular multiuser network

The received symbol vector of  $K$  ground users is given by

$$\mathbf{y} = \mathbf{H}^H \mathbf{F} \mathbf{s} + \mathbf{n} \quad (1)$$

where  $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \dots, \mathbf{h}_K]$  and  $\mathbf{h}_k \in \mathbb{C}^{N \times 1}$  is the channel vector between the UAV BS and the  $k_{\text{th}}$  ground user,  $\mathbf{F} \in \mathbb{C}^{N \times K}$  is the precoding matrix. In the conventional MIMO communication system, the number of RF chains  $N_{\text{RF}}$  is equal to  $N$ , which is impractical for mm-wave system because  $N$  is very large. In addition,  $\mathbf{s}$  is the transmitted symbol vector for  $K$  ground users and  $\mathbf{n}$  is the additive white Gaussian noise (AWGN) vector.

In this paper, we focus on the downlink transmis-

sion when the UAV BS stays stationary in the air and frequency division duplex (FDD) mode is considered. And the spatial multipath channel model is adopted, the downlink channel vector between the  $k_{\text{th}}$  ground user and the UAV BS is written as<sup>[7]</sup>

$$\mathbf{h}_k = \beta_{k,0} \alpha(\gamma_{k,0}, \psi_{k,0}) + \sum_{l=1}^L \beta_{k,l} \alpha(\gamma_{k,l}, \psi_{k,l}) \quad (2)$$

where  $\beta_{k,0}$  and  $\beta_{k,l}$  are the complex path losses of the LOS and the  $l_{\text{th}}$  non-line-of-sight (NLOS) path.  $\alpha(\gamma, \psi)$  is the  $N \times 1$  steering vector of the UPA array and is given by<sup>[11]</sup>

$$\begin{aligned} \alpha(\gamma, \psi) &= \alpha_{\text{el}}(\gamma) \otimes \alpha_{\text{az}}(\psi) \\ \alpha_{\text{el}}(\gamma) &= \frac{1}{\sqrt{N_v}} [e^{-j2\pi i \gamma}]_{i \in \Gamma(N_v)} \\ \alpha_{\text{az}}(\psi) &= \frac{1}{\sqrt{N_h}} [e^{-j2\pi k \psi}]_{k \in \Gamma(N_h)} \end{aligned} \quad (3)$$

where  $\Gamma(N) = \{l - (N-1)/2; l=0, 1, \dots, N-1\}$  is a symmetric set of indices centered around zero,  $\gamma_{k,l} = \frac{d_v}{\lambda} \cos \theta_{k,l}$  and  $\psi_{k,l} = \frac{d_h}{\lambda} \sin \theta_{k,l} \cos \varphi_{k,l}$ . ( $\theta_{k,l}, \varphi_{k,l}$ ) represents the elevation and azimuth angles of departure (AOD) of the  $l_{\text{th}}$  path,  $\theta_{k,l} \in (0, \pi)$  and  $\varphi_{k,l} \in [0, 2\pi)$ .  $d_v$  and  $d_h$  are the distance between the two antenna in the vertical and horizontal direction and  $d_v = d_h = \frac{1}{2}\lambda$ .  $\lambda$  is the wavelength of the carrier. In this paper, a purely LOS channel model is considered and  $\mathbf{h}_k \approx \beta_{k,0} \alpha(\theta_{k,0}, \varphi_{k,0})$  since  $|\beta_{k,0}| \gg |\beta_{k,l}|$  in mm-wave communication<sup>[8]</sup>.

Denote the  $N \times N$  beamforming matrix as  $\mathbf{U} = [\alpha(\bar{\gamma}_0, \bar{\psi}_0)_1, \alpha(\bar{\gamma}_0, \bar{\psi}_1)_2, \dots, \alpha(\bar{\gamma}_{N_v-1}, \bar{\psi}_{N_h-1})_N]^H$ . And each column of  $\mathbf{U}$  is an array steering vector at different spatial frequency  $\bar{\gamma}_m = \frac{1}{N_v} \left(m - \frac{N_v-1}{2}\right)$  and  $\bar{\psi}_n = \frac{1}{N_h} \left(n - \frac{N_h-1}{2}\right)$ , where  $m=0, 1, \dots, N_v-1$  and  $n=0, 1, \dots, N_h-1$ . Meanwhile,  $\mathbf{U}$  is a unitary DFT matrix and each column of  $\mathbf{U}$  is orthonormal. The beamspace channel is given by

$$\mathbf{H}_b = \mathbf{U}\mathbf{H} = [\mathbf{h}_1^b, \mathbf{h}_2^b, \dots, \mathbf{h}_K^b] \quad (4)$$

$\mathbf{h}_k^b$  has a sparse structure<sup>[8]</sup> which means there are only a small amount dominant elements in  $\mathbf{h}_k^b$  among the total  $N$  elements. By exploiting this property, only a

few beams are selected, which called beam selection. And the received symbol vector in B-MIMO model is given by

$$\mathbf{y}_s \approx \mathbf{H}_s^H \mathbf{F}_s \mathbf{s} + \mathbf{n} \quad (5)$$

where  $\mathbf{H}_s = [\mathbf{H}_b(i, :)]_{i \in \Omega_s}$ ,  $\Omega_s$  is the set of selected beams' indices and  $|\Omega_s| = N_b \ll N$ .  $\mathbf{F}_s \in \mathbb{C}^{N_b \times K}$  is the corresponding low dimensional beamspace precoding matrix. And the complexity of hardware system is reduced from  $O(N)$  to  $O(N_b)$ .

## 2 Beam Selection Scheme Assisted by UAV Mobility

Compared with conventional fixed BS, the UAV BS brings another degree of freedom—UAV mobility, which could be utilized to help improve network performance. In this section, a beam selection scheme assisted by UAV mobility called BRS-UM for a mm-wave UAV cellular network is proposed. The proposed scheme contains two steps. At first, the optimal position of UAV BS is identified in order to reduce power leakage problem. Subsequently, a simple power focused beam selection criterion called beam reselection (BRS) is executed and guaranteed to allocate a unique beam for each user.

### 2.1 Problem Formulation

As shown in Fig. 1, the UAV position is denoted as  $(x_u, y_u, h_u, \delta)$  and  $\delta \in \left[-\frac{1}{2}\pi, \frac{1}{2}\pi\right]$  is the orientation angle of UAV. The  $k_{\text{th}}$  ground user location is denoted as  $(x_k, y_k, 0)$ .  $R_{k,u} = \sqrt{(x_u - x_k)^2 + (y_u - y_k)^2}$  is the distance between the  $k_{\text{th}}$  ground user and the projection of UAV BS in the  $x$ - $y$  plane. Then the  $|\cos \theta_k|$  and  $|\sin \theta_k \cos \varphi_k|$  of the  $k_{\text{th}}$  ground user could be expressed as

$$|\cos \theta_k| = \frac{R_{k,u}}{\sqrt{R_{k,u}^2 + h_u^2}} \quad (6)$$

$$|\sin \theta_k \cos \varphi_k| = \frac{h_u}{\sqrt{R_{k,u}^2 + h_u^2}} |\cos(\varphi_{k,0} + \delta)| \quad (7)$$

where  $\varphi_{k,0}$  represents the azimuth AOD relative to the UAV BS when  $\delta=0$  and is given by

$$\varphi_{k,0} = \begin{cases} \arccos \frac{x_k - x_u}{R_{ku}}, & y_k - y_u \geq 0 \\ \arccos \frac{x_k - x_u}{R_{ku}} + \pi, & y_k - y_u < 0 \end{cases} \quad (8)$$

The ground users are assumed to be static in this paper, so  $(\theta_k, \varphi_k)$  are only determined by the position of UAV BS  $(x_u, y_u, h_u, \delta)$ .

**Property 1** When there exists a pair of  $(\theta_k, \varphi_k)$  that satisfies the condition that  $\bar{\gamma}_m - \frac{1}{2}\cos \theta_k = 0$  and  $\bar{\psi}_n - \frac{1}{2}\sin \theta_k \cos \varphi_k = 0$ ,  $\mathbf{h}_k^b$  has only one non-zero element.

**Proof** Define the  $j_{\text{th}}$  row of  $\mathbf{U}$  as  $\alpha(\bar{\gamma}_m, \bar{\psi}_n)_j^H$ , and  $\alpha(\bar{\gamma}_m, \bar{\psi}_n)_j^H = \alpha(\bar{\gamma}_m)^H \otimes \alpha(\bar{\psi}_n)^H$ ,  $j = mN_h + n$ . And the  $j_{\text{th}}$  element of  $\mathbf{h}_k^b$ ,  $h_k^b(j)$  can be expressed as

$$h_k^b(j) = \beta_k \left\{ \left[ \frac{1}{N_v} \frac{\sin \left( \pi N_v \left( \bar{\gamma}_m - \frac{1}{2} \cos \theta_k \right) \right)}{\sin \left( \pi \left( \bar{\gamma}_m - \frac{1}{2} \cos \theta_k \right) \right)} \right] \times \left[ \frac{1}{N_h} \frac{\sin \left( \pi N_h \left( \bar{\psi}_n - \frac{1}{2} \sin \theta_k \cos \varphi_k \right) \right)}{\sin \left( \pi \left( \bar{\psi}_n - \frac{1}{2} \sin \theta_k \cos \varphi_k \right) \right)} \right] \right\} \quad (9)$$

When  $\bar{\gamma}_m - \frac{1}{2}\cos \theta_k = 0$  and  $\bar{\psi}_n - \frac{1}{2}\sin \theta_k \cos \varphi_k = 0$ ,  $\mathbf{h}_k^b$  has only one non-zero element and  $h_k^b(j) = \beta_k$ . It implies that the  $k_{\text{th}}$  ground user is exactly located in the corresponding beam center and has no power leakage to other beams. Otherwise, it will have power leakage to adjacent beams. And our goal is to reduce the power leakage problem by exploiting UAV mobility. In other words, an optimal position of UAV BS needs to be identified to minimize the distance between ground users and their corresponding beam center.

According to Ref. [8], when  $h_k^b(j)$  is bigger, the power leakage will become less. And our goal of this paper is to maximize  $h_k^b(j)$  with the help of UAV mobility. In Eq. (9),  $h_k^b(j)$  has two variables: elevation direction variable  $\bar{\gamma}_m - \frac{1}{2}\cos \theta_k$  and azimuth direction variable  $\bar{\psi}_n - \frac{1}{2}\sin \theta_k \cos \varphi_k$ . For elevation direction, the distance between each adjacent array steering vector in spatial frequency domain is  $\frac{1}{N_v}$ . And the minimum distance between  $\frac{1}{2}\cos \theta_k$  and all elevation array steering vectors in spatial frequency domain could be

expressed as

$$\text{dis}_{\text{el}}(\cos \theta_k) = \min \left[ \text{mod} \left( \frac{1}{2} |\cos \theta_k|, \frac{1}{N_v} \right), \frac{1}{N_v} - \text{mod} \left( \frac{1}{2} |\cos \theta_k|, \frac{1}{N_v} \right) \right] \quad (10)$$

Similarly, the minimum distance between  $\frac{1}{2}\sin \theta_k \cos \varphi_k$  and all azimuth array steering vectors in spatial frequency domain is expressed as

$$\text{dis}_{\text{az}}(\sin \theta_k \cos \varphi_k) = \min \left[ \text{mod} \left( \frac{1}{2} |\sin \theta_k \cos \varphi_k|, \frac{1}{N_h} \right), \frac{1}{N_h} - \text{mod} \left( \frac{1}{2} |\sin \theta_k \cos \varphi_k|, \frac{1}{N_h} \right) \right] \quad (11)$$

And the optimization problem is formulated as

$$\forall k, \begin{cases} \min_{(x_u, y_u, h_u, \delta)} \text{dis}_{\text{el}}(\cos \theta_k) \\ \min_{(x_u, y_u, h_u, \delta)} \text{dis}_{\text{az}}(\sin \theta_k \cos \varphi_k) \end{cases} \quad (12a)$$

$$\text{s. t. } x_u^2 + y_u^2 \leq R_{\text{in}}^2 \quad (12a)$$

$$\delta \in \left[ -\frac{1}{2}\pi, \frac{1}{2}\pi \right] \quad (12b)$$

However, the above optimization problem is difficult to solve since the modification of UAV BS's position will change the  $(\theta, \varphi)$  of all ground users. Then we relax the optimization problem into a sub-optimization format:

$$\min_{(x_u, y_u, h_u, \delta)} \sum_{k=1}^K \text{dis}_{\text{el}}(\cos \theta_k) \quad (13)$$

$$\min_{(x_u, y_u, h_u, \delta)} \sum_{k=1}^K \text{dis}_{\text{az}}(\sin \theta_k \cos \varphi_k) \quad (14)$$

$$\text{s. t. } (12a) (12b)$$

## 2.2 Step 1: Identify UAV BS Optimal Position

In the following, a method to identify the optimal position of UAV BS which achieves Eq. (13) and Eq. (14) is described. The position of UAV BS has two parts: hovering location  $(x_u, y_u, h_u)$  and orientation angle  $\delta$ . First, a set  $\Phi$  that contains all the coordinates of candidate hovering locations of UAV BS is denoted as

$$\Phi = \{ (x_u, y_u, h_u) : x_u = r_u \cos \alpha_u, y_u = r_u \sin \alpha_u \} \quad (15)$$

where  $r_u = i\Delta r$ ,  $i = 0, 1, \dots, N_r$  and  $\alpha_u = t\Delta\alpha$ ,  $t = 0, 1, \dots, N_\alpha$ .  $\Delta r$  and  $\Delta\alpha$  are the minimum resolution determined by the minimum move range of UAV.  $N_r =$

$$\left\lfloor \frac{R_{in}}{\Delta r} \right\rfloor \text{ and } N_\alpha = \left\lfloor \frac{2\pi}{\Delta\alpha} \right\rfloor.$$

Similarly, a set  $\Theta$  that contains all the candidate orientation angles of UAV BS is defined as

$$\Theta = \left\{ \delta; \delta = -\frac{1}{2}\pi + q\Delta\delta, q=0,1,\dots,N_\delta \right\},$$

$$N_\delta = \left\lfloor \frac{\pi}{\Delta\delta} \right\rfloor \quad (16)$$

From Eq. (6), Eq. (7) and Eq. (8), it is found that  $|\cos \theta_k|$  is merely determined by the hovering location of UAV BS and  $|\sin \theta_k \cos \varphi_k|$  is determined by the both parts. Based on this, a method is proposed to identify the optimal position of UAV BS  $(x_u^o, y_u^o, h_u^o)$  which could achieve Eq. (13) and Eq. (14) step by step:

① Based on all the positions of ground users known at UAV BS,  $\sum_{k=1}^K \text{dis}_{el}(\cos \theta_k)$  is calculated using Eq. (6) and Eq. (10) for each candidate hovering location in  $\Phi$  and find the optimal element  $(x_u^o, y_u^o, h_u^o)$  which achieves Eq. (13);

② Based on the result  $(x_u^o, y_u^o, h_u^o)$  from ①,  $\sum_{k=1}^K \text{dis}_{az}(\sin \theta_k \cos \varphi_k)$  is calculated using Eq. (7), Eq. (8) and Eq. (11) for each candidate orientation angle in  $\Theta$  and find the optimal  $\delta^o$  which achieves Eq. (14).

In this way, the optimal position of UAV BS is identified.

### 2.3 Step 2: Beam Reselection

In this section, a simple power focused beam selection criterion called beam reselection is introduced. After the UAV BS is deployed in the optimal position obtained from Step 1, the largest beam in the beamspace channel vector is selected for each ground user firstly. When the same beam is selected by more than one user, it will cause performance loss and the waste of corresponding RF chains<sup>[9]</sup>. So beam reselection process is required for users who select the same beam.

Define  $b_k \in \Omega$  is the indice of selected beam of  $k_{th}$  ground user and  $\Omega = \{1, 2, \dots, N\}$  is the complete set of all indices. Then divide the users in two subsets;

same beam user subset  $A_{SU}$  and different beam user subset  $A_{DU}$ ,  $A_{SU} \cup A_{DU} = \{1, 2, \dots, K\}$ . The beams selected by users in  $A_{DU}$  comprise the selected beams set  $\Omega_s = \{b_k | k \in A_{DU}\}$ . And define the complement of  $\Omega_s$  to be unselected beams set  $\Omega_{UNS} = \Omega - \Omega_s$ . The main idea of BRS is described as follow:

① Divide all  $K$  users into  $A_{SU}$  and  $A_{DU}$  according the beams they selected. Afterwards, divide all the beams into  $\Omega_s$  and  $\Omega_{UNS}$  according to user division;

② For users in  $A_{SU}$ , for example,  $b_k = b_j, k \neq j, k, j \in A_{SU}$ . Suppose that  $|h_k^b(b_k)| \geq |h_j^b(b_j)|$ , then user  $k$  remains the selected beam and  $\Omega_s = \Omega_s \cup \{b_k\}$ ,  $\Omega_{UNS} = \Omega - \Omega_s$ . And user  $j$  selects the largest beam in  $\Omega_{UNS}$ . The same operation is applied for other users in  $A_{SU}$ ;

③ Repeat ① – ② until  $A_{SU}$  is empty and every user select a unique beam, hence  $|\Omega_s| = K$ .

Since for each user the largest beams are allocated with the current set in each iteration. And a unique beam would be allocated to each user in the end of the algorithm.

## 3 Numerical Results and Analysis

In this section, numerical results are presented to analyze the performance of the proposed BRS-UM scheme compared with the conventional fixed BS 1/2-beam selection (1/2BS-FB) scheme, where The base station is fixed at the original  $(0,0)$ <sup>[8]</sup>. The ground users are uniformly distributed in the cell. According to Friis transmission formula<sup>[12]</sup>,  $|\beta_k|^2 = \frac{\lambda^2}{16\pi^2(R_{k,u}^2 + h_u^2)}$ . The simulation parameters are listed in the Table 1 except other demonstration. All the numerical results are generated through over 20000 times Monte Carlo simulations. To evaluate the performance of the proposed scheme, the system achievable sum rate is considered.

As shown in Fig. 2, the system achievable sum rate with different beam selection schemes is presented. And the full dimension ZF system is also provided for comparison. It is observed that the proposed BRS-UM scheme achieves a better performance than 1BS-FB scheme and only shows a less gap from 2BS-FB

scheme. The performance of beam reselection scheme for fixed BS (BRS-FB) is also presented and only achieves small improvement compared with 1BS-FB. It implies that power leakage problem is the main reason to the system performance loss. And the power leakage problem is reduced by exploiting UAV mobility. Although the full dimension ZF system achieves the best performance due to all beams are selected,  $N_{\text{RF}} = N$ , it suffers from high RF hardware complexity.

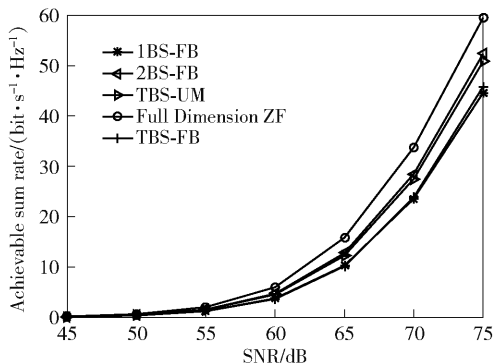


Fig. 2 Simulation results of achievable sum rate versus SNR with different benchmarks

Fig. 3 shows the power efficiency of different schemes with different number of users. It is observed that the proposed BRS-UM scheme achieves the best power efficiency performance because BRS-UM scheme uses fewer RF chains and achieves near optimal sum rate. When the number of users becomes larger, the power efficiency both becomes worse due to the increase of the number of RF chains. And the full dimension ZF achieves the worst power efficiency because of high number of RF chains.

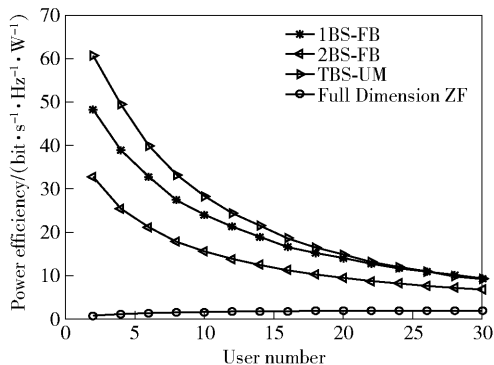


Fig. 3 Simulation results of power efficiency versus user number with different benchmarks

## 4 Conclusions

In this paper, we have proposed a beam selection scheme assisted by UAV mobility for a mm-wave UAV cellular multiuser network. The proposed BRS-UM scheme has two main advantages: 1) the power leakage problem among the users is greatly reduced by making use of UAV mobility; 2) beam reselection avoids that the same beam is selected by different users. Numerical results demonstrate that the proposed BRS-UM scheme achieves almost optimal sum rate performance and higher power efficiency compared with conventional fixed BS beam selection scheme. Extending the BRS-UM scheme to a mobile scenario, where the ground users are not static, is our future work.

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### 3 结束语

适用于概率成形高速光传输系统的调制格式识别是未来实现灵活速率光网络非常实际的问题。笔者提出的基于四次方特征值的调制格式识别方法复杂度较低,在低信噪比条件下即可有效识别主流的PS-16QAM/PS-64QAM及传统均匀分布高阶调制格式。仿真结果表明,光信噪比达到15 dB时,使用本方法的调制格式识别准确率在90%以上。

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