

Adaptive scheduling for millimeter wave multi-beam satellite communication systems

ZHOU Zhengyi¹, FENG Wei¹, CHEN Yunfei², GE Ning¹

1. Tsinghua National Laboratory for Information Science and Technology Department of Electronic Engineering, Tsinghua University, Beijing 100084, China
2. School of Engineering, University of Warwick, Coventry CV4 7AL, UK

Abstract: In space information networks, the performance of the satellite-terrestrial links is crucial for downlink data delivery. Due to their relatively wide bandwidth, the use of mmWave (millimeter wave) signals is promising to enhance satellite communications. Adopting on-board antenna arrays can mitigate the attenuation associated with mmWave signals, and can also enable multi-beam transmissions. However, the number of RF (Radio Frequency) chains is usually limited in practical applications, which makes it extremely difficult to properly schedule users. In general, this scheduling problem is NP-hard. In this paper, we propose two scheduling algorithms that can be used to solve this problem with relatively low computational complexity. Intuitively, the correlated users are separated by the proposed schemes, which implies that the spatial diversity gain of multiple beams can be exploited. Simulation results show that the proposed algorithms can achieve nearly optimal performance in terms of the achievable sum rate of the system.

Key words: millimeter wave, satellite, scheduling, beamforming, antenna arrays

Citation: ZHOU Z Y, FENG W, CHEN Y F, et al. Adaptive scheduling for millimeter wave multi-beam satellite communication systems[J]. Journal of communications and information networks, 2016, 1(3): 42-50.

1 Introduction

Rapidly increasing demand for higher data rates has become a challenging problem for next generation satellite communication systems, and one of the most significant constraints is the shortage of available bandwidth. To address this situation, either new spectrum must be made available, or higher spectral efficiency must be achieved.

The mmWave band promises to offer abundant spectral resources^[1,2]. Satellite communications in the Ka band and above have been investigated^[3-5], and

mmWave channels have been found to be generally LoS (Line-of-Sight)-dominated because mmWave signals suffer from severe attenuation^[6]. With much smaller wavelengths, mmWave technology enables a large number of antennas in a given area. Antenna arrays driven by smart beam selection algorithms can be utilized to mitigate mmWave signal attenuation^[6]. The deterioration of system performance under LOS-dominated channel conditions can be significantly alleviated by directed beamforming. The hybrid beamforming scheme shown in Fig.1 further ensures a feasible implementation framework for large arrays

by reducing the number of RF chains^[7]. Channel estimation methods and precoding algorithms are also investigated in detail in Refs.[7-12].

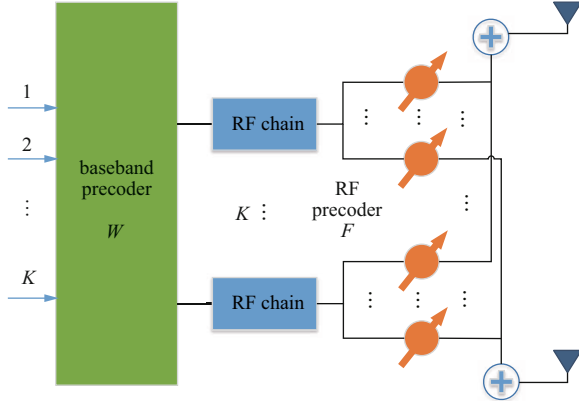


Figure 1 Implementation of hybrid precoding

In order to provide reasonable system capacity, the number of active users in the system should be no more than the number of RF chains^[13]. This can be addressed by network densification in terrestrial wireless communications. However, scheduling is inevitable in satellite communications systems, as shown in Fig.2. It is not wise to arbitrarily choose active users from among all the users to be served because serving nearby directional users simultaneously is extremely challenging for beamforming^[14]. As a result, the quality of service (QoS) is heavily degraded no matter what precoding algorithm is adopted. The ideal scheduling method

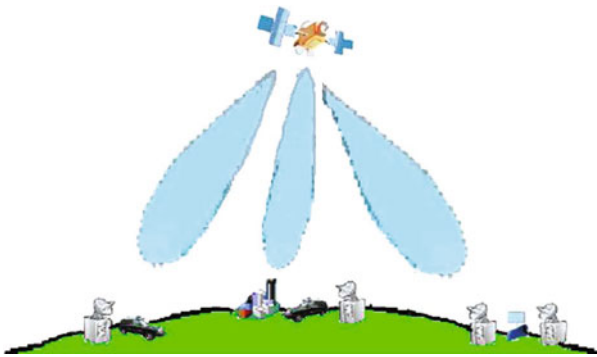


Figure 2 Satellite systems with mmWave hybrid beamforming arrays

divides closely located users into different time slots, and ensures active users in the same time slot can be easily distinguished in order to obtain spatial multiplex gain.

This paper focuses on the scheduling problems in satellite communication systems that use mmWave hybrid beamforming antenna arrays. The scheduling model is formulated in Section 2, scheduling algorithms are proposed in Section 3, simulation results are shown in Section 4, and the paper is concluded in Section 5.

2 Problem formulation

We assume that there are a total of N users in need of service within our satellite communication system, which has a channel matrix $\mathbf{H} \in \mathbb{C}^{N \times M}$, where M is the size of the satellite antenna arrays, and K ($K < N$) RF chains are available due to practical implementation constraints. This means that the satellite is capable of serving at most K users in one time slot, assuming that each user requires one independent data stream. The N users are divided into G groups with K_1, K_2, \dots, K_G users in each group and corresponding channel sub-matrix $\mathbf{H}_1, \mathbf{H}_2, \dots, \mathbf{H}_G$ respectively. It takes G time slots in the aggregate to serve all G groups of users.

For simplicity, we let $G = N/K$ be an integer, and create an average partition, as follows.

$$K_1 = K_2 = \dots = K_G = K. \quad (1)$$

In time slot m , we adopt the mmWave uniform rectangular array (URA), and perform hybrid beamforming to serve the K users with channel matrix \mathbf{H}_m . The hybrid precoding model is stated in detail in Refs.[7,8,10]. If the transmitted symbol vector is denoted as \mathbf{x} , the received symbol of the K users together can be expressed as

$$\mathbf{y} = \rho \beta \mathbf{H}_m \mathbf{F}_m \mathbf{W}_{nr} \mathbf{x} + \mathbf{n}, \quad (2)$$

where ρ is the multiplier for antenna gain, β is the

multiplier for pathloss, and $\mathbf{F}_m \in \mathbb{C}^{M \times K}$ is the analog precoding matrix satisfying

$$[\mathbf{F}_m]_{i,j} = \frac{1}{\sqrt{M}} e^{j2\pi\phi_{i,j}}, \quad (3)$$

$\mathbf{W}_m = [\mathbf{w}_{m,1}, \mathbf{w}_{m,2}, \dots, \mathbf{w}_{m,K}] \in \mathbb{C}^{K \times K}$ is the baseband digital precoding matrix. $\mathbf{n} \in \mathbb{C}^{K \times 1}$ is the complex additive white Gaussian noise vector with diagonal covariance matrix. \mathbf{x} satisfying

$$\mathbb{E}[\mathbf{x}\mathbf{x}^H] = \frac{P}{K} \mathbf{I}_K, \quad (4)$$

where P is the total transmit power. The digital precoder \mathbf{W}_m is normalized to meet the total power constraint

$$|\mathbf{F}_m \mathbf{W}_m|_F^2 = K. \quad (5)$$

The clustered mmWave channel model characterizing the limited scattering feature^[7,8,10,11,15,16] is employed here for the downlink channel matrix of the K users in the group $\mathbf{H}_m = [h_{m,1}, h_{m,2}, \dots, h_{m,K}]^T \in \mathbb{C}^{K \times M}$. The column $h_{m,k}$ is the channel vector of the k th user in the m th group. Taking into account the LoS-dominated characteristics and the attenuation of the mmWave signals, we employ two paths for the channel model including the LoS path.

$$\mathbf{h}_{m,k} = \sqrt{\frac{M}{2}} \sum_{i=1}^2 \alpha_{m,k}^i \mathbf{a}(\phi_{m,k}^i, \theta_{m,k}^i), \quad (6)$$

where $\alpha_{m,k}^1 \sim \mathcal{CN}(0,1)$, $\alpha_{m,k}^2 \sim \mathcal{CN}(0, \sigma^2)$ are the complex gains of the paths with the Rician factor σ^2 . $\phi_{m,k}^i$ ($\theta_{m,k}^i$) is the azimuth (elevation) angle of the corresponding user, and $\mathbf{a}(\phi_{m,k}^i, \theta_{m,k}^i)$ is the antenna array response vector determined by the geometric architecture of the arrays. For URA,

$$\mathbf{a}(\phi, \theta) = \frac{1}{\sqrt{M}} [1, \dots, e^{j\frac{2\pi}{\lambda} d(m \sin \phi \sin \theta + n \cos \theta)}, \dots, e^{j\frac{2\pi}{\lambda} d((N_h-1) \sin \phi \sin \theta + (N_v-1) \cos \theta)}]^T, \quad (7)$$

where N_v (N_h) is the number of antennas in the vertical (horizontal) direction within the arrays ($N_h N_v = M$). m, n are the indices of each antenna element,

$$0 \leq m \leq (N_h-1), 0 \leq n \leq (N_v-1).$$

The SINR (Signal-to-Interference-plus-Noise Ratio) of the k -th user in the m -th group can be expressed as

$$\text{SINR}_{m,k} = \frac{\frac{\rho\beta P}{K} |\mathbf{h}_{m,k}^T \mathbf{F}_m \mathbf{w}_{m,k}|^2}{\sum_{j \neq k} \frac{\rho\beta P}{K} |\mathbf{h}_{m,k}^T \mathbf{F}_m \mathbf{w}_{m,k}|^2 + \sigma_{m,k}^2}. \quad (8)$$

The corresponding achievable rate is then

$$r_{m,k} = \text{lb}(1 + \text{SINR}_{m,k}), \quad (9)$$

and the achievable sum rate of the group is calculated by

$$R_m = \sum_{k=1}^K r_{m,k} = \sum_{k=1}^K \text{lb}(1 + \text{SINR}_{m,k}). \quad (10)$$

During all of the G time slots, the achievable sum rate of the N user can be given by

$$C = \sum_{m=1}^G R_m = \sum_{m=1}^G \sum_{k=1}^K r_{m,k}. \quad (11)$$

We employ the precoding algorithms proposed in Ref.[8] in our simulation. For the analog precoder,

$$[\mathbf{F}_m]_{i,j} = \frac{1}{\sqrt{M}} e^{j2\pi\phi_{i,j}}, \quad (12)$$

where $\phi_{i,j}$ is the phase angle of the channel element $[\mathbf{H}_m]_{i,j}$. For the digital precoder, an equivalent channel $\tilde{\mathbf{H}}_m = \mathbf{H}_m \mathbf{F}_m$ is seen at the baseband. When zero-forcing (ZF) precoding is applied, the digital precoder is then given by

$$\mathbf{W}_m = \tilde{\mathbf{H}}_m^H (\tilde{\mathbf{H}}_m \tilde{\mathbf{H}}_m^H)^{-1} \mathbf{A}. \quad (13)$$

The diagonal matrix \mathbf{A} is designed to normalize the precoding matrix in order to meet the power constraint in Eq.(5).

It is evident that different partitions of users lead to different performance since the SINR of each user is jointly determined by the precoding and channels, not to mention that the precoders are specifically designed based on the channel sub-matrix. The achievable sum rate of the system can be substantially increased if we employ smart partitions. The problem can be represented as

$$(\mathbf{H}_1^*, \mathbf{H}_2^*, \dots, \mathbf{H}_G^*) = \arg \max_{\substack{\{\mathbf{H}_1, \mathbf{H}_2, \dots, \mathbf{H}_G\} \\ \text{a partition of } \mathbf{H}}} \left\{ \sum_{m=1}^G \sum_{k=1}^K \text{lb}(1 + \text{SINR}_{m,k}) \right\}. \quad (14)$$

3 Proposed scheduling scheme

It is NP-hard to exhaustively search for the optimal partition due to the sheer number of combinatorial grouping choices. On the other hand, random partitions lead to performance deterioration due to the strong correlation between channels in a satellite system. In this section, two heuristic scheduling algorithms are proposed to solve this problem. When there are a large number of users connected within the system that need to be grouped, the proposed algorithms employ recursive methods in order to quickly complete the task.

It has been observed that the benefits of hybrid precoding are in the power boost and interference cancellation of beamforming. When channels between different users exhibit a strong correlation, the interference cancellation becomes much more challenging, and the performance gain of precoding becomes non-existent. Therefore, we will divide these strongly correlated users into different slots in order to approach the optimal performance level, but with much lower computational complexity.

Based on the above principles, we start by searching for the pair of users who share the strongest channel coherence among all pairs of users, and then create two queues with each of the first pair of users as the head of a queue. This operation is then repeated for the remaining users, and each user is placed next in line in one of the two queues. After all users have been traversed, there are two sub-groups. Recursively, we can develop more elaborate partitions. Theoretically, this algorithm is focused on canceling the globally strongest coherence, and thus it has a performance that is superior to other recursive

algorithms. The corresponding time complexity is approximately

$$O(M^2 N^2 \log N), \quad (15)$$

where M is the number of transmitting antennas and N is the number of users.

If there are large numbers of connected users, we developed an alternate algorithm that has an almost linear time complexity instead of nearly square order complexity. If we consider the case of an arbitrary user, for instance, User 1, calculate the channel vector coherence coefficients between User 1 and other users, sort them into descending order, and separate the odd and even indices in order to balance the channel correlation of the odd and even sub-groups. Then the corresponding time complexity is approximately

$$O[M \log N (\log N + M^2)], \quad (16)$$

where M is the number of transmitting antennas and N is the number of users.

We refer to Algorithms 1 and 2 as using the inter-group-coherence-balancing method and the globally-strongest-coherence-cancellation method respectively. The pseudocode for one single bisected stage is shown below.

Algorithm 1 Inter-group coherence balancing

Input: DL channel \mathbf{H} of size $m \times n$

Output: Two sub-channels $\mathbf{H}_1, \mathbf{H}_2$

- 1: $flag = 0;$
- 2: **for** $i = 1$ to n
- 3: $a_i = \left| \frac{\mathbf{h}_1^H \mathbf{h}_i}{\|\mathbf{h}_1\| \cdot \|\mathbf{h}_i\|} \right|;$
- 4: **end for**
- 5: **for** $flag < n$
- 6: $j = \text{argmax}_k \{a_k\};$
- 7: put h_j into $\mathbf{H}_1;$
- 8: $a_j = 0;$
- 9: $flag = flag + 1;$
- 10: **if** $flag < n$
- 11: $j = \text{argmax}_k \{a_k\};$

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12:   put  $\mathbf{h}_j$  into  $\mathbf{H}_2$ ;
13:    $a_j = 0$ ;
14:    $flag = flag + 1$ ;
15: end if
16: end for

```

Adopting the bisected methods, we divide one group of users into two sub-groups. Recursively doing the work on the sub-groups $\mathbf{H}_1, \mathbf{H}_2$, we can finally complete the scheduling.

Algorithm 2 is more considerate but has a higher degree of computational complexity. We start by finding the most correlated pair, and then separate them into two groups. This is completed for all remaining users.

Algorithm 2 Globally strongest coherence cancellation

Input: DL channel \mathbf{H} of size $m \times n$

Output: Two sub-channels $\mathbf{H}_1, \mathbf{H}_2$

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1:    $flag = 0$ ;
1:    $a_{i,j} = 0; 1 \leq i \leq n; 1 \leq j \leq n$ ;
2:   for  $i = 1$  to  $n - 1$ 
3:     for  $j = i + 1$  to  $n$ 
4:        $a_{i,j} = \frac{|\mathbf{h}_i^H \mathbf{h}_j|}{|\mathbf{h}_i| \cdot |\mathbf{h}_j|}$ ;
4:     end for
5:   end for
5:   for  $flag < n$ 
6:      $(i, j) = \operatorname{argmax}_{i,j} \{a_{i,j}\}$ ;
7:     put  $\mathbf{h}_i$  into  $\mathbf{H}_1$ ;
8:      $a_{i,k} = 0, i + 1 \leq k \leq n$ ;
8:      $a_{k,i} = 0, 1 \leq k \leq i - 1$ ;
9:      $flag = flag + 1$ ;
10:    if  $flag < n$ 
12:      put  $\mathbf{h}_j$  into  $\mathbf{H}_2$ ;
11:       $a_{j,k} = 0; j + 1 \leq k \leq n$ ;
12:       $a_{k,j} = 0; 1 \leq k \leq j - 1$ ;
14:       $flag = flag + 1$ ;
15:    end if
16:  end for

```

4 Simulation results

4.1 Time complexity verification

To verify the time complexity analyses, we change the scale of users to be grouped, and keep a record of the corresponding time for the simulated implementation of the two algorithms. The results shown in Figs.3 and 4 can be regarded as confirmation of the theoretical analyses. Algorithm 1 exhibits almost linear complexity while Algorithm 2 exhibits time complexity of nearly square order.

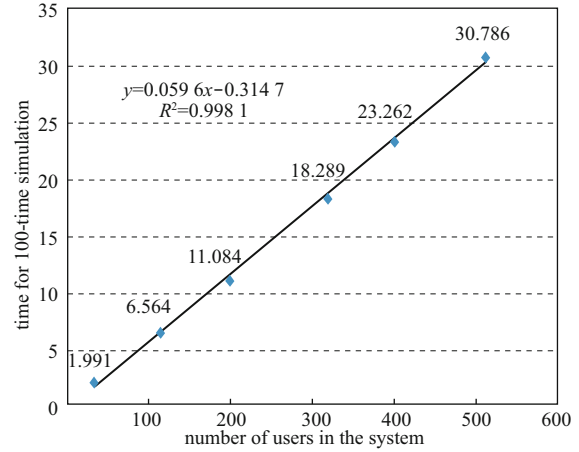


Figure 3 Algorithm 1 time complexity verification

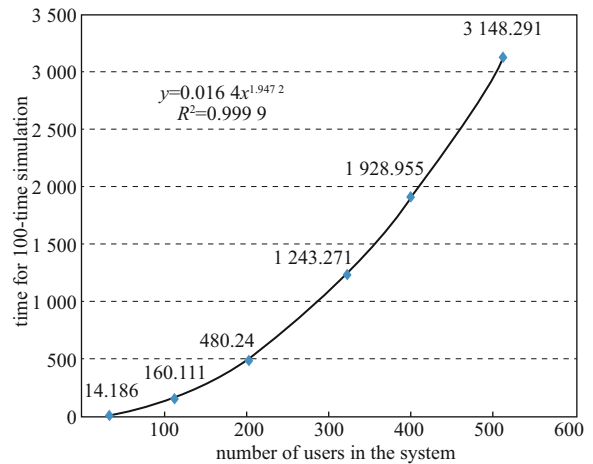


Figure 4 Algorithm 2 time complexity verification

4.2 Achievable sum rate comparison

Noticing that Eq.(8) can be rewritten as

$$SINR_{m,k} = \frac{|h_{m,k}^T \mathbf{F}_m \mathbf{w}_{m,k}|^2}{\sum_{j \neq k} |h_{m,k}^T \mathbf{F}_m \mathbf{w}_{m,j}|^2 + \frac{K \sigma_{m,k}^2}{\rho \beta P}}, \quad (17)$$

if we take a reasonable assumption $\sigma_{m,k}^2 = \sigma^2$, we can define

$$\eta = \frac{\rho \beta P}{K \sigma^2}. \quad (18)$$

η can be considered as the received SNR (Signal-to-Noise Ratio) without precoding. We adopt η as the abscissa instead of the total transmitting SNR since it makes no difference.

In order to consider practical situation, we employ both directionally fixed and directionally adaptive beamforming scenarios in our simulation. In directionally fixed beamforming, the precoders are designed based on K fixed directions, and remain unchanged during all of the G time slots. The advantage of this scheme is that the implementation is low complexity because only one precoder setting is needed; however, the rate performance is poor due to the lack of channel state information in the design of the precoders. In directionally adaptive beamforming, targeted precoders are devised for each group that take into account the characteristics of the channels being used.

In Fig.5, the optimal solution obtained after exhaustive searching is compared with the proposed algorithms, where $N = 8$, $G = 4$, and $K = 2$. For values of N larger than 10, the simulation tends to collapse due to the astronomical number of pairs produced. This is why no optimal upper bound is displayed in the simulation results in this paper.

The simulation results are based on the following conditions: $N = 256$, $G = 8$, $K = 32$, and 16×16 URA. We simulated the random/optimized scheduling scheme

with directionally fixed/adaptive ZF beamforming in order to investigate the performance of our proposed method. The rate- η curves are shown and the probabilistic properties are investigated using CCDF (Complementary Cumulative Density Functions).

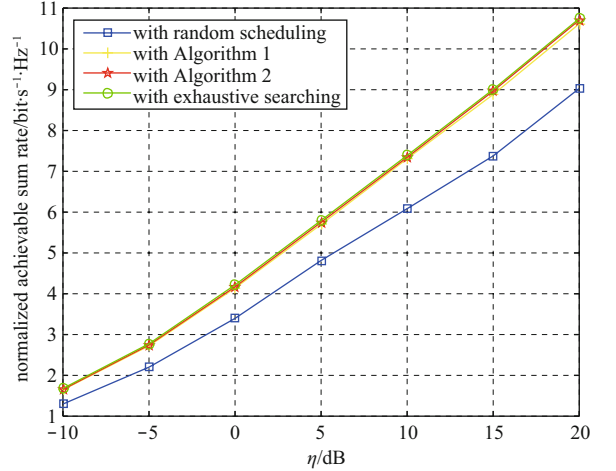


Figure 5 Capacity performance with ZF precoder in satellite systems

In the figure legends, RD is short for random scheduling, OP1 for optimized scheduling with Algorithm 1, OP2 for optimized scheduling with Algorithm 2, F for directionally fixed, A for directionally adaptive, and BF for beamforming.

We have three conclusions based on the simulation results as shown in Figs.6 and 7.

1) With directionally adaptive BF, the sum rate is much higher than that of fixed BF regardless of the scheduling scheme. This is due to the fact that the precoders in adaptive BF are designed based on the location of the users, while fixed BF adopts fixed precoders regardless of where the users are actually located.

2) With directionally adaptive BF, optimized scheduling is capable of increasing the sum rate when compared to the sum rate with random scheduling. This is due to the fact that the optimized scheduling algorithm ensures that there are no closely related

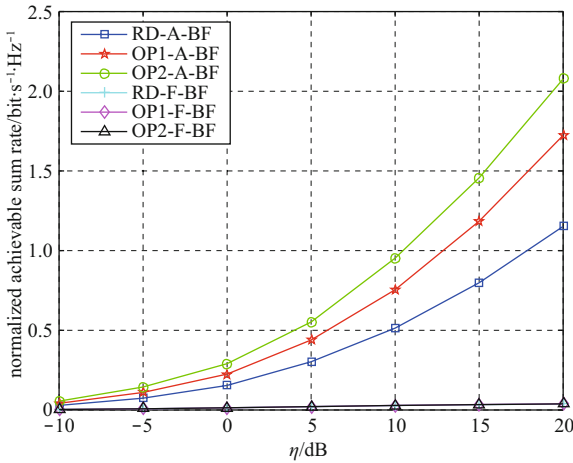


Figure 6 System sum rate with ZF precoder in satellite systems

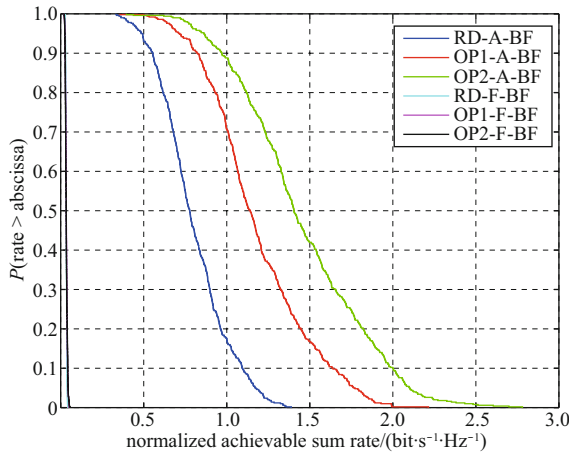


Figure 7 CCDF with ZF precoders in satellite systems ($\eta = 5$ dB)

users in one group to deteriorate system performance. In addition, in adaptive BF, the precoders are designed based on the locations of the users. Consequently, Algorithm 2 has a higher computational complexity although it also provides better performance than that of Algorithm 1.

3) With directionally fixed BF, optimized scheduling algorithm provides no benefit. Even though the scheduling algorithm separates related users into different groups, the fact that fixed BF

uses fixed precoders means that the algorithm cannot benefit from this advantage. As a result, the sum rate remains virtually unchanged under the different scheduling schemes.

We also investigated the sum rate performance of our proposed scheduling algorithms with adaptive BF in land wireless communication systems, and the results are shown in Fig.8. In this case, the performance of Algorithm 2 is superior to that of Algorithm 1.

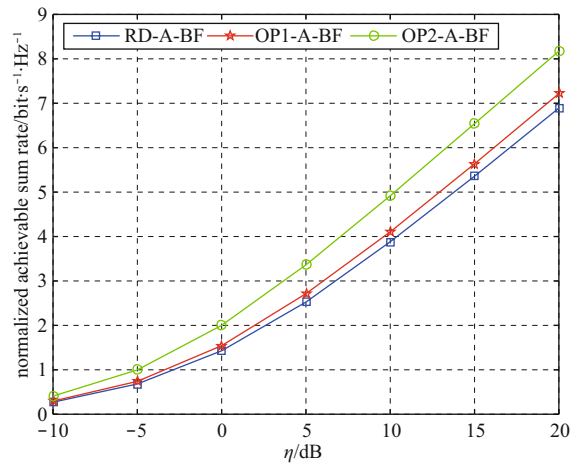


Figure 8 Adaptive BF with ZF precoding in land wireless systems

Generally in satellite systems, there are a large number of users in the network, and resources are severely limited, such as time, frequency, hardware, power, etc. Under these conditions, the level of computational complexity in most cases determines the feasibility of a particular algorithm. Since Algorithm 1 requires only a linear sequence of vector correlation computations, it is more feasible. On the other hand, due to the strong correlations between satellite channels, if the simple cost of preventing the worst pairs from being aggregated in the same group can be accommodated, then the system sum rate can be considerably improved.

5 Conclusion

In this paper, we proposed two optimized algorithms for scheduling, each with different computational complexities.

We have performed simulations of these algorithms in various scenarios and conclude that, if the scheduling algorithms that incorporate adaptive BF are adopted, then the achievable sum rate of the system can be considerably improved in terms of both the mean value and probability distribution. Algorithm 1 may be more preferable in satellite systems that have insufficient resources because it provides reasonable performance while having an extremely low computational complexity in contrast to Algorithm 2 when ZF precoding is adopted. We have further verified the feasibility of the proposed algorithms in land wireless systems. However, there is much potential improvement in designing an optimal scheduling scheme, especially when time-frequency-space resources must be dynamically and synergistically allocated. This is a topic for future research.

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About the authors



ZHOU Zhengyi was born in Hubei, China. He received a B.E. degree in electronic engineering from Tsinghua University, China, and is now a Ph.D. candidate in communications and information systems at Tsinghua University. His research interests include MIMO, precoding, and antenna systems and techniques. (Email: zhou zhengyi@126.com)



CHEN Yunfei received his B.E. and M.E. degrees in electronics engineering from Shanghai Jiao Tong University, Shanghai, China, in 1998 and 2001, respectively. He received his Ph.D. degree from the University of Alberta in 2006. He is currently working as an associate professor at the University of Warwick, U.K.. His research interests include wireless communications, cognitive radios, wireless relaying and energy harvesting.



FENG Wei was born in Inner Mongolia, China. He received his B.S. and Ph.D. degrees in electronic engineering from Tsinghua University, China, and is now an assistant professor of electronic engineering at Tsinghua University. His research interests include distributed MIMO systems, coordinated resource allocation for wireless networks, and antenna array techniques for deep space communications. (Email: fengwei@tsinghua.edu.cn)



GE Ning [corresponding author] was born in Xi'an, China. He received his B.S. and Ph.D. degrees in electronic engineering from Tsinghua University, China, and is now a professor of electronic engineering at Tsinghua University. His research interests include communication ASIC design, short range wireless communications, and wireless communications. (Email: gening@tsinghua.edu.cn)